SPACE HABITABILITY
Integrating Human Factors into the Design Process to Enhance Habitability in Long Duration Missions

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To the ones who think that
the beauty of life is part of human progress.

Abstract

Astronauts work in the most extreme environments and under life-threatening conditions in order to expand human knowledge in outer space. Radiation, adaptation to microgravity, isolation, and user-system interaction are some of the many challenges that strongly affect the level of habitability in space and, as a consequence, human performance, safety, and well-being. Knowing how these elements impact on humans is of paramount importance when it comes to ensuring user performance, safety, and mission success. Until now, human factors – the discipline that is concerned with the interactions between humans and other elements of a system – have not been taken into account appropriately, which is why the level of habitability on space stations, from the Mir to the current International Space Station, is reportedly low. As underlined by the European Cooperation for Space Standardization, the integration of sound human factors into all project phases, starting from the very beginning, has become a primary necessity, in particular considering the approaching scenario of long duration/range missions. As a means for dealing with this need, this thesis proposes a new conceptual model, which focuses on incorporating human factors principles right from the preliminary design phase into all aspects of long-duration/range human mission projects in order to improve habitability.

The new conceptual model, referred to herein as the 'Integrated Design Process (IDP)', incorporates three key design principles: habitability factors, a user-centered approach, and a holistic methodology. The conceptual model was tested against existing models in four separate studies. Specifically, study one involved students from various disciplines employing the model to assist in the design of a Moon Base. Study two involved the Extreme-Design research group employing the model to investigate habitability debriefing procedures and sensor stimuli during a simulation mission at the Mars Desert Research Station. Study three involved students from the Human-Machine System Chair at TU-Berlin designing space equipment for human-machine-environment system operations. The fourth study involved a multidisciplinary team at the German Space Agency (DLR) employing the model to design a closed-loop habitat facility for long duration space missions. The results of these studies revealed that employing the IDP model during the design phase improved self-rated habitability when compared to the current methods. These results suggest that employing such a model during the design phase of a space mission will improve habitability of the item under development, thus improving user performance, safety, and ultimately mission success. The implications of such a model extend beyond application in space and include other environments where individuals are expected to live and work in confined areas for extended periods of time, such as in research laboratories in Antartica. It can also be applied in megacities as well as in retirement homes.

Abstract auf Deutsch

Astronauten arbeiten in den extremsten Umgebungen und unter lebensgefährlichen Bedingungen, um das Wissen der Menschheit über den Weltraum zu erweitern. Radioaktive Strahlung, Anpassung an die Schwerelosigkeit, Isolation und Mensch-Technik-Interaktion sind nur einige der vielen Herausforderungen, welche sich gravierend auf die Bewohnbarkeit des Weltalls auswirken und damit auch auf die Leistungsfähigkeit, die Sicherheit und das Wohlbefinden eines Menschen. Kenntnisse über den Einfluss dieser Faktoren auf den Menschen sind von größter Bedeutung wenn es darum geht, Leistungsfähigkeit, Sicherheit und den Erfolg der Mission zu gewährleisten. Human Factors, eine Fachrichtung welche die Interaktion zwischen Menschen und anderen Elementen des Systems behandelt, wurde bis heute nicht angemessen berücksichtigt, welches Berichten zufolge die Ursache für das geringe Niveau der Bewohnbarkeit von Raumstationen, von der Mir bis hin zur derzeitigen Internationalen Raumstation, ist. Wie die European Cooperation for Space Standardization betonte ist die Integration von fundiertem Human Factors-Wissen in allen Projektphasen von Anfang an eine primäre Notwendigkeit, insbesondere in Anbetracht des immer warscheinlicher werdenden Szenarios einer Langzeitmission. In dieser Arbeit wird ein neues konzeptionelles Modell als Lösungsweg für den Umgang mit diesen Bedürfnissen vorgeschlagen, welches den Schwerpunkt auf die Einbeziehung von Human-Factors-Prinzipien in alle Aspekte einer bemannten Langzeitmission setzt, um die Bewohnbarkeit im All zu verbessern.

Das neue konzeptionelle Modell, nachstehend als "Integrated Design Process (IDP)" bezeichnet, umfasst drei wichtige Designprinzipien: Faktoren der Bewohnbarkeit, einen benutzerzentrierten Ansatz und eine ganzheitliche Methodik. Das konzeptionelle Modell wurde in vier Studien im Vergleich zu existierenden Modellen untersucht. An der ersten Studie waren Studenten aus verschiedenen Fachrichtungen beteiligt, welche das Modell einsetzten, um die Gestaltung einer Mondbasis zu unterstützen. An der zweiten Studie war der Arbeitskreis Extreme-Design beteiligt, welcher das Modell einsetzte, um Verfahren zum Bewohnbarkeits-Debriefing sowie Sensorenreize während einer simulierten Mission auf der Mars Desert Research Station zu untersuchen. An der dritten Studie waren Studenten des Lehrstuhls Mensch-Maschine-Systeme der TU Berlin beteiligt, welche Raumausrüstung für Systemabläufe in einer Mensch-Maschine-Umgebung entwarfen. An der vierten Studie war ein interdisziplinäres Team im Deutschen Zentrum für Luft- und Raumfahrt (DLR) beteiligt, welches das Modell beim Entwurf eines closed-loop Habitat-Systems für Langstreckenmissionen anwendete. Die Ergebnisse dieser Studien zeigten, dass im Vergleich zu den aktuellen Methoden die Verwendung des IDP-Modells während der Entwurfsphase die Bewohnbarkeit verbessert.

Die Vermutung liegt daher nahe, dass die Verwendung eines solchen Modells in der Planungsphase einer Weltraummission die Bewohnbarkeit und als Folge die Leistungsfähigkeit des Menschen und dessen Sicherheit verbessern und letztendlich zum Erfolg der Mission beitragen kann. Die Auswirkungen eines solchen Modells gehen über die Anwendung im Weltraum hinaus und schließen auch andere Umgebungen mit ein, in welchen Menschen in geschlossenen Räumen für längere Zeit leben und arbeiten müssen, wie beispielsweise in Forschungslaboren in der Antarktis, aber auch in Megastädten und Altenheimen.

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PREFACE

After more than fifty years of space exploration we have failed as a society to build a "space culture". Space professionals need to admit that they are not expert at developing culture; they must work in collaboration with professionals in the arts and humanities if we wish to continue human expansion and exploration of space.

Just as the Chinese emperor burned his fleet of ships to focus on the internal affairs of his empire, so we on Earth must find ways to build a sustainable society on the planet. If space culture is to be part of the solution, we have urgent work to do with professionals in the arts and humanities to make sure that it is not five hundred years before humans again step on another celestial body. We must explore all possible ways of involving professionals from the arts and humanities in all aspects of space activities.

(Roger Malina, 17 September 2009,
personal communication to Irene Schlacht)

We are just beginning our explorations
(Carl Sagan, 2002)

1. INTRODUCTION

The introduction chapter shows the strategy used to deal with the sustainable integration of humans into the space habitat system and presents the goal, motivation, context, methodology, and chapter organization of this dissertation.

Have you ever been to Mars?

> We landed on Saturday, 20 February 2010. "It was the most exciting moment of my life," said the Commander. After the landing we had to get on with the hard reality of living in isolation and the related problems. “I'm really frustrated that we don't have the possibility to go outside freely, to exercise. I think an exercise bike would help me a lot," said our geologist Sara, and the other crew members agreed with this. On Mars you cannot go freely inside and outside the habitat, and each time you want to go out, you need to first schedule an Extra Vehicular Activity (EVA). When it is your turn to perform an EVA, you need support to get dressed in the complex suit, the heavy oxygen bag, helmet, and gloves; you must check communications and get the ok. When you are out, it is really cold, movements are constricted, simple activities are complex, the suits get warm easily, and you start to sweat. "Not to be able to take a shower after sweating is a hard thing," said the Commander.
>
> To arrive on Mars is a great accomplishment, but living here is not an easy task. Just think about this: You don't have any mobile phone connection; neither a toilet that you can flush, as you don't have much water, nor even the possibility to eat fresh food. This will give you just an inkling of the difficulties. The habitat is a really complex autonomous system, and if you want to live, you need to get it working. You need to manage many daily tasks: from purifying the black water in the greenhouse system to dealing with the Martian sand that even gets in the air that you breathe, and on top of all that you must accomplish your research. We spent the first days adapting to the new context (think jet leg), making the habitat work, and syncing up with the demanding control communications. After that, we were able to celebrate some big successes. The Crew Physicist and Health and Safety Officer recorded her first solar flare. I successfully managed the first phase of the Mars Habitability Experiment. And today our engineers, who are responsible for the house system, proudly reported that everyone in the crew performed EVAs.
>
> After many difficulties and just as many satisfying experiences, we are becoming a team. Now for us the vibration of the Hab is like a mother's heartbeat for her baby.
>
> Crew 91 sends greetings from the Mars Desert Research Station.
>
> Irene Lia Schlacht
>
> Crew Human Factors specialist / Journalist

1.1 Research Motivation

The design of long duration human space missions is a highly complex and expensive process that involves different kinds of expertise, such as: structure, configuration, space environment, environmental control and life support system, HF (Human Factors), crew performance, radiation, electrical power system, thermal control system, communication system, in-situ resource utilization, operation and risk analysis, health and medical care, cost estimation, future options and development, outreach and marketing, transportation and logistic, mobility and robotics (SSDW, 2009).

In this complex and expensive process, the interrelations between all those factors and humans determine the quality of life and performance. This interrelation is part of HF and in long duration missions focuses on habitability design. Until today, HF have not been adequately considered and are usually planned to be integrated only into the final phase of the design process, when the available budget is already gone. As illustrated in *Figure 1.1*, currently, only enginering expertise regarding physical and functional elements (e.g., vibration, noise, human imput and output) is considered from the start of the mission design process (Larson, 1992). As a consequence, there is a situation of low habitability, also connected with low usability of the system, which affects the quality of life and performance of the astronauts (Johansson, 2010).

Due to the complexity of the mission design process it is easy to lose sight of one of the astronauts' main goals in space exploration: the acquiring and, just as relevant, the communication of new knowledge. To reach this goal, is it important to create the best possible conditions to support human performance. For this reason the mission design process should be interdisciplinary – i.e., based on the most advanced technologies in the engineering field. At the same time, however, it should be supportive of the astronauts' complex operational, physical, psychological and socio-cultural needs. Those needs should be integrated into and interrelated with the habitat system. For that reason, not only engineering factors are of design importance, but "human" aspects as well, like the privacy of a living or dining area, or separation for reasons of confidentiality (Messerschmid & Bertrand, 1999). The different perspectives have to be purposely interrelated with HF design using a user-centered approach and holistic methodology in order to support the "human" aspects within quality of life and performance. Indeed, to reach maximum performance, humans must be at the center of the designing process and qualitative life dimensions should be supported, which, in the case of habitability, are: usability, livability, and flexibility.

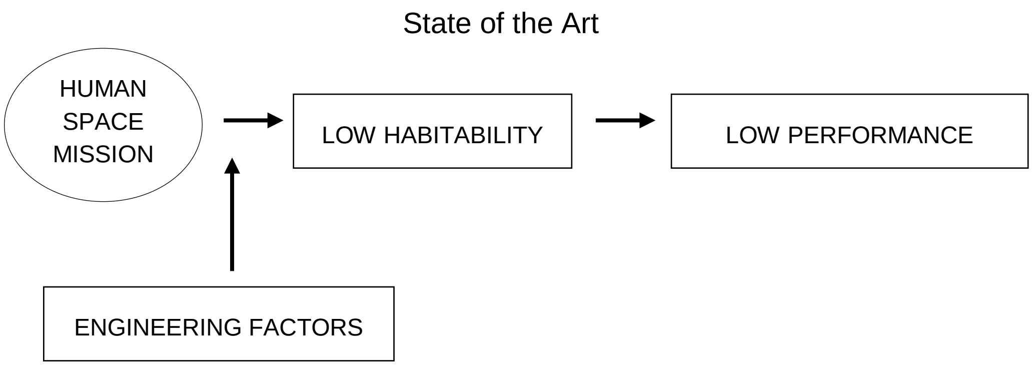


Figure 1.1: State of the art. Projects based only on engineering factors do not support the level of habitability needed to realize the best performance and acquire new knowledge.

This research is based on the idea of achieving proper integration of the "human" aspect throughout the entire mission designing process, from start to finish, in order to guarantee system habitability and to strengthen the crew's ability to successfully perform their mission and return safely to Earth (Osburg, 2002; Bishop, 1999).

1.2 Goal

In order to improve habitability in space, this research presents the concept of a new design model (*Figure 1.2*) that integrates HF design into the mission design process: the Integrated Design Process (IDP). The IDP aims to improve habitability during long duration space missions by designing usability, livability, and flexibility from the first step of the project. The IDP is a design model composed by combining habitability factors, a user-centered approach, and a holistic methodology. Throughout this model, the goal is to design a sustainable living system capable of supporting user experiences and thereby fostering acquisition of knowledge, increasing performance, and ensuring mission success.

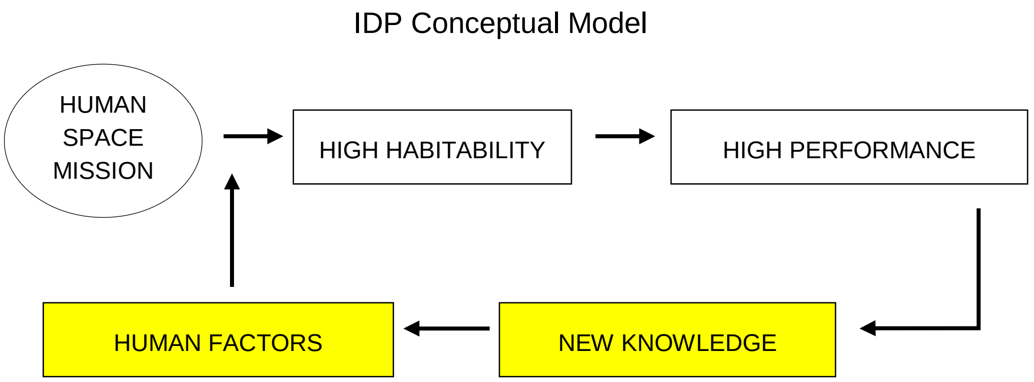


Figure 1.2: IDP integrates HF from the start of the design process. This enhances habitability and, as a consequence, increases the astronauts' performance also in terms of acquiring new knowledge applicable to human factors.

Goal: To increase habitability by enhancing the capability for designing human space missions through the application of the IDP.

To reach this goal, is it important to follow a concise strategy that is the structured along the sequential fullment of meta-objectives.

The meta-objectives are:

1. To find possible field challenges and their roots
2. To discover solutions to the challenges
3. To create the context for the application solution
4. To apply the solution
5. To verify the resolution of the challenges
6. To achieve the main goal

1.3 Research Context

The research context focuses on two main topics:

- The current habitability conditions of astronauts in long duration missions
- The mission design process that led to these habitability conditions

Of all the places where humans can live, space is the most extreme. Isolated from Mother Earth and society, the spaceflight environment is characterized by temperature extremes, microgravity, solar and galactic cosmic radiation, lack of atmospheric pressure, and high-speed micrometeorites. While these factors induce a host of physiological, biomedical, and environmental stressors to flight crews, long duration spaceflight has revealed an additional group of stressors that impacts crew performance and safety: low habitability (Morphew, 2001).

This factor needs to be adequately considered in human mission design, a multidisciplinary approach based on humanities as well as science, which has not been considered so far. One of the reasons for this lack of consideration can be found in the difficulties of sharing language between different disciplines. Indeed, as explained by Masali, the possibility of building a bridge between different paradigms of the various scientific and humanities fields requires, in addition to an intention to interact, adequate knowledge of how the interlocutor thinks, plans, and acts. The important point is the use of an understandable shared scientific language, which is already an extensive preliminary work that remains to be done (Masali, 1994).

Habitability

Habitability is a qualitative dimension, supported by the application of HF. The demand for habitability is undergoing changes: Following the initial constraints related to short duration missions, we now have to face the conditions of long duration and long distance missions. As a consequence, habitability is required to support performance. With the stringent technical specifications for launch vehicles and transport into space, a very tight framework for the creation of habitable space is set. More than that, from the days of the Cold War, the military orientation of space agencies still does not allow the HF perspective to be applied, even today. These constraints result in very complex interaction between the habitat and the inhabitant (Häuplik-Meusburger, 2011) or, in other words, in low habitability.

Shannon Lucid (1996) reported that storage on the Mir was a big problem. In her debriefing, she explained that there was no real storage place and the hardest thing was to find stuff. “When you have found it, you are 99% complete with anything. This is time consuming. It’s like being in someone’s garage and there is no place to put anything. And if I moved too fast through stuff, I would end up bruised or I would scrape myself or something. But the problem is that you would get stuff in your eye once in a while.” This statement allows us to understand how storage problems impact the level of habitability and, as a consequence, performance and safety.

Today, at the ISS (International Space Station), the storage and object location problems remain unsolved. This was reported in 2010 by astronauts Frank De Winne and Ernst Messerschmid at the ILA (International Aerospace Exhibition) in Berlin during the astronauts’ public meetings organized by DLR (Forschungszentrum der Bundesrepublik Deutschland für Luft- und Raumfahrt).

Author: How can habitability be improved for long duration missions?

Frank De Winne: "In missions you are always looking for little things".

Indeed, these problems have yet to be resolved. They show that space habitat orientation today still does not support HF. Ernst Messerschmid (D1-Spacelab Astronaut 1985 with a flight on Challenger and former Head of the European Space Agency -ESA- Astronaut Centre) confirms that HF are fundamental to long duration missions. Storage system improvement and solutions for finding little objects are relevant matters that need to be looked at from the perspective of HF. This gap was also reported by Shannon Lucid (1996) in the debriefing interview where she explained: In essence, the lack of human factors could be characterized as a safety hazard, “all that human factor type thing is not present either in the Soyuz or Mir. As one cosmonaut explained it to me in Star City, the Soyuz was built by engineers, and they never asked for any input from people who were actually going to use it”.

Mission Design

In any habitat system design where HF have no place, habitability is consequently low. To support performance in long duration missions, increasing habitability is a prerequisite. The first step in HF research, based on human-centered design, is the user analysis, wherein input from people who are going to use the product or service is collected. Performing this user analysis on users and space employees, the author has been able to confirm how the space context today is still not based on HF. In a questionnaire based on a literature review, different options were proposed as relevant user needs for long duration missions. On this question, 5 out of 6 astronauts who replied selected “Privacy” as a need. However, the results from the majority of space employees (8 out of 13) did not coincide with the astronauts’; indeed, the latter preferred “open space”.

This result clearly shows an obvious gap: The employees are oriented more towards physical quantities, whereas the astronauts express the need for a qualitative dimension. Indeed, the qualitative dimensions of the project are not satisfied. Having defined habitability as”the quality of life in an environment”, it is possible to understand that habitability is the key concept to work on.

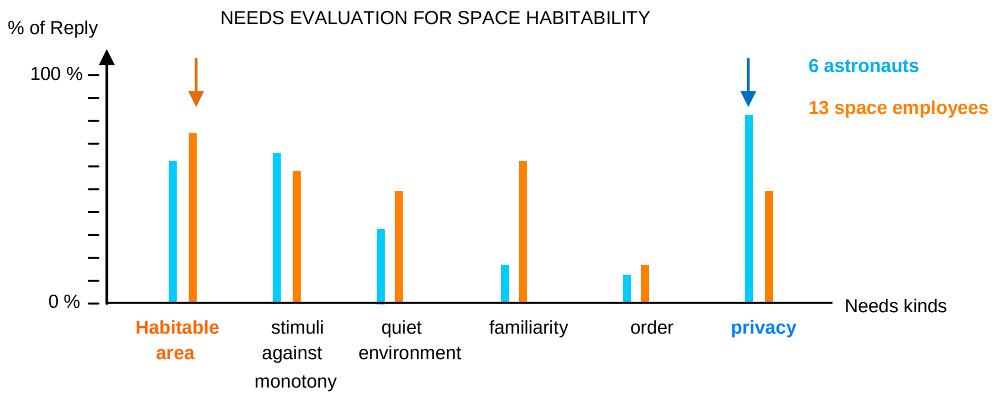


Figure 1.3: Needs evaluation for space habitability

HF qualitative dimensions such as sensations and feelings can be designed and planned on the basis of the user's needs, which in this research are considered as a fundamental part of habitability. Those dimensions, typically approached by human-centered design and humanities, are nowadays not involved in mission design. In order to design habitability, we need all the knowledge available, such as art, science, engineering, and design and, as a consequence, a multidisciplinary approach ought to be the first step in mission design. Humanities and science disciplines need to be involved just as much as engineering disciplines in order to support both the quantitative and qualitative dimensions of mission design.

One of the foremost endeavors of space exploration is furthering the progress of knowledge. Indeed, as the director of ESA explains: "Today space activities are pursued for the benefit of citizens, ..to pursue their dreams, to increase their knowledge" (Dordain, 2003). NASA, too, confirms that the aim of space research is also "to reach for new heights and reveal the unknown so that what we do and learn will benefit all humankind" (NASA, 2011d). Given that humans have many vital needs and are moreover difficult to control, an oversimplified solution would obviously be to remove humans from the system and substitute them with remotely controlled robots, which are also able to acquire new data and knowledge, even with more accurancy, but not creatively. Indeed, knowledge should be acquired both scientifically and creatively. According to the ESA astronaut Ernst Messerschmid: "Creativity is important in manned exploration missions; it distinguishes the astronaut from robots as they are prepared for the unexpected" (Schlacht & Ono, 2009). The JAXA astronaut Mohri Mamoru explains that the scientific approach aimed at discovery should be applied in parallel to a creative and artistic one aimed at communication: "I came to understand the "origin of life" on the Earth shining blue in the light of the sun. And I came to feel that what I needed was not scientific expression, but rather artistic expression, to be able to tell this to many people" (2008). If knowledge gain is one of the main purposes of space exploration, the involvement of arts and humanities is itself "inextricably tied to the process of creating human civilization", confirms Malina (Malina courtesy communication, 1989, as cited in Woods, 2001).

As previously stated, this thesis seeks to establish a new design model that integrated human factors, within human-centered approach and holistic methodology, to increase habitability during the design process for human space missions. The support of sensory, cultural, and emotional human needs turns out to be intrinsic to the new design model, and hence demonstrates the need of an interdisciplinary design methodology based both on scientific disciplines and humanities such as design, architecture, arts, anthropology and psychology into human space mission design in a multidisciplinary way.

In conclusion, as mentioned by Chris McKay, "human factors need to integrate more explicitly into the design and operations of space missions, as well as in the science questions we address. This is particularly true for long term research bases on the Moon and human missions to Mars" (McKay personal communication 2011).

1.4 Research Process and Methodology

This thesis proposes the IDP as a new design process in the field of long duration human space missions. The design process has been built as a logical development of the research path pursued throughout many years. It is therefore presented here as part of the research challenges in order to explain the research methodology.

Research Path

The complex of investigations started during the author's undergraduate studies at the Design Faculty of the Politecnico di Milano technical university, where the author was able to thoroughly confront design theory with the hard reality of space habitat conditions, thanks to an internship at Thales Alenia Space in 2005. This knowledge has been further developed throughout the PhD research. During the internship, the researcher performed the first user analysis based upon astronaut interviews. She continues researching the users until today, meeting astronauts at conferences and public events. Attending international conferences, the researcher was also able to meet and select space experts from humanities and scientific disciplines willing to cooperate on a common project dealing with the improvement of space habitability through HF research. After the literature review and astronaut interviews, the author coordinated an experiment with a multidisciplinary team to address one important knowledge gap related to habitability: human visual adaptation in space. Knowledge about visual perception modification due to the space environment is a mandatory priority for habitat interface design. The author opted for visual perception as the most important perceptive function in space. Led by the authors, the first interdisciplinary project, Cromos, investigated chromatic and achromatic perception in microgravity and was chosen to be performed in parabolic flight by the European Space Agency (ESA) in 2006.

This first successful experience became the basis for the creation of the Extreme-Design Multidisciplinary Research Group. The group, which has been applying a multidisciplinary methodology for implementing habitability since 2007, included in HF research the fields of medicine, art, anthropology, architecture, HF, design, anthropometry, ergonomics, engineering, and psychology, among other disciplines. Based on this concept, the group has been able to develop various projects, experiments, and publications. Working in cooperation with the Extreme-Design Group since 2007, the researcher followed structured research phases (*Table 1.1*), which enabled her to develop the IDP as a concept for a new methodology model that integrates HF and is based on the qualitative dimension. The researcher has been able to apply this model by working in different projects related to human space missions. The first experience was the student Space Station Design Workshop, where she had the opportunity to integrate the IDP as the Human Factors specialist and group tutor. Particularly relevant was the habitability project developed for the Mars Mission simulation at the Mars Desert Research Station in 2010 and 2011. During the experiment, extensive habitability investigations with elements of a qualitative dimension were performed. Creative interaction with plants, colors, fragrances, and natural sound were carried out, with the six-member crew undergoing intensive debriefing on habitability problems. The IDP was also applied in student courses led by the author: the Habitability of Space Systems Seminar and the Human-Machine System Multidisciplinary Team Project. The researcher also guided research groups from other universities through multidisciplinarity by exposing the engineering-oriented and artistic-oriented groups to both humanities and scientific perspectives and solutions. With this methodology, the groups were able to find human-centered design and holistic solutions oriented towards increasing the quality of habitability in human space missions. Finally, the IDP concept model was applied at the first workshop led by the

German Space Agency (DLR) on human habitat design at the DLR Concurrent Engineer Facility.

As a future goal, the methodology is being proposed for application at the interdisciplinary Concurrent Design Facility (CDF) of the European Space Agency (ESA).

Table 1.1: Research methodology phases

PHASE 1 ANALYZE IT	PHASE 2 FIND THE CHALLENGES	PHASE 3 APPROACH IT	PHASE 4 SOLVE IT	PHASE 5 VERIFY THE SOLUTION
User analysis	Focus on challeges	Approach the challenges	Solution hypothesis	Solution verification
Astronaut interviews, research of user conditions based on user-centered approach	Definition of habitability challenges in LDM considering multidisciplinary habitability factors	Multidisciplinary team (scientific disciplines and humanities) holistically approached the challenges	Integration of HF qualitative dimension into space mission project to find innovative design solution	Verification of project quality and innovation to support user habitability and performance
LDM = Long Duration Mission				

Research Challenges

Needless to say, putting together a doctoral dissertation on the field of space travel is no easy task. There are two main challenges: the first one is the restricted and not easily accessible field and the low number of users. The second one is the low sensitivity of the persons involved in the field with respect to human factors and humanities.

The field is quite new, especially if one considers space exploration to have begun in earnest with Gagarin in 1961, meaning that there are only exactly 50 years of data to explore. The main work on habitability was done by the Russians in the 1960s. However, this work is difficult to access due to the language barrier and also because of restrictions on document access. Indeed, apart from Europe, the space field is generally and strictly connected to a military background, and information access is classified and thus limited. Moreover, there is only one active space habitat where up to six users can live and work for up to six months on a continuous basis: the ISS. For this reason, carrying out research in this field is particulary difficult, as there is only one facility and few users are available for all researchers. To overcome these difficulties, the author attempted to adopt a strategy based on cooperation with international experts, which was explained in the previous part *Research Path*.

Nevertheless, facing the reality of a space industry dominated by the engineering-oriented fields, the author throughout the doctoral research has sought to develop projects that would lay the research foundations for increasing sensitivity regarding HF and promoting HF disciplines as a viable strategy for improving human life conditions and performance, but also for decreasing costs. She concomitantly applies this research within both academic and industrial contexts while collaborating with scientific and humanities experts.

1.5 Organization of Chapters

This introduction provides the background for the challenges involved in space habitat design and the reasons for undertaking a dissertation on this topic. This provides the groundwork for the subsequent chapters of this thesis.

- Chapter 1: *INTRODUCTION*

The introduction aims to present the goal, motivation, context, methodology, and chapter organization of the overall dissertation.

- Chapter 2: *STATE OF THE ART*

This presents the main elements of the current space habitat design, identifying and describing the factors that play a key role in the process of habitat design:

- Habitability and human factors models in relation to the aerospace context
- Operational, physiological, environmental, psychological, social, and cultural factors applied to the space environment
- Space system elements: user, spacecraft system, environment, and mission
- Mission design process currently used both in space and in the human factors field

The methodologies used include a literature review, visits to various facilities, and consultation of field experts.

- Chapter 3: *PROBLEM: CRITICAL ANALYSIS OF HABITABILITY CHALLENGES*

This chapter presents current and future habitability challenges and the investigation of their causes. The focal point is user need investigation as the basis for a critical analysis of the state of the art of habitat design. The methodologies used include the analysis of the user, based upon interviews with 14 astronauts, mission debriefings, and a literature review. The causes of the challenges are investigated both from the historical perspective of spacefilight development and also regarding the lack of methodologies for a human factors design process.

Chapter 2 about the state of the art and chapter 3 about the challenges serve as a basis for the concept of a new design model, presented in chapter 4, and its application to the conceptual design of habitability solutions presented in chapter 5.

- Chapter 4: *SOLUTION:*
  INTEGRATED DESIGN PROCESS

Following the identification of the gaps in the current design process in chapter 3, the creative focus of chapter 4 is on overcoming these with the concept of a new design process. This chapter provides a detailed description of the new design model that aims to overcome challenges and improve habitability.

The user-centered approach and the holistic methodology were adapted by the author to serve as the foundation of a new design process that integrates habitability factors. The methodologies used include the cooperation of and consultation with field specialists.

- Chapter 5: *APPLICATIONS: HABITABILITY DESIGN PROJECTS*

Chapter 5 presents four cases studies where the new model was applied to the conceptual design of habitability solutions for long duration space missions. The practical applications were performed in interdisciplinary projects and workshops both within student and professional contexts. As a part of the conceptual model process, the results of each singular case study were evaluated in comparison to the current methodology.

- Chapter 6: *CONCLUSION*

The final chapter offers a critical review of the overall achievements, and a summary regarding the contributions of the new design model, and identifies possibilities for further research.

Table 1.2: Chapter topic, content, and methodology

CHAPTER	TOPIC	CONTENT	METHODOLOGY
1. *INTRODUCTION*	Research motivation PhD goal and context Research methodology PhD structure	AIM OF RESEARCH	Knowledge acquired during: - conferences - workshops - discussions with professionals at various facilities (e.g. ESA-ESTEC)
2. *STATE OF THE ART*	Habitability, Space system elements, Design process Conclusion	CURRENT STATE OF RESEARCH	Literature review and consulta-tion with experts
3. *PROBLEM: CRITICAL ANALYSIS OF HABITABILITY CHALLENGES*	Habitability challenges, User investigation, System gaps, Multidisciplinarity Conclusion	CHALLENGES / SYSTEM GAPS	- Astronaut interviews and questionnaires - Investigation of habitability problems in current and future contexts
4. *SOLUTION: INTEGRATED DESIGN PROCESS (IDP)*	On the IDP: - Habitability factors - User-centered ap-proach - Holistic design - Comparison with ESA Concusion	SOLUTION MODEL	- Cooperation with experts from different disciplines - Consultation with profession-als in the field - Brainstorming with specialists
5. *APPLICATIONS: HABITABILITY DESIGN PROJECTS*	Methodology application: - Moon Base design - Sensory stimulation - Creativity - Debriefing procedures - Innovative tools - Closed-loop habitat Conclusion and process verification	PROJECT VISIBILITY	Concept's application to: - Coordinating multidisciplinary team research - Tutoring and participating in habitat design workshops - Organizing and participating in mission simulation experiment - Cooperation with: Extreme-Design research group, SSDW Stuttgart, MMS team project and Seminar, DLR FLaSH project
6. *CONCLUSION*	Dissertation achieve-ments: - Achievement review - Contributions of the work - Future applications	CONCLUSION	Critical review of the overall work, with support of specialists

"The sea is dangerous and its storms terrible,
but these obstacles have never been
sufficient reason to remain ashore…
to meet the shadowy future without fear
and conquer the unknown"
(Ferdinand Magellan, Explorer, 1520
cited after Watkins, 2010)

2. STATE OF THE ART

This part of the dissertation focuses on the current state of the art in habitability and human factors research and the application to long duration missions, the interrelations between system elements in such space missions, the design process related to human factors, and the design process applied in space missions.

Progress made in recent decades has now reached a point where long duration human space missions can be prepared. At the same time, a paradigm shift from basic survival-in-space to habitability, performance, and crew efficiency, issues more appropriate to long duration mission missions, can be observed (Osburg, 2002). Habitability, and as a part of it, performance and crew life, would focus on the current long duration mission in the ISS and on future projects such as for Low-Earth Orbit, Near-Earth Object, Mars, but also supporting the opening of access to the space environment to the public via space tourism. A defined structure is applied to cover all the habitability aspects: however, each habitability topic and factor is strictly influenced and connected, and their effects are not isolated, (Blume Novak, 2000 A 132).

Table 2.1: Possible examples of interrelations between habitability topics and factors (table borders are dashed on purpose to represent the connections between topics)

FACTORS & TOPICS	Operational	Physiological	Environmental	Psychological	Socio-Cultural
Human (Astronaut)	Performance Training Selection	Physiological health	Exaptation	Motivation, psychological support	Crew dynamics Art, Religion
Machine (Habitat)	Human-Machine interaction	Life support system	Environmental control	Spatial confinement	Social isolation, free time activities
Environment (Space)	In-situ resource utilization Mg effects on task	Mg effects on body	Natural environments	Earth-out-of-view effects	Knowledge about the environment
Mission (Space exploration)	Mission Design Process Mission Control Mission Duration and Distance				

2.1 HABITABILITY MODELS

This subchapter is dedicated to the definition and the design models applied to the concept of habitability and human factors, in particular presenting examples of generic human factors application and focused aerospace and space applications.

Habitability is addressed by the HF discipline, which is the application of HF to long durationliving and working conditions (Messerschmid, 2009, Messerschmid & Bertrand, 1999). As a consequence, habitability factors are HF applied to long duration living and working conditions.

The habitability factors may be many and diverse, according to the different definitions and models of habitability and HF. In this chapter, selected researches are presented that have been carried out in the HF field applied to space habitability.

The topics investigated are:

- Definitions and models of habitability factors and HF
- Operational, physical, psychological, and psycho-social factors in space
- Overview of space life aspects and their relationships to habitability factors

2.1.1 Habitability and Human Factors

In this section, the differences and communalities between the definitions of habitability and HF are defined.

Habitability

In the SSP 50005 international standard, realized jointly by the Italian Space Agency (ASI), the Canadian Space Agency (CSA), the European Space Agency (ESA), the National Aeronautics and Space Administration (NASA), and the National Space Development Agency of Japan (NASDA), "habitability is defined as the quality of life in an environment" (AA.VV, 1999).

This dissertation approaches habitability at the level of the quality of life that can be supported by such a habitat. In short, a high level of habitability is the optimal condition for life, while low habitability only allows for survival. Non-habitable environments are environments that do not support life. A more complete definition can be found in an earlier NASA report:

> "Habitability can be considered as that equilibrium state, resulting from human-machine-environment-mission interactions which permits man to maintain physiological homeostasis, adequate performance, and psychosocial integrity" (Fraser, 1968 p. V).

According to the SSP 50005 international standard,

> the term includes quality standards to support the crew's health and well-being during duty and off–duty periods. The basic level of habitability deals with the direct environment, like climate, food, noise, light, etc., influencing primarily human physical conditions. The extended level of habitability is introduced to take care of the long–term conditions of stays in orbit and nurture not only the individuals' physical health but also the mental/psychological health. Experience has shown that with the passage of time, dele-

terious effects of isolation and confinement gain prominence (AA.VV, 1999 p. 1-3 paragraph 1.6.8).

This definition points out the relevance of the physiological as well as psychological effects of long duration mission isolation.

Other frequently quoted definitions are:

- Habitable or livable is defined in the Oxford dictionary (2011) as habitableness, “suitable to live in”, and suitable as: “right or appropriate for a particular person, purpose, or situation”.
- In NASA’s Human Requirements for Extended Spaceflight (Living Aloft), habitability is defined as “general term which connotes a level of environmental acceptability” (Connors, 1985, p. 59). *Acceptable* means “adequate, though not outstanding or perfect” (Oxford dictionary, 2008). Indeed, the definition does not support the idea of quality shown in the more contemporary definition provided by NASA in conjunction with the other agencies (AA.VV, 1999).
- Messerschmid defines habitability as the living conditions concerning work and the domestic environment (2008). “The degree of habitability directly influences a factor which is important for the mission: crew performance. This term includes the crew´s ability to fulfill its tasks correctly and in a reliable manner”. Performance is influenced by physiological conditions, working capacity, and psycho-social aspects (Messerschmid & Bertrand, 1999 p. 413).
- The “Summary of the Current Issues Regarding Space Flight Habitability” by NASA´s operational and habitability team leader states: “Habitability is defined by the physical interface between the human user and the system/environment; habitability can also be described as the usability of the environment”. Good habitability decreases crew errors or other performance issues. “Some aspect of habitability, such as religious practices, personal space, nutritional requirements, or palatability, temperature, and illumination can vary across cultural groups”. (Blume Novak, 2000, A131).

In summary, taking into account the different definitions presented here, habitability is influenced by the interaction between humans, machines, and the environment, as well as by psychological and social factors such as territoriality and privacy. In addition, other elements also influence the quality of life, such as daily schedule or astronaut training and selection. The multidisciplinarity of these topics justifies the interdisciplinary approach followed here.

In conclusion, habitability refers to:

- Quality of life
- System usability
- Human-machine-environment mission interactions
- Physiological, psychological, social, and cultural factors.
- Performance, health, and well-being during duty and off-duty periods

Human Factors

HF are defined "as the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance" (IEA, 2000).

Messerschmid & Bertrand define habitability as a concept addressed by the HF discipline (Messerschmid, 2008; Messerschmid & Bertrand, 1999). HF is defined as the conjunction of ergonomics and habitability, where ergonomics is relevant for working environments for short-term activities and habitability for living and working environments for long-term activities (Messerschmid & Bertrand, 1999).

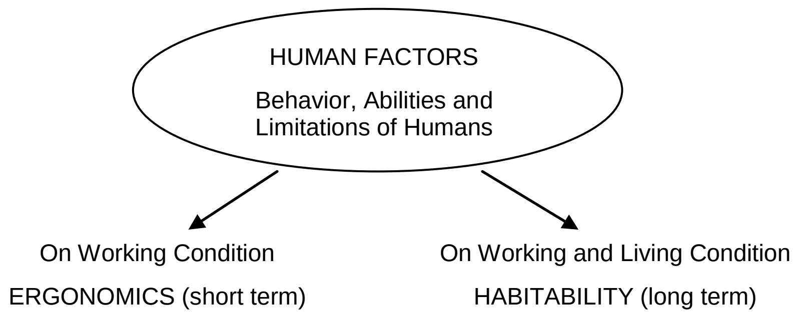


Figure 2.1: HF notion model (Messerschmid & Bertrand, 1999 p. 394)

Indeed, time is the most important variable in the habitability concept; in fact, "habitability requirements for space flights are driven by mission duration" (Woolford & Mount; 2006). "For brief periods", quoting the NASA requirement Living Aloft, "almost any arrangement that does not interfere with the health of the individuals or the performance of their jobs would be acceptable. Over the long term, conditions must support not only individuals' physical, but also their psychological health." (Connors, 1985, p. 59).

However, there is another variable that, although it is obvious, is not part of the standard requirement: the distance from Earth. This variable should be added to the quoted requirement, resulting in:

"Human factors and habitability requirements for space flights are driven by mission duration and distance."

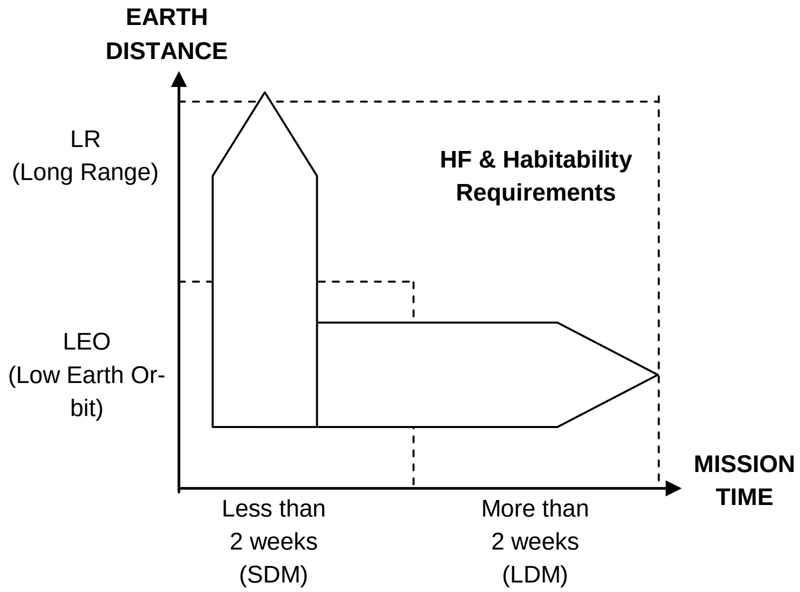


Figure 2.2: HF and habitability relevance increase with mission duration, but also with distance.

This approach is a new vision that gives proper characteristics to the term "human factors" (HF), which has always been commonly recognized as the American synonym of the European term "ergonomics" (IEA, 2000).

HF is considered a "specific branch of Industrial Design" (Ferraris, 2004 p. 22), which integrates both quantitative and qualitative project variables in a multidisciplinary manner, supporting functional but also affective, emotional, and cultural user needs through a user-centered approach.

The relation between HF and user-centered design is also expressed in the following quote:

> Human factors design typically involves examining the total system, comprising an account of how users interact with the device(s) to perform their tasks on a workstation under a specific environment. Its objective is to ensure human-centered design, such that systems, jobs, products, user interfaces and environments, are designed to complement the physical and mental abilities of users, and also accommodate their limitations. Human-centered design begins with an understanding of users' characteristics and the tasks they are expected to perform. Functional support features and user interfaces are then designed to ensure safe and effective operation, so as to maximize the productivity of the overall system. Human-centered design ensures products and systems that are functionally appropriate and user friendly, and thus well accepted by their users (Lin & Chui, 2001).

In conclusion: To overcome habitability problems foreseen in long duration missions and increase performance and well-being, "it is important to provide methods to increase human reliability and performance. Both can be affected by many factors such as age, state of mind, emotions and propensity for common mistakes, errors and cognitive biases. A promising approach to overcome human errors and malpractice is to provide … methods that take into account human factors" (Dzaack et al., 2010 p. 1).

In summary, HF design aims at:

- Integrating multidisciplinary quantitative and qualitative project variables
- Complementing the physical and mental abilities and limitation of users
- Appling user-centered design approach
- Optimizing human well-being and overall system performance

2.1.2 Habitability Models

To investigate habitability and HF, different models have been proposed. In this section, the most frequently used and credited models applied to the aerospace and space fields are described.

Models in Aerospace

The SHEL (Software, Hardware, Environment, Liveware) model (Edwards, 1972 cited after Hawkins, 1987) and the "building block" model (Hawkins, 1984 cited after Hawkins, 1987) are based on the same concept and continue to be the HF models most often validated and used in the aerospace fields (Prof. Takashi Toriizuka, personal communication Berlin 2011).

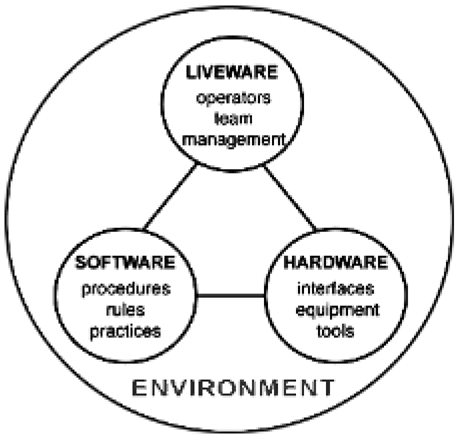


Figure 2.3: SHEL Model (Edwards, 1972 retrieved from Università di Siena, 2001)

The SHEL model is based on the following points:

- "Hardware represents any physical and non-human component of the system, such as equipment, tools, manuals, signs, etc.
- Software represents any component such as rules, procedures, policies, norms, practices, and any other formal or informal rule that defines the way in which the different components of the system interact with each other.
- Liveware represents any human component in his relational and communicational aspects.
- These resources don´t interact in void but in a socio-political and economic environment, which affects the functioning of the system.

According to the model, the analysis of the socio-technical systems should focus on the interactions among these resources. For HF researchers the most important interactions are the ones including the Liveware component: L-H, L-S, L-L" (Edwards, 1972 cited after Università di Siena, 2001).

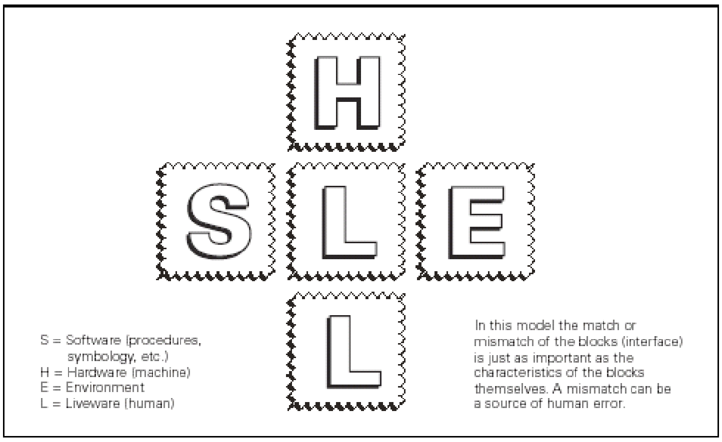


Figure 2.4: SHELL Model (Hawkins, 1987 retrieved from Atlas Aviation, 2004)

Unlike the SHEL model, the "building block", commonly denominated as SHELL model, is structured as follows:

> Liveware is the man at the center. Yet the man is subject to many variations in his performance and suffers from many limitations, most of which are now predictable in general terms. It might be said that the edges of this block are not simple and straight and so the other components of the system must be carefully matched to them if stress in the system and eventual breakdown are to be avoided.

An important characteristic of this central component is that people are different, which influences, for example, motivation or attitudes. "While it is possible to design and produce hardware to a precise specification and expect consistency in its performance, this is not the case with the human component in the system, where some variability around the normal, standard product must be anticipated" (Hawkins, 1987 pp. 21-22). However, this variability may be controlled with training, selection, and standardized procedures.

The other components of the SHELL model are described in terms of their interaction with humans, which is called Liveware in this context.

- Liveware-Hardware: interface studied in the context of human-machine systems
- Liveware-Software: not a physical aspect of the system, like procedures and computer programs
- Liveware-Environment: all the measures and instruments aimed at adapting man to match the environment, like using an oxygen mask to counteract the effect of high altitude.
- Liveware-Liveware: the crew's influence on behavior and performance. This concerns teamwork, crew cooperation, leadership, and personal interactions.
- Other, not HF-focused components: Hardware-Environment, such as equipment packaging; Hardware-Software, e.g., aspects of the equipment instructions manual (Hawkins, 1987 pp. 21-22).

"Although the cultural dimension is considered as part of the liveware and environment components of the SHELL model, Crew Resource Management and increases in airline mergers and internationalization emphasise the importance of explicitly recognising and addressing culture and cross-cultural issues." (Keightley, 2004 cited after Perry & Perezgonzalez, 2010).

Considering these factors, the "modified SHELL model" below also addresses culture.

- Liveware-Culture: provides interpretative differences for individual behavior and the values and expectations that affect the interfaces between the human operator and aviation system components (Keightley, 2004 retrieved after AviationKnowledge).

Yet another version of the SHELL model is SHELL-Team or SHELL-T, which emphasizes social factors. The SHELL-T model is based on modeling team performance and considers several interacting SHELL units (Cacciabue, 2004 cited after Perry & Perezgonzalez 2010).

Models in Space

One of the most highly credited models is given by the content of "Living Aloft, Human Requirements for Extended Spaceflight" by NASA, here reported in a schema. The model approach includes factors related to physical environment, health and leisure, privacy, and complex effects (Connors, 1985).

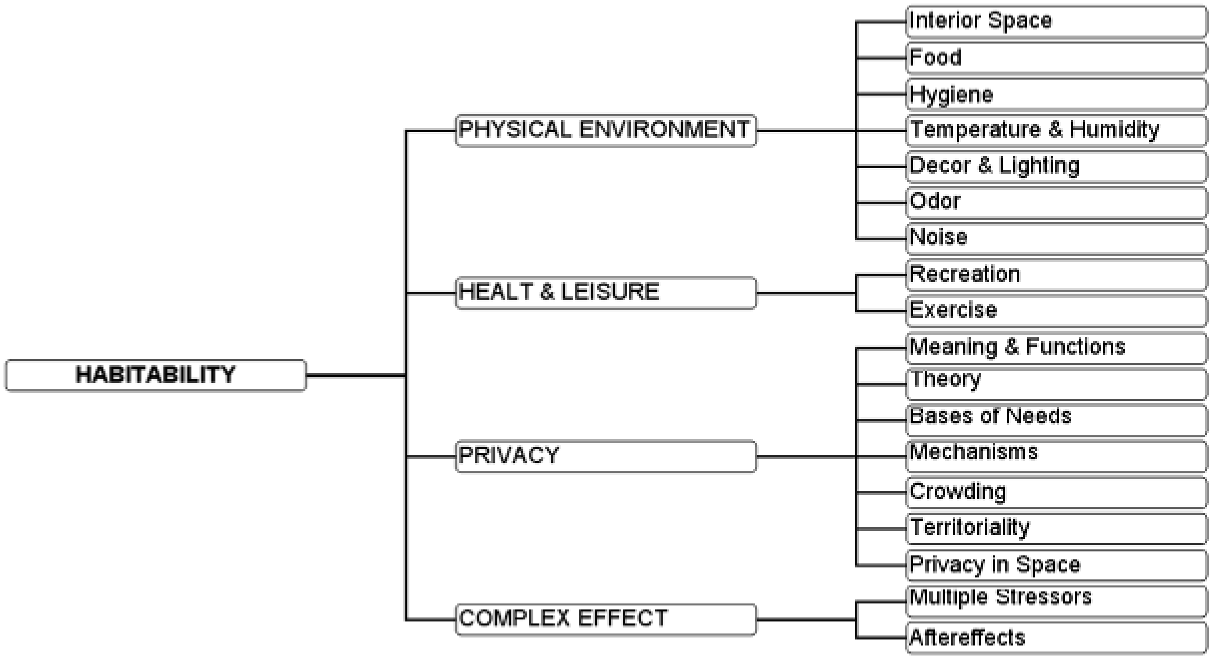


Figure 2.5: NASA structure of habitability requirements (Connors, 1985)

However, the more recent Human Integration Design Handbook (NASA, 2010b) considers habitability in terms of the following topics: Food and nutrition, personal hygiene, body waste management, countermeasures, medical, stowage, inventory management, trash management, sleep, clothing, housekeeping and recreation.

A proper HF model has been introduced by JAXA with the publication by Dr. Takao Yamaguchi in "A Human Factors Approach for Japanese Experiment Module Development". The model proposed for the Kibo ISS module is based on four major factors: Habitability, Operations, Physiology, and Psychology.

- "Habitability is composed of the factors which provide a shirt-sleeve environment for astronauts living and working inside the space module without wearing space suits.
- Operation is composed of the factor which provides the job support environment for astronauts performing their mission.
- Physiology is composed of the factors which provide the environment for maintaining astronaut's health.
- Psychology is composed of the factors which establish a suitable environment for stabilizing astronaut's mental health" (Yamaguchi, 2000 p. A108).

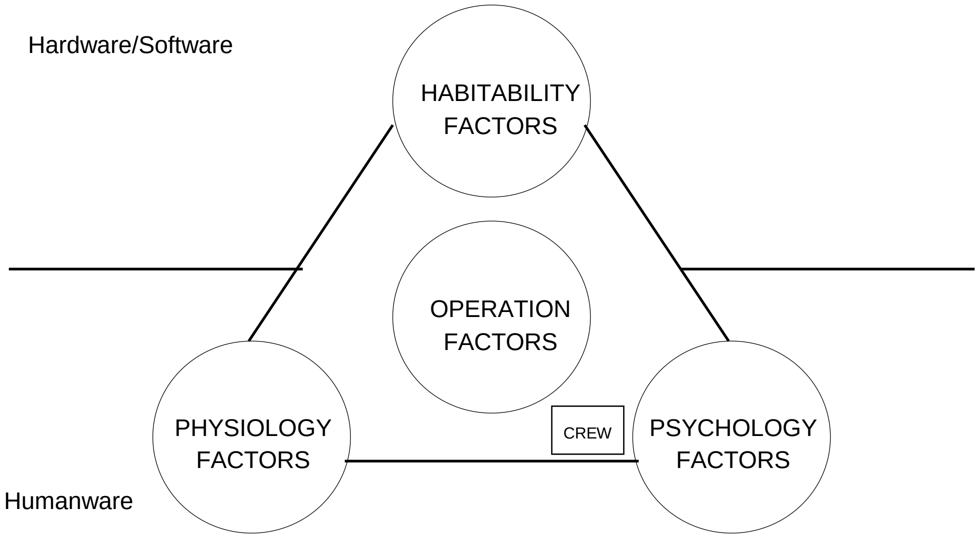


Figure 2.6: Kibo HF model: four factors affecting the astronauts, the hardware, and the software (Yamaguchi, 2000 p. A109)

The relevance of these factors has to be identified in relation to system performance, functions, and mission goal of the human space system. However, the habitability and operation factors are more relevant for the work environment, whereas the physiology and psychological factors are more relevant in the living environment.

The HF model should be integrated into the entire mission design phase, also supporting those factors with requirements and validation measurement to be performed during operation in space.

2.1.3 Interdisciplinary Habitability Design

Human factors and habitybility are interdisciplinary design discipline. Habitability factors are the HF applied to long duration tasks related to the user´s living and working conditions in long duration missions (Messerschmid & Bertrand, 1999).

Design Factors

Considering the previous models, five interrelated factors have been selected in order to cover all factors that apply to humans: operational, physiological, environmental, psychological, and socio-cultural. The description and application of these factors in the space field are part of the next sections. Here, the reasons for selecting them are given:

- Operational factors refer to the hardware from the SHEL and SHELL models.
- Physiological factors refer to the Kibo model.
- Environmental factors refer to the SHEL and SHELL models.
- Psychological factors refer to the psychological factors from the Kibo model.
- Socio-cultural factors refer to the liveware from the SHEL and SHELL models, as well as from the modified SHELL and SHELL-T models.

It is important to remember the the habitability factors are interdisciplinary, they are tightly interconnected and their effects are not isolated. For example, reducing lighting [Environmental factors], which may be considered an aspect of habitability, may contribute to errors or increase task time [Operational factors]. In addition, reduced lighting may be a source of irritation and, thus contribute to mental or emotional fatigue [Psychological factors]. However, the exact quantity of light that produces these effects may vary with culture [Socio-cultural factors]. Moreover, light also has an influence on the circadian cycle and the absorption of vitamin D [Physiological factors] (Blume Novak, 2000 A 132).

Habitability in Space

In space, life is very different compared to the daily life on Earth; eating, working, sleeping – everything is different; even the normal posture is influenced. This section provides an overview of the most typical aspects of life in space and the habitability factors related to them.

Figure 2.7: Astronauts eating inside the ISS Zvezda Module (© NASA, http://spaceflight.nasa.gov/gallery/images/shuttle/sts-116/hires/s116e06068.jpg)

To provide an overview of the astronauts' life in space, the ISS as the only space station at this time has been selected as the sample scenario for analyzing the different life aspects and their relations to the habitability factors. This was performed based on comments and explanations from people directly involved in space flight and may help to get a better understanding of what these activities entail. Interviews with NASA experts and astronauts like Dr. Voss (veteran of five space shuttle flights, 1997 to 2000) and Dr. Lu (veteran of two space shuttle flights in 1997 and 2000, and one ISS 6-month mission in 2003) were studied and are reported for each aspect in *Appendix A* (NASA, 2011b).

In the following, a detailed analysis of each aspect as presented by the astronauts, as well as possible relations with habitability factors is presented in *Table 2.2*. The table shows how each life aspect is covered by more than one habitability factor. This is a key concept for understanding that habitability factors are not rigid compartments that identify only a certain aspect of life, but are rather dynamic and interrelated.

Table 2.2: Possible relations between habitability factors and aspects (aspects are described in Appendix A)

	HABITABILITY FACTORS				
HABITABILITY ASPECTS	OPERATIONAL	PHYSIOLOGICAL	ENVIRONMENTAL	PSYCHOLOGICAL	SOCIO-CULTURAL
Movements and Proxemics	■	■			■
Neutral Posture	■	■	■		
Eat	■	■		■	■
Sleep	■	■	■	■	■
Personal Hygiene		■			■
Work	■	■			■
Performance & Work Load	■	■	■	■	■
Habitat Maintenance	■	■			■
Physical Exercise		■		■	
Free Time				■	■
Motivation	■	■	■	■	■
Index: gray=applicable					

2.2 HABITABILITY FACTORS

Considering the habitability model analyzed in the previous sections, operational, physiological, environmental, psychological, and socio-cultural factors have been selected *as the main factors. This subchapter aims to present the application of these interdisciplinary habitability factors in long duration space missions.*

2.2.1 Operational Factors

Operational factors include tasks, task management, and instruments for accomplishing a task, e.g., interfaces, software, equipment, and procedures (Edwards, 1972 cited after Università di Siena, 2001). Task accomplishments are the mission goal. To accomplish such tasks by performing at the maximum level, the system needs to be usable.

System Usability

One of the first questions to approach to support the usability of such systems is "which tasks should be allocated to humans and which to machines. In general, machines are good at doing high-speed, repetitive tasks and tasks that are dangerous or that require great strength. In general, humans are good at doing tasks that are unstructured, that require flexibility, or that require judgment and decision-making ability" (Martin, 2006 p. 127). As explained in *section 2.1.1*, habitability may also be defined as the usability of the environment (Blume Novak, 2000). This definition, even if restrictive in comparison to the Messerschmid one (2008), points out a fundamental aspect of habitability. If the system has low habitability and as a consequence low usability, performance will decrease. However, this relation increases with mission duration. In space, the habitat is so complex that it has to be considered as a machine. To perform human-machine tasks, the complex habitat system needs to be usable: easy to learn and to use (i.e., efficient, flexible, and powerful) (Mayhew, 1999) in other words, user-friendly and intuitive. In the context of long duration missions, the importance of system usability increases enormously. Indeed, on short duration missions, the mission control support or rescue opportunity is accessible, but in long duration missions, the astronaut's autonomy for task management becomes both a reality and a need.

Task Performance

Performance is "a task or operation seen in terms of how successfully it is performed" (Oxford, 2011). HF experts try to increase performance by reducing errors, increasing productivity, and enhancing safety and comfort (Wichens & Hollands, 2000).

Factors that affect task performance are mainly:

- User fitness (psychological or physical limitations, mood, motivation…),
- Task (workload, duration, typology…)
- System usability (environmental conditions, intuitive and user-friendly interface, instrument technology…) (Blume Novak, 2000; Hawkins, 1987; Messerschmid & Bertrand 1999, Whitmore, 2000)

Task performance is here considered as the quality of the task result influenced by operational, physical, psychological, and socio-cultural factors such as motivation or mood (Withmore, 2000). Indeed, although tasks are considered to be mainly a part of the operational factors, it is important to underline once more the interaction and interconnection between all factors.

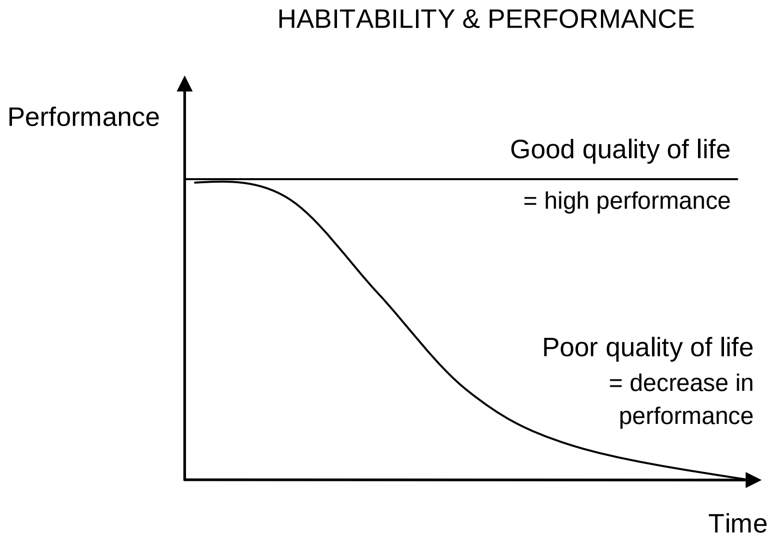


Figure 2.8: Hypothetical relation between habitability and performance. If quality of life is low, as mission duration increases, performance decreases; if quality of life is good, performance will not decrease. To support high performance, the relevance of quality of life will increase with the increase of mission duration.

Today, the average stay of astronauts on the ISS is around six months; the future exploration of the Moon and Mars will require a significant increase in the duration of the mission. Considering that "habitability and human factors requirements are strongly driven by mission duration" (Mount, 2006 p. 11; Woolford & Mount, 2006), the quality of habitability conditions becomes an essential issue for the success of any human long duration mission.

Creative Performance

How can astronauts deal with problems related to a task that has never been performed before? How can operation be guaranteed in an unknown context? And how, in this context, will they be able to find a solution to the problem? The answer may be creative performance. It is commonly believed that creativity is used by engineers to find solutions to problems and by artists to communicate personal interior states. However, we can also use imagination, fantasy, and the creative process to improve everyday life and performance in space. The following section deals with this topic; it is based on the publication "Creative Process to Improve Astronaut Reliability" (Schlacht & Ono, 2009). Prof. Dr. Ernst Messerschmid in a personal communication (Stuttgart, July 2009) emphasized the importance of creativity, particularly in finding solutions to unexpected and unknown problems: "Creativity is important in manned exploration missions. It distinguishes astronauts from robots as humans are prepared for the unexpected." He explains that in space exploration, astronauts are there also to represent the entire human race. This is why it is so important to send humans and not only machines; this is why astronauts have to be able to bring the human culture along, such as art expression or history knowledge. Also, quoting Csikszentmihalyi (1996), to represent humans, astronauts need to be creative, as "creativity is the central source of meaning in our lives". "We share the 98% of our genetic makeup with chimpanzees. What make us different are our language, values, artistic expression, scientific understanding and technology. (…) Without creativity, it would be difficult indeed to distinguish humans from apes" (p.1). As mentioned by M. Masali (personal communication, 2009), "creativity is part of our biological characters developed by natural selection as an exaptation, an archetype of human adaptation. It is what helps us to adapt in the Space environment."

- Problem Solving

The Space Architect Barbara Imhof in a personal communication (June 2009) explains that "creativity is an expression of discovery and can lead to invention and this is happening in all professional areas", not only in the artistic one. Creativity can effectively find solutions when a human is dealing with space missions to investigate the "unknown." "Houston, we've got a problem." These famous words, spoken by astronaut Jim Lovell from space in April 1970, prompted a public demonstration of creative solution-finding aptitude. "The Apollo 13 mission in 1970 is an example of a complex mission where unpredicted events nearly caused a disaster. Earthbound engineers' creativity (and adhesive tape) saved the lives of the astronauts including devising an hour long assembly sequence to mate a square CO2 scrubber canister with a round hole" (Jones, 1995). "What fuelled that process was reverse vision" (King, 1996).

- Lateral Thinking

In problem solving, reverse vision or lateral thinking are the central parts of the creative process. Creativity need not begin with insight. "It is sometimes a reactive force, triggered when all else fails. It's a response to a new order of things. We experience our highest creativity not in doing business as usual, but when there is the most at stake and failure is a possibility but not an option. When our fixed assumptions about how things operate won't do, a new mission must be launched". "Forget the flight plan," was ordered in the Apollo 13 mission. "From this moment on we are improvising a new mission. How do we get our men home?" (King, 1996).

- Creativity as a Prerequisite for Astronaut Selection

Today, creative skill is a prerequisite for astronauts from the Canadian Space Agency (CSA, 2009b): "They have also been tested for their creativity, teamwork skills and physical fitness." NASA also requires of the astronaut candidate "creativity, ambition, teamwork, a sense of daring, and a probing mind" (NASA, 2008). Creativity is a skill that helps in everyday life and must be part of the astronaut's selections and trainings. For example, "visual art can be useful both to visualize and communicate creative invention and also to express personal situation. Art media like musical instruments or visual art, through a focused training, can be used to activate creative processes" (Villani, personal communication 2009). Darlene Lin, from NASA, led an astronaut training experiment at Pavilion Lake Research Project that included an artist-in-residence program. Lin states in "Learning by doing: A Hitchhikers' Guide to the Scientific Training of Moon and Mars Bound Astronauts" (2009): "Humans are set to return to the Moon. Astronauts will be chosen from a variety of backgrounds. As we train them for their missions, we also want to put the heart and soul of humanity back in Space exploration." The Association for the Advancement of Artificial Intelligence (AAAI) published a paper that underlines how in astronaut training creativity acquires a crucial role for Moon or Mars missions: "Whereas the repair of Apollo 13 heavily involved ground engineers telling astronauts what to do, this type of help won't work for Lunar and Martian habitation. In the Apollo case, the engineers had a good understanding of the problems, because they had very good models of the situation -- exact duplicates of equipment.

On Mars or Moon, problems are likely to occur which involve terrain interaction that cannot be duplicated exactly. This is something that a person on site will be best able to analyze (feel, see, etc.) The communication lag from Mars may also prevent effective contingency solutions. The astronauts themselves will be the best ones to solve unexpected time-critical events" (Yim, 2006).

2.2.2 Physiological Factors

Physiological factors are related to the human body (Yamaguchi, 2000; Edwards, 1972 cited after Università di Siena, 2001; Hawkins, 1987). This section focuses in particular on the physiological effects of microgravity conditions. As explained by a NASA Astronaut: "In space, the eyes, inner ears, muscles, joints, and skin cannot rely on gravity as a constant indicator of position and orientation. The brain must learn to rearrange the relationships among the signals from these sensory systems when processing the information in order to produce correct responses. This rearrangement requires a period of adaptation. Before adaptation occurs, crewmembers often experience space motion sickness (SMS), difficulty determining orientation and controlling motion, and the illusion that the body or environment is moving even when both are stationary. Many of these same problems recur upon return to Earth, since another period of adaptation is needed to readjust the body back to the sensation of gravity. Length of recovery time is related to the duration of the mission" (NASA, 2003).

Physiological Systems

The human body has been shaped by evolution in the presence of the earth's gravity. Microgravity, on the other hand, induces in humans an adaptive process that impacts the whole organism and in particular the following systems (Buckey, 2006; Clément, 2005; Grigoriev and Egorov, 1992; Nicogossian et al., 1994, cited after Kanas & Manzey, 2003 & 2008):

1. Cardiovascular system (with effects on fluids distribution and sensory perception)
2. Musculo-skeletal system (with effects like atrophied musculature and bone demineralization)
3. Vestibular/sensory-motor system (with effects on orientation and coordination)

The initial effects are related to the cardiovascular system and the vestibular/sensory-motor systems, in contrast to the musculo-skeletal system, which seems to be affected from the start but develops more slowly thereafter (Kanas & Manzey, 2008). Most of the psychological functions that are immediately affected by microgravity show a rapid adjustment to this new environmental condition during the first 4-14 days in space, and most of the physiological systems reach a new steady state of "normal" functioning within four to six weeks (Nicogossian et al., 1994 b, cited after Kanas & Manzey, 2003; 2008). "All of these physiological responses eventually lead to a physiological de-conditioning in space which might interfere with a healthy return to Earth if no countermeasures are applied" (Kanas & Manzey, 2008 p. 16). "With respect to extremely long missions such as a trip to Mars, the part-time provision of artificial gravity may represent the best integrated countermeasure for de-conditioning effects" (Bukley et al., 2007, cited after Kanas & Manzey, 2008 p. 27).

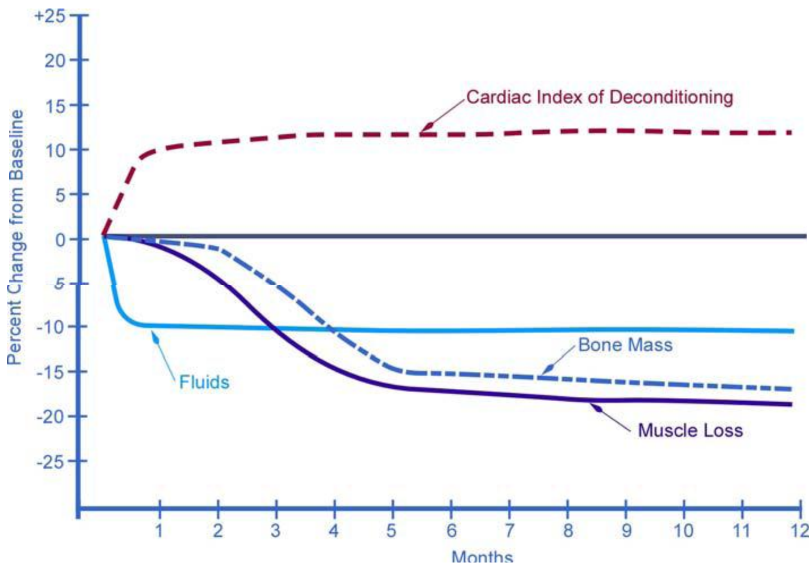


Figure 2.9: Physical changes in 0g
(Nicogossian et al., 1993, cited from NASA, 2010b Figure 5.1-1)

1. Cardiovascular system

When there is no gravity, the baroreceptor reflex (compensate for pressure differences by changes of body orientation in relation to gravity) will not be used and the orthostatic tolerance (maintenance of all bodily functions in upright position) needs to adapt. In the first 6 to 12 hours in space, fluids continue to be pushed against gravity into the upper part of the body immediately affecting the cardiovascular system (Kanas & Manzey, 2003). The fluid shift in the upper part of the body increases the central blood volume and the intracranial pressure (Charles et al., 1994). In the first days, this causes headache and puffy face effects or facial swelling, which affect the sense of smell and taste (Clément, 2005) and which also leads to difficulties in interpreting facial expressions as non-verbal cues (Cohen, 2000). As a reaction, “the human body’s regulatory mechanisms start immediately to excrete the excess fluid” (Ferraris, 2004 p. 67), reducing the body fluids to one third during the first three days. This adaptation process causes fainting and cardiovascular problems to the astronaut upon returning to Earth (Clément, 2005).

2. Musculo-skeletal system (with effects such as atrophied musculature and bone demineralization)

Regarding the bone demineralization process, the astronaut Sean Kelley explains: “Astronauts upon entering a microgravity environment quickly start losing bone mass. The process appears to be the same as a condition frequently found in aging women, osteoporosis. The condition is accelerated over what is found on Earth. Since bones are primarily made up of calcium, another potential side effect/concern is the formation of kidney stones. The calcium leaching from the bones is transferred to the blood stream, and can collect in the urine system as kidney stones” (Sean Kelley, 1999, in NASA, 2011).

3. Vestibular/sensory-motor system (with effects on orientation and coordination)

This affects 85% of non-career astronauts such as scientists who are less well trained (Davis et al., 1988; Matsney et al., 1983), and occurs in the first minutes of exposure to microgravity, lasting for up to 7 days (Kanas & Manzey, 2003). Possible alternatives to pharmacological treatment of SMS are behavioral techniques such as biofeedback or autogenic feedback training (Cowings and Tosacano, 2000).

The technical reason for the effects on the vestibular/sensory-motor system (given in Kanas and Manzey, 2003; 2008) is explained next. The otolith in the vestibular system is responsible for linear acceleration and gravity (direction of the vertical). Gravity-dependent signals from the otolith provide (Howard, 1986, cited after Kanas & Manzey, 2003; 2008) input for upright position and movement on earth (vestibule-spinal reflexes) and coordination of head and eye movement (vestibule-ocular reflexes). Without gravity, the otolith no longer provides any information about the local vertical and these two subcortical mechanisms are distorted, thereby affecting the following (André-Deshays et al., 1993; Clarke et al., 2000; Clément, 1998, cited after Kanas & Manzey, 2003, 2008): congruence between visual-vestibular-proprioceptive signals, which leads to spatial disorientation, visual illusions, and space motion sickness; eye movement and gaze stability, leading to difficulties with compensating the head movement in order to maintain ocular fixation on a visual target.

Perception

The human body undergoes profound changes in space as already mentioned (cf. *section 2.1.2*). These changes also affect sensory perception. Taking also into account the particularly dangerous and extreme conditions of space, perception is particularly relevant in the field of space habitability; for this reason, perception is here analyzed with particular attention. It is analyzed here as an aspect of physiological factors because of the strong physical influence of the space environment on the human physiology. However, it is usually treated as a part of cognitive psychology, since it also encompasses aspects of physiology and other disciplines.

Until now, it is not completely clear how sensory perception is affected in space. It seems that the cardiovascular system and fluids shift caused by the microgravity may be the cause of the changing perception. As seen in the fluids shift affecting the sense of smell (Woolford & Mount, 2006), although changes were found in all the senses, this may also be influenced both by the microgravity effect and the local ISS conditions (Schlacht et al., 2008b, 2009).

Table 2.3: System of perception in space (Schlacht et al., 2008b p. 2)

SYSTEM:	PERCEPTION IN µG	ISS CONDITIONS
Visual	Diminishes; mildly altered	visual confusion; constant visual stimuli
Auditive	Sharpened	noisy: intolerant after 30 days
Gustatory	Diminishes; altered	taste variation
Olfactory	Diminishes	presence of bad smell
Tactile	Diminishes	difficulty with stimuli variation
Vestibular	Silent (otolith gravity/vertical receptors)	difficulty with orientation

Among the senses, vision (perception of movements, shapes and colors) is the most important brain function which allows one to perceive external reality; indeed 80% of the sensorial information about the world is of a visual kind (Mahnke & Mahnke, 1987; NASA, 2010b, 1995; Kosslyn et al., 1995; Romanello, 2002). In particular, “color is thus an important attribute that humans use to identify objects, but is now also widely used in visual communication systems” (NASA, 2010b p. 138, part 5.4.10). In microgravity, visual perception becomes even more relevant: “Astronauts rely on the visual sense to perform every aspect of their missions, including reading text, scanning instruments, observing their environment, executing tasks, and communicating with other crewmembers” (NASA, 2010b p. 119 part 5.4.1). According to Mallowe (2001), in microgravity visual perception is of primary importance particularly in perceiving signals for orientation because in weightlessness “people suppress vestibular signals and become increasingly dependent on vision to perceive motion and orientation”. NASA thus reports in the standard Living Aloft (Connors et al., 2004): “Because of the importance of vision to the conduct of space missions, it was suggested in the early literature that the 0-g environment could alter visual capabilities.” Considering the importance of vision to the accomplishment of space missions, the spacecraft’s visual design has to be achieved bearing in mind the strong psycho-physiological modifications that occur within the extreme environment of outer space.

In the context of long duration space missions, the HF related to this minimal difference in perception may become key factors for the well-being and performance of the astronauts (Schlacht, 2007). Until now, “no studies of visual performance have yet been conducted in long duration mission” (Rhatigan et al., 2005, cited from NASA, 2010b p. 143 part 5.4.12.1). “One notable visual phenomenon of space flight is light flashes caused by interactions between energetic cosmic ray particles and elements of the visual system” (NASA, 2010b p. 143 part 5.4.12.1). Taking into account the high relevance of the visual and interface design for habitability, the author has carried out a comprehensive literature review, with a special focus on investigation and experiments on visual perception and visual reaction in microgravity conditions.

As a conclusion of the author’s research in the area of perception, the main factors to be considered for the design of an ergonomically based interior include (Schlacht & Birke, 2010b):

- Angle of sight

The eye and gaze movement parameters also reflect changes in arousal and describe levels of fatigue and vigilance that result in changes in the visual field (Rötting, 2001, 2001b). These variables should be considered for further investigation in space conditions.

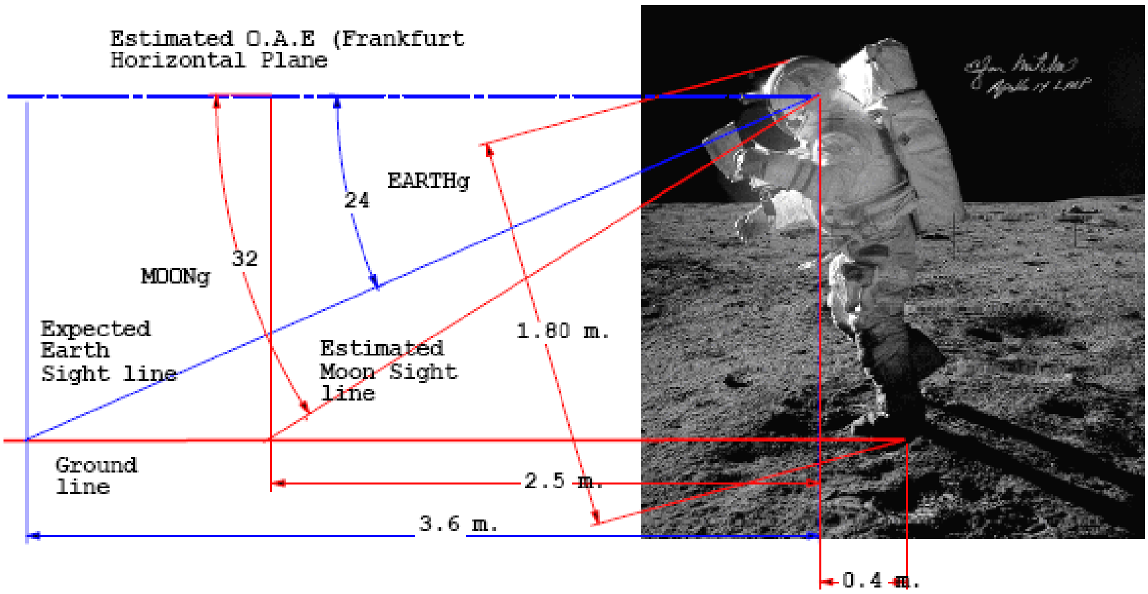


Figure 2.10: Interpretation of Earth-Moon walking posture and sight-line (Image. Apollo 14, Edgar Mitchell 2.6.1971 © NASA, computer modified from M. Masali, 2009)

- Astronaut myopia

The effect of the limited dimensions of the modules is a lack of opportunity to focus on distant objects; the continuous demand for proximal sight and the consequent constant accommodation of the crystalline lens generate myopia. This problem persists in any narrow dwelling such as in any Moon or Mars base where the radiation shield will limit the presence of windows and possibilities for extra-vehicular activities (Schlacht & Birke, 2010b).

- Perception of depth

Underestimation of the actual distance of objects on the depth plane has been reported in microgravity and lunar ghravity conditions (Clément et al., 2008; Courtland, 2008). However, as the otoliths of the vestibular system are responsible for 3D orientation and are affected by microgravity, it can be hypothesized that depth perception is influenced by different gravities. Further studies are needed (Schlacht & Birke, 2010b).

- Achromatic perception

The absence of atmosphere and air creates a sharp difference between sunny and dark areas, requiring time for visual adaptation between bright illumination and stark darkness. Astronaut Buzz Aldrin also confirmed this: “Continually moving back and forth from sunlight into shadow should be avoided, because it’s going to cost you some time in perception ability” (Jones, 2009).

- Cromatic Perception

According to space architecture scholar Daniele Bedini from the International Space University in Strasbourg, the eye perceives more attenuated colors in the absence of gravity as a consequence of less oxygen contribution (Rita, 2000). Because of the effect of weightlessness, the crystalline lens become more spherical; this change in the chromatic aberration and consequently images is focused on a different part of the retina with a different concentration of RGB receptors and rows receptors. As a result of the CROMOS experiment led by the author in parabolic flight, the stimulation of rods and blue cones decreased (Schlacht et al., 2009).

- Visual orientation

“Considering weightlessness, as on board of a spacecraft, visual interface acquires even more importance than usual. In floating conditions, the space interaction changes, acquiring tridimensionality. In comparison with the 2D walking surface, the 3D floating volume makes the entire interior surface usable. This changes entirely the way to make use of space, there is no up and down and the concept of floor, wall and ceiling does not make sense anymore, thus enhancing orientation difficulties” (Schlacht & Birke, 2010). Moreover, in weightlessness orientation proceeds only visually, as Mallowe (2001) explains: “It is observed that with exposure to weightlessness, people suppress vestibular signals and become increasingly dependent on vision to perceive motion and orientation”. Visual orientation reactions have been investigated with WIUD (Where Is Up and Down) between 2008 and 2009 by the Chair of Human-Machine Systems at Technische Universität Berlin. The finding shows that an interior colors orientation system, like the one used in the Russian module Swesda, and orientation labels showing human pictograms tend to increase orientation skills (Schlacht et al., 2009b).

Figure 2.11;2.12;2.13;2.14: ISS Interior of the modules; Zvezda Russian Module; Destiny American module; Destiny without orientation label; Destiny with orientation label.

2.2.3 Environmental Factors

In detail, the environmental factors are related to the factors outside the habitat and are properties of the external environment, like radiation, temperature, or micrometeorites. The environmental controls are part of the machine system and include noise, temperature, vibration, and all the environmental factors that affect life inside the habitat (Yamaguchi, 2000; Edwards, 1972 cited after Università di Siena, 2001; Hawkins, 1987).

Considering the importance of the natural environment on human well-being, one can thus understand how the relevance of habitability will increase if humans are living in isolation inside a habitat that is completely artificial. Natural environments can be used as a basis for finding the factors that can be applied to increase the habitability. As the American Faber Birren (1900 - 1988), a relevant figure for color research applied to perception, art and physics, explains: “In response to environment, people expect all of their senses to be moderately stimulated all the times. This is what happens in nature, and it relates not only to color and changing degrees of brightness, but to variation in temperature and sound. The unnatural condition is one that is static, boring, tedious und unchanging. Variety is indeed the spice–and needed substance–of life” (Birren, 1983 p. 167).

Humans have always been evolving with nature. In comparison with the Earth’s natural environment, the fundamental element bound to be missing in an isolated and artificial habitat is variability of stimulation. M.D. Vernon, a British psychologist, has written thus: “Variation is a fundamental characteristic to stimulate the human performance. Normal consciousness, perception and thought can be maintained only in a constantly changing environment. When there is no change, a state of ‘sensory deprivation’ occurs; the capacity of adults to concentrate deteriorates, attention fluctuates and lapses, and normal perception fades” (Birren, 1982 p. 28).

In the design of habitat, it is therefore necessary, in order to enhance the efficiency and well-being of the crew, to recall the normal physical and psychical conditions whose characteristics are variety and variability in time (Bretania, 2003).

Sensory Monotony and Variety

Sensory deprivation – under-stimulation, or, more correctly in the context of the space habitat, sensory monotony (Manzey courtesy personal communication, 2010) – is one of the key problems of long duration space missions. In his book on color and light in human-made environments, Frank Mahnke, President of the IACC (International Association of Colour Consultant/Designers), explains: “Persons subject to under-stimulation showed symptoms of restless, excessive emotional response, difficulty in concentration, irritation, and in some cases, a variety of more extreme reactions" (Mahnke & Mahnke, 1987 p. 5). In order to avoid sensory monotony in terrestrial isolation, stimuli are needed. However, there should not be any overload point of overstimulation. As Mahnke has explained, balance is the goal: "Unity involves various components and parts fitting together into a coherent unit. Complexity involves more variation. Extreme unity (monotony or sensory deprivation) can lead to under-stimulation and extreme complexity to overstimulation" (Mahnke & Mahnke, 1987 p. 4). "We know now that under-stimulated environment is as unacceptable as the overstimulated one. Taking all research collectively, it is safe to conclude and suggest that color variety is psychologically most beneficial. It is not just that one color is better than another for a specific purpose, that one may be considered psychologically exciting or another calming, but a variety of stimulation and change in atmosphere is required to establish a sound milieu" (Mahnke & Mahnke, 1987 p. 6).

Complexity and Variety

"Terrestrial designs feature variety, but a variety which flows from a theme. Individuals experiencing this theme also have the opportunity of experiencing other themes in the course of a day. In space the number of designs must be limited. We need to ascertain what constitutes acceptable versus unacceptable variety in this closed environment" (Connors et al., 2004 p. 68). In terms of temporal and spatial change, "stimuli arouse attention through the ability to increase the perceiver's level of complexity" (Dember and Earl, 1957 p. 1). "[This] is evidence that people prefer greater environmental complexity with time (Dember and Earl, 1957, after Connors et al., 2004 p. 68). "If so, we should plan for increasingly complex arrangements as spaceflight lengthens" (Connors et al., 2004 p. 68).

The concept of unity, complexity and balance requires constant change and variability. This "balance" may be achieved by studying the harmony, contrast, and affective value of the systems elements, as explained by Mahnke (Mahnke & Mahnke, 1987) in relation to environmental design. Complexity may lead to confusion, while unity may lead to tedium: "We demand the play of opposite forces" (Ellinger, 1963 p. 27). The Earth's environment plays an essential role in human evolution. Humans have been shaped by evolution for millions of years according to Earth's environmental condition. This is why one needs to look at human evolution to understand how the human being interacts with the environment and how s/he is able to live in different environments such as outer space. Considering that humans have evolved on Earth to live on Earth, the consolation they get from their home planet may strongly affect the human being's psycho-physiological stability. Wind, seasonally changing color, light variation, day cycle, fragrances, temperatures, and unplanned environmental events such as rain are part and parcel of the earthly reality in which humans evolve. Those stimuli are in fact part of the natural conditions for human life.

The JAXA astronaut Naoko Yamazaki, after 15 days on the Shuttle Discovery mission STS-131 (5 April 2010), describes the situation this way: On "re-entry and landing, when I stood on the ground, I was filled with emotion about how great it was to be back on Earth again. I felt Earth's nature all around me. The relaxing sensation of the wind on my face made me feel so grateful for nature" (Nishiura, 2010 p. 2). With these words, Yamazaki underlines the importance of the Earth's natural environment. In space you are isolated from this environment, constrained in completely artificial conditions with no natural events like those which occur on Earth. Indeed, the environment plays a fundamental role in terrestrial life: "Human beings receive 80 percent of their information from the environment" (Mahnke, 1996 p. 10). "Nervousness, headaches, lack of concentration, inefficiency, bad moods, visual disturbances, anxiety, and stress usually are blamed on everything except a guilty environment, which may often be the root cause" (Mahnke, 1996 p. 3), particularly if we are isolated inside this environment.

Natural and Artificial Environments

There are many factors that need to be taken into account when developing architecture: temperature, the availability of space, zoning, etc. However, "color and light are major factors in our architectural environment [because] they have great impact on our psychological reactions and physiological well-being" (Mahnke, 1996 p. 3). Considering the relevance of color and light and in order to better understand the strong influence that the natural and human-made environment has on human well-being, the effect of natural and artificial light is analyzed here.

"During the last two decades it became increasingly clear that sunlight (natural global solar radiation) has profound effects on the human organism" (Mahnke & Mahnke, 1987 p. 43). Natural light is of vital importance for humans as Mahnke explains, "all life on Earth is determined by the radiation of the sun" (Mahnke, 1996 p. 6). Color, too, which guides animals in their behavior, is only light reflection. Indeed, light has an effect on human behavior and psychological reaction but it also creates a physical reaction. "Through our evolutionary development as a species we have inherited reactions to color that we cannot control, …explain and …escape [from]" (Mahnke, 1996 p. 9). The psychologist Ulrich Beer explains: "We are immediately, instinctively and emotionally moved… as soon as we perceive the color" (Beer, 1992 p. 11). Those are called primary psychological reactions. In the goals of a conference on the medical and biological effects of light in New York, it was stated: "Environmental light produces numerous biological effects related to health beyond simply affecting vision and cutaneous pigmentation" (as quoted in Mahnke, 1987 p. 46). In comparison with artificial light, it has been demonstrated that "constant exposure to artificial light has biological implications" (Mahnke & Mahnke, 1987 p. 44).

Already in the 1980s, John Ott, the director of the Environmental Health and Light Research Institute of Sarasota, Florida, after a lifetime of investigation into the influence of light and color on animal, plants and human, pointed out: "Every chemical, mineral, vitamin, or substance of any kind that we take into our bodies as food has a maximum wavelength absorption characteristic of electromagnetic energy. We also know that this wavelength energy penetrates the skin and interacts directly at the molecular level with the chemicals and minerals in the blood supply" (Ott, 1985 p. 21). Moreover, he explains that "light received through the eyes stimulates the pineal and pituitary glands. These glands control the endocrine systems that regulate the production and release of hormones controlling body chemistry" (Ott, 1985 p. 25).

Table 2.4: Human reactions to sunlight (Mahnke & Mahnke, 1987 p. 46)

SOLAR RADIATION EFFECT THROUGH THE SKIN AND EYES		
Ultraviolet	Visible spectrum	Infrared
Skin Actinic, Erythema effect Vitamin D stimulation Physiological effects of a general nature	Pineal organ activation Endocrine and autonomic effect Entrainment of circadian rhythms	Skin heating Vasodilatation Body temperature influence and as a consequence physical and

	Performance and fatigue effects Cognitive, behavioral and emotional correlates	mental performance influence Cold, heat, and pain sensation

In conclusion, the environment stimulates a human psycho- physiological reaction, and light and color are the major factors in it. As Mahnke summarizes it, "research has proven that light and color affect the human organism on both a visual and non-visual basis. It is no longer valid to assume that the "only" significant role of light and color is to provide adequate illumination and a pleasant visual environment" (Mahnke, 1996 p. 3).

2.2.4 Psychological & Socio-Cultural Factors

Psychological factors are the factors involving the astronauts' mental health (Yamaguchi, 2000), and socio-cultural factors are those factors related to the human cultural component and its relational and communicational aspects (Edwards, 1972; cited after Università di Siena, 2001). Habitat and laboratories have been specially developed on Earth to shield against extreme environmental conditions. In such conditions, humans may experience psychological effects caused by life's danger, high work load, social isolation, spatial confinement, temporal confinement, environmental isolation, and monotony (Kanas & Manzey, 2003) but also the effect of Earth being out of view. While each of the extreme environments may have one or more of these conditions, the space environment has them all.

Psychological and Socio-Cultural Factors

The following considerations are all based on the review of different field publications: AA.VV. 1999; AA.VV. 1999b; Clément, 2005; Connors et al., 2004; Manzey, 2009; NASA, 2011, 2010b, 1995; Jorgensen, 2010; Kanas & Manzey, 2003; Schlacht et al., 2008b. In detail, these elements can be addressed in space at the psychological and socio-cultural level:

- Life danger and work load

In an environment where humans are not naturally at home, the danger of life is particularly high. Adding to the high cost are the high performance and work load expected of the astronauts so that the first factors of psychological stress are quite understandable (Kanas & Manzey, 2008).

- Social isolation

So far, crews are composed of three to six members. Telephone and video transmissions with friends and family members are possible; however, in the case of a mission to Mars, the delay could be as much as 44 minutes. This kind of isolation has strong repercussions at the social level. Indeed, one particularly important task will be picking a team of astronauts who can both work and get along with each other on a trip lasting at least two years, spent mostly within the confines of a not-so-big spacecraft sailing through the dark (Farrar, 2008).

- Cultural issues

The actual crews are formed from members with different specializations, hobbies, cultures, languages, and religions. The official languages are English and Russian. Cultural activities are considered only as free time. Cultural issues have a great relevance on long duration missions. The numbers of men and women, their ages and even their cultural upbringings must be carefully calculated to try to prevent what could be potentially devastating cosmic quarrels. “You can't just take a walk and get away from somebody”, the space psychologist Kanas said (Farrar, 2008).

- Spatial confinement

The area available in the spacecraft is limited. In the case of EVA, astronauts will be able to move around the station for a short period of time and only with high technological support and until now under the risk of radiation. Under these circumstances, the addition of space must be studied in relation to the group, individual, private, and public needs, separating areas with zoning research (AA.VV., 1999b).

As explained in the Space Stations book by Messerschmid: Aboard a space station, there is a wide range of activities which, naturally, are mainly performed simultaneously in a very confined work and living environment. The different activities are divided into private/public and individual/group activities in a coordinate system. Correspondingly, the larger the distance between two activities, the larger their potential incompatibility (Messerschmid & Bertrand, 1999).

Figure 2.15: Locations of space module functions with functional relationships analysis (AA.VV., 1999b, SSP50008, MSIS-86, Figure 8.3.2.2-2). Grouping the activities according to psychological and physiological needs (private, public, group, individual) is fundamental for increasing habitability.

- Temporal confinement

The mission duration should be planned and studied well in advance with the appropriate supporting technology. Up till now, unplanned mission interruptions are difficult to troubleshoot, and can be dangerous and very expensive.

- Environmental isolation and monotony

In space stations, isolation within natural human environments incorporates a normal earthly cycle with diurnal and nocturnal rhythms, the change of seasons, and seasonal weather such as rain and wind. This effect on humans amounts to "sensory deprivation" (quoting Jorgensen, 2010 p. 250) or maybe more appropriately "sensory monotony" (cf. s*ection 2.2.3*, part *Sensory Monotony and Variety*). This needs to be considered even if the basic natural conditions such as pressure and oxygen are artificially provided, or not provided as in the case of earthly gravity. Most of the natural sensorial stimulations such as the smell of nature are not present. Fragrances in particular are forbidden on the space station, as one of the main requirements of object design for the ISS is to be non-flammable and odorless. However, due to human smells, the ISS is anything but odorless. And if one is to also consider the crowdedness of the visual environment and the noise production from the life support system, the ISS can be considered as being overstimulating. Indeed, "Although the environment of space may prove to be understimulating in some respects, it may prove to be overstimulating in others" (Connors et al., 2004 p. 70).

- Earth out of view

In a Mars mission, "We don't know what is going to happen" explains Kanas. Yet the big unknown, according to Kanas, does not involve who astronauts will not be able to talk to or what gifts they will not be able to get, but instead what they will not be able to clearly see: planet Earth (Farrar, 2008). This factor is only possible during space missions such as orbiting around the moon. The effects are comparable to losing the home view in an unknown desert. Indeed, as reported by the author in the 2010 mission simulation on the Mars Desert Research Station, at least two of the six crew members reported high earth rate disorientation, making it impossible to proceed with the extra vehicular activity (EVA). Prof. Dietrich Manzey, a former ESA psychologist, is the researcher who discovered the "Earth out of view" effect with Nick Kanas, space psychologist professor at the University of California, San Francisco. More studies need to be carried out in this regard in relation to a long duration and long distance mission to Mars (DGAP, 2010; Farrar, 2008; Kanas & Manzey, 2008).

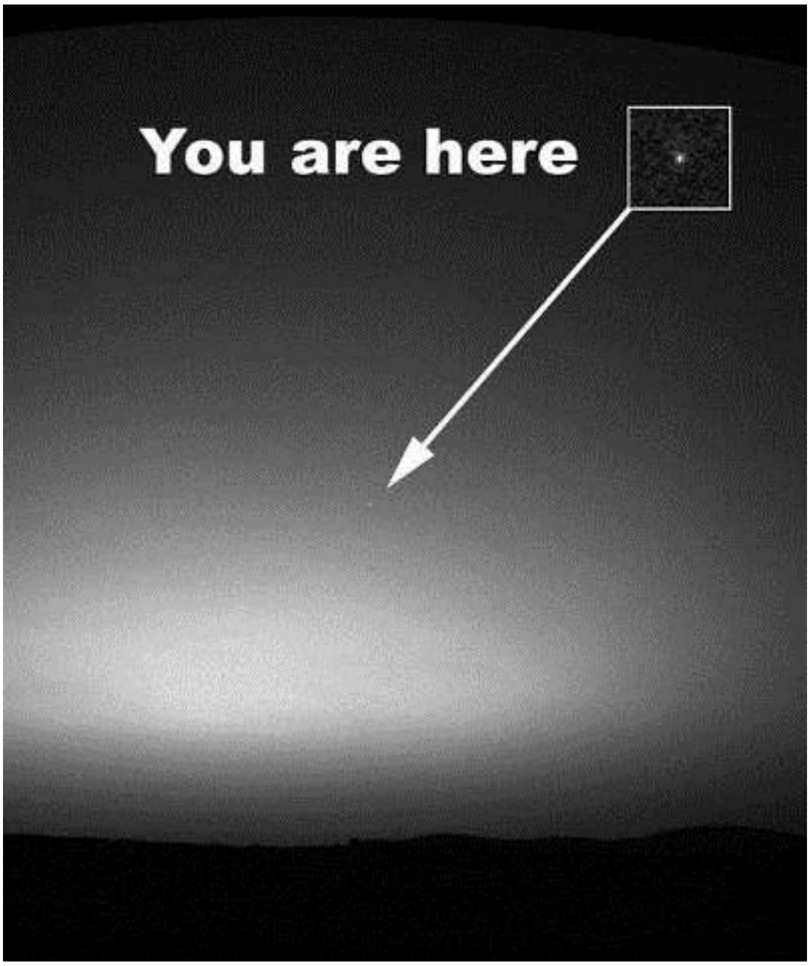


Figure 2.16: Out of earth view (Earth as seen from Mars, http://thesituationist.files.wordpress.com/2008/06/earth-from-mars.jpg)

- Interaction in isolation

The isolation of space missions also has other effects, such as on the interaction with reality, which can be classified into two types: direct and indirect. Of course, the crew cannot have direct access to the external unpressurized environment, but more than that, as listed in the table below, it can be seen that even the crew and crew relations may be indirect because the noise problem interferes with communication and the crew may use the intercom tools even to communicate within the same area (Schlacht et al., 2008b).

Table 2.5: Interaction with the external reality in space (Schlacht et al., 2008b)

RELATION	DIRECT (without tools)	INDIRECT (through tools)
ISS Crew/ ISS Habitat	Direct with body	NO
ISS Crew/ Environment	NO	Indirect but in real time: with window, with E.V.A. through the suits
ISS Crew/ ISS Crew	Direct with body	Indirect but in real time: because of the noise problem, in order to communicate also within the same area, crew may use “intercom”
ISS Crew/ Earth	NO	Indirect is limited to the visual perception through the helmet or the window or with video chat and not in real time with pictures.

- Third-quarter phenomenon

All those constraints have a psychological impact on the astronaut. If the mission is divided into four stages, one can apply the theory of the "third-quarter phenomenon" with an increase of demotivation observable in analogue environments. The most psychological and psychiatric "third-quarter phenomenon" symptoms are reported by Kanas and Manzey (2008, pp. 37-38) and are summarized here. "Significant psychological changes can take place during this stage, mainly in mood, in response to the monotony and boredom that result from low workload, hypo-stimulation, and restricted social contacts due to separation from family and friends" (Kanas & Manzey, 2008 p. 37). According to Russian experience, the most critical stage is when the astronaut reaches the work routine that runs between the 6th and 12th week of the mission (Grigoriev et al., 1987; Gushin et al., 1993, cited after Kanas & Manzey, 2008 p. 37). "Observed behavioral reactions include emotional lability and hypersensitivity, increased irritability, and a considerable decline of vigor and motivation, but also perceptual sensitivities and preference may be altered during long-duration space missions" (Kanas & Manzey, 2008 p. 37). For example, it was observed that after 3–5 months astronauts and cosmonauts started to have hypersensitivity to loud sounds (Grigoriev et al., 1988; Kelly and Kanas, 1992, cited after Kanas & Manzey, 2008 p. 37) and also "to prefer stimulating music after several weeks in space or even expressed the wish to hear some Earthbound sounds or noise" (Grigoriev et al., 1987, cited after Kanas & Manzey, 2008 p. 37). Also at this stage, the Asthenia syndrome has been observed. "[This] is associated with feelings of exhaustion, hypo-activity, low motivation, low appetite, and sleep disturbances. It might eventually be followed by states of euphoria, depression, and an accentuation of negative personality traits" (Myasnikov and Zalmaletdinov, 1998, cited after Kanas & Manzey, 2008 p. 37). However, solutions are possible if planned. For example, "It is evident that depression and asthenia reactions can be resolved with increased audio-visual contact with family and friends on Earth before full-scale psychiatric problems develop" (Gushin, 2003, quoted after Jorgensen, 2010).

Countermeasures

The countermeasures here described are:

- Sensorial stimulation and self-awareness
- Sublimation process
- Art as therapy

The effects of astronauts' confinement have been researched in places like Antarctic laboratories, caves, submarines, detention centers, and isolation chambers. Loss of motivation, depression, and insomnia are only a few effects that can negatively influence reasoning ability. Creative expressions like art media, including music, painting, and poetry, offer a great potential for the welfare of people living in discomfort and isolated conditions and may be considered as a countermeasure for psychological and socio-cultural problems. This concept was analyzed by the author and presented in Schlacht & Ono, 2009. Creative self-expression will improve the astronauts' creative skills, life quality, and mental stability. It focuses on private, subjective feelings in contrast to the obligations and limited relationships in isolated situations. A creative moment must be free; it cannot be planned, but can be a leisure activity. According to the space psychologists Kanas and Manzey (2003, p. 130) "leisure time activities in Space are very important, they help to counter boredom and monotony." Creative processes are focused on problem solving or self-expression. The subject achieves the best result when he activates this process freely, by "personal needs" instead of a commissioned work in a constricted time frame. Quoting the research of Teresa Amabile (1983), "Intrinsic motivation is conducive to creativity, but extrinsic motivation is detrimental" (p. 15). In an isolated environment the creative process is necessary to survive the monotony, stimulus deprivation, and boredom. It is essential to being, to psychological survival, and to avoid just acting like a machine. Sailors isolated on the sea for long journeys employ their spare time to make artistic expressions like batons and miniature ship models out of whalebones. Like sailors, astronauts may create a new form of art if we give them the opportunity.

- Sensorial stimulation and self-awareness

Lack of solar light, absence of wind and seasonal changes are characteristic of the synthetic habitat in Space. In long duration missions, this "sensorial deprivation" affects astronauts. The variation of stimuli such as the change of seasons is a "natural condition" and a "sensorial stimulation". It ensures archetypal brain activity: it helps avoid mental drowsiness and maintain alertness (Mahnke, 1996). "As a countermeasure to heavy workloads or monotony, astronauts have drawn on leisure activities imported from earth or invented in situ" (Häuplik-Meusburger, et al. 2008). Creative entertainment like social games "can maintain and enhance manual dexterity, mental alertness and social interaction amongst crew" (Häuplik-Meusburger, et al. 2008). A group of architects and designers has presented to the International Space Conference in 2008 a game designed for microgravity environments and aimed to stimulate creativity and positive socialization on space missions. The "Space game" is designed "to make the most of the kinetic and sensorial potential of reduced gravity conditions" (Häuplik-Meusburger, et al. 2008).

Applied in social play, to the personal state expression, or as a problem solving strategy, in all cases creativity stimulates the learning process and self-awareness in relation to the environment (Martius, 2008). Self-awareness acts against the mental drowsiness generated by stimulus deprivation in a monotonous, artificial, and isolated space dwelling.

- Sublimation process

Astronauts in isolation must constantly keep their self-control, without the freedom to express personal instincts or emotions. On long duration missions, conflict within the crew may happen and the astronauts will not be free to leave the mission early or to change crew members; moreover, it will not be possible to take a break or go off on vacation for a few days. The astronauts have to constantly control their feelings, repressing instincts like aggressiveness or sexual impulse. In this context, psychological support through creative expression can be helpful. Yamanaka (2003) stated that artistic expression "touches, encourages, and provides a way to express emotions." By means of the sublimation concept, energy derived from a sexual or emotional impulse is channeled from its original purpose into positive social activity such as intellectual investigation or artistic endeavor – in short, into creative activity. Playing, painting, music, sculpture, or daydreaming can activate this process. According to Malchiodi's theory (2006), the creative process is a means of imaginative, authentic, and spontaneous self-expression; an experience that, over time, can lead to personal fulfillment, emotional equilibrium, and self-development. Since prehistory, art has always been an element of human expression to communicate with the external world (Rubano, 2005).

Creative expression is a psychological countermeasure to isolation, which "includes all actions and measures that alleviate the effects of the extreme living and working conditions of Space flight on crew performance and behaviour" (Kanas & Manzey, 2003, p. 131). Creative expression will become essential in extreme isolation, as in a Mars mission where the astronauts will have remote psychological support.

- Art as therapy

In space habitats, where astronauts face social isolation, discomfort, and emotional repression, art can be used as therapy. This is what happens in hospitals, prisons, and mental health institutions with "art therapy." Art therapy was born thanks to the contribution of psychoanalysts like Winnicott and Melanie Klein and from Dubuffet´s Art Brut (art made by mentally ill people). It develops from the theory that "artistic creation is a focused and organised activity like children's play; it is based on the transformation, through symbolic activity, of emotion in expressed cognitive elements" (Caterina, 1998, p. 54). In art therapy, artistic expression is a way to balance emotions and to contribute to well-being (Caterina, 1998, p. 51). This principle also supports the "sublimation theory". As a matter of fact, putting inner emotion into the external artistic "vase" helps to release tensions. However, visualizing feelings as an external thing has another important effect: it brings more knowledge of our personal emotional experience (Rubano, 2009). Francesca Rubano, a specialist in Art Brut, Art Therapy, and Relational Art, points out that ArtTherapy is a key solution for mental stability in isolation, as a countermeasure to limited communication and limited social relations (personal communication, September, 2009).

2.3 SPACE SYSTEM

After analyzing the habitability factors in the previous subchapter, this subchapter introduces the elements of the system that concur with the design of these factors. These include the astronaut, the space habitat system, the space environment, and the mission.

Humans can artificially create systems that can fulfill all their needs while offering high quality of life. Moreover, they can also adapt themselves to such an extreme system, using the process of adaptation. In space, it is important to do both to increase habitability – designing the best habitat and training and selecting those astronauts who can adapt best to the conditions.

This section focuses on the contribution of a range of disciplines that varies from anthropology via human evolution and adaptation to environmental design. Indeed, human evolution and adaptation have been found critical to an understanding of human reactions and needs in the space environment.

In particular, the effects, processes, and needs of habitability factors will be looked at in the interactions between:

- Human: Astronaut needs and adaptation
- Machine: Space habitat system
- Environment: Space as extreme environment
- Project: Mission destination

2.3.1 Human (Astronaut)

The space environment is considered to have the most extreme conditions in which humans have had to stay. Short duration missions are based on a period of less than two weeks' time and long duration missions are longer than two weeks (Kanas & Manzey, 2008). After two weeks' time of isolation in an extreme environment, the human psychological condition becomes particularly important. A mission to Mars is based on a concept of three years' time. In anticipation of exploring always more distant destinations in the universe, future missions are based on the concept of long duration missions.

Astronauts' needs are divided into basilar and physiological ones and advanced and psychological ones (SSP 50005, AA.VV, 1999). The former relate to the survival of the organism in short duration missions (SDM), while the latter are concerned with supporting motivation, productivity, and comfort for long duration missions (LDM).

Mission Duration

Short Duration Mission

From a physiological standpoint in short duration missions, human beings on the Moon require at least the following (Larson and Pranke, 1999):

- Atmosphere: The habitat must provide 101.3 kPa total pressure with about 21% of O_2 and 78%-79% N2. Further, CO_2 levels must be kept to tolerable limits; humidity has to be kept between 25 and 70%, and a ventilation system must be provided;
- Temperature: must be kept between 18.3 and 26.7° C;
- Radiation protection: This can only be partially assured by covering the habitat with advanced multilayer plastic materials, metal, water, or regolite (lunar terrain).
- Food and water: Caloric requirements depend mainly on age, gender, tasks, and physical characteristics of the environment. Food and water are generally stowed by means of tanks and then processed by a physical-chemical life support system.
- Human waste management: Liquid and solid human waste has to be disposed of in order to maintain an appropriate hygiene level in the environment.
- Sleeping time: Sleep is a basic physiological need and must be included in the time schedule of astronauts' daily activities.
- Hygiene care: includes personal body hygiene, which is fundamental for preventing fungal infections; habitat environment and clothing cleaning system must be considered.

Long Duration Missions

From a psychological and ergonomics perspective, the following needs have been identified as particularly relevant in long duration missions (Aguzzi, 2005):

- Interior design: Lighting, vibration, noise, and odor are issues that need to be controlled.
- Zoning: There must be dedicated working areas, including areas for carrying out scientific experiments required by the mission or for creating a private place.

- Psychological and socio-cultural needs: implies evaluation of workloads, relationship with the rest of the crew, the need for privacy, and the interaction with tools, facilities, and the related technology. Working and living in a confined environment with a multi-ethnic, multi-gender, and multidisciplinary team requires the definition of a common code of practice and behavior in private and communal areas in the habitat.

HABITABILITY NEEDS IN SPACE:

SDM → LDM

SDM	LDM
Air conditioning	Interior design
Food and water supply	Zoning
Illumination	Privacy
Noise level	Hygiene
Odors	Work schedule
Actuation forces	Crew composition
Vibrations	Psychological care
Medical care	Communication
Safety considerations	Motivation

Experience shows that with increasing mission duration
the effects of isolation and confinement become predominant

Figure 2.17: Habitability aspects for short and long duration missions (Messerschmid, 2008)

From a motivational point of view, physiological, psychological and HF support is not sufficient. There is also a human need to evolve, to discover, to progress, and to express oneself. These concepts refer to the "self-actualization needs" reported by Maslow's Theory of Motivation (Maslow, 1943; Maslow and Lowery, 1998 cited after Straker, 2010). In his needs hierarchy represented as a pyramid, the basic needs are reported at the pyramid base; they coincide with the ones reported by Messerschmid (2008) as SDM needs. The needs towards the top of the pyramid are related to long duration missions as reported by Messerschmid (2008). Needs like self-actualization, which are at the top of the pyramid, have, until now, not been part of any consideration in mission design (Johansson, 2010); however, they may be considered as part of "Psychological care and motivation" reported by Messerschmid (2008). More than that, there are a "myriad of different, constantly changing individual needs" (Kutschera and Ryan, 2010) that are today still being totally ignored.

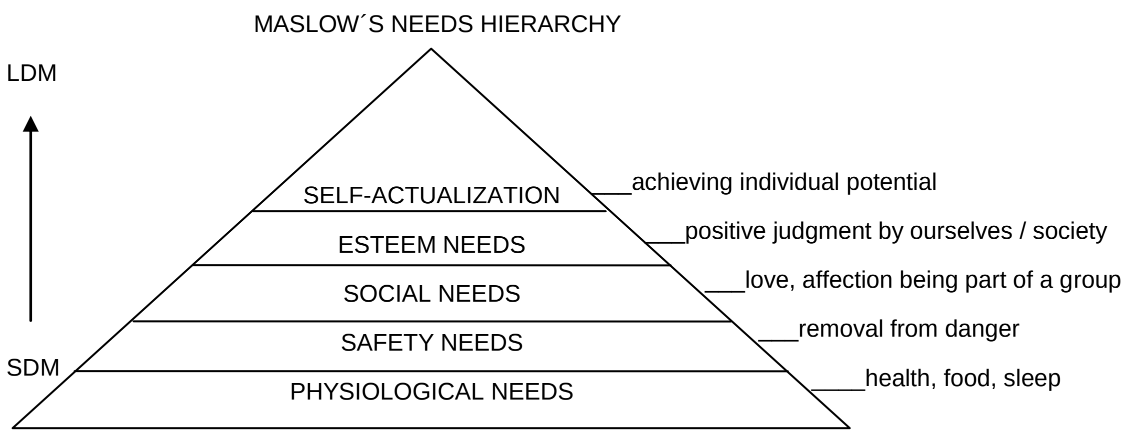


Figure 2.18: Maslow´s needs hierarchy (Straker, 2010)

Mission Distance

The relevance of habitability is given by the duration of the mission but also by the distance. This parameter needs to deal with the user's autonomy but also with the need of performance and habitybility (cf. following tables). There is a strong difference between being on a 56-million km journey to Mars and just orbiting in Low Earth Orbit (LEO) inside the ISS at 400 km from Earth. The distance from Earth strongly affects the habitability needs. Considering, for example, a mission to Mars, we will have to deal with extreme psychological and socio-cultural factors (cf. *section 2.2.4*) that have only been encountered to a minor degree or even never before, like the "Earth out of view" phenomenon. With the 44-minute communication delay between the two planets, no familiar conversation will be possible, nor can there be ground-based psychological support sessions. As Kanas explains, moreover those astronauts "will not be able to receive surprise presents, like special cookies or favorite movies, which are often brought to the space station on supply shuttles when someone starts feeling homesick or maybe a little blue. Thus, decking out the Martian-bound craft with family photographs, special trinkets, books and even plants will be crucial for a mostly monotonous extraterrestrial road trip that will bring a whole new meaning to the "are we there yet?" question. If someone becomes sick – either physically or mentally – the crew has to be ready to cope with that, too. "If someone gets suicidal, you have to take care of it on board," Kanas said. Mission Control might also have to make some tough calls, like whether to tell an astronaut about a death in his or her family or other tragedies back home" (Farrar, 2008). Indeed, one focal point of the distance variable is the autonomy and the reliability of the user.

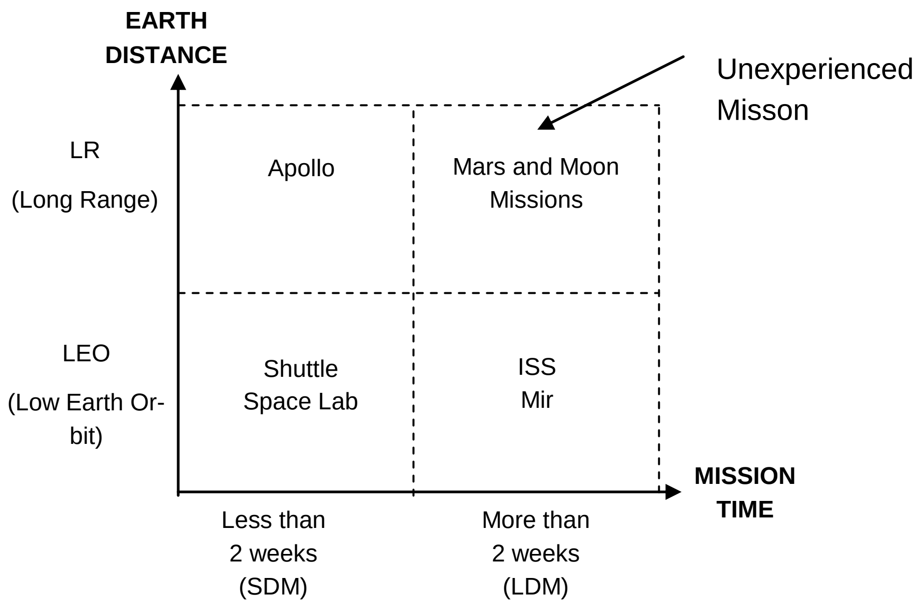


Figure 2.19: Mars and Moon are unexperiencied mission with long duration/range.

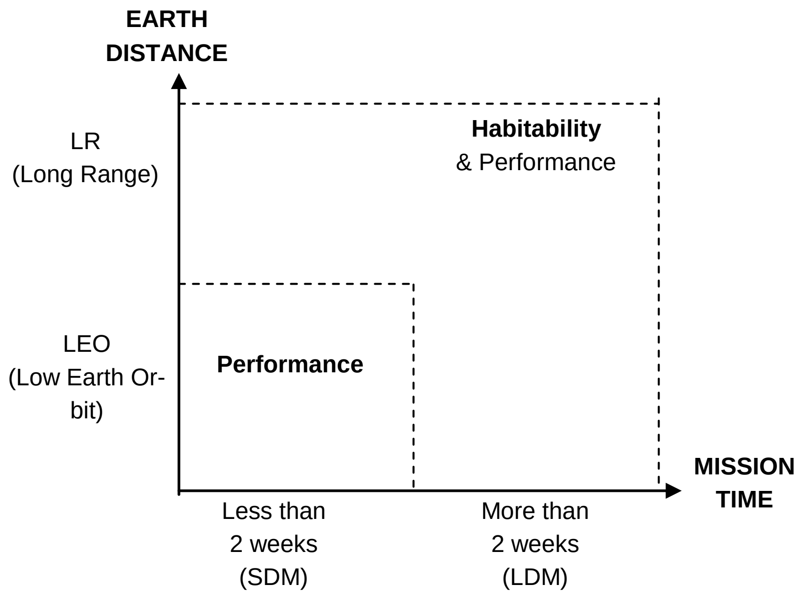


Figure 2.20 & 2.21: Habitability relevance increases with mission duration as well as with distance.

Human Adaptation

The levels of habitability and performance in space are closely related to the human capacity for adaptation, which is also called human-system integration. A well-designed habitat and a mission with "a good habitability can decrease the probability that the environment will contribute to crew error or other performance issues". "In the case where the environment cannot be adapted to the human, research indicates the human does have the ability to adapt to the environment" (Blume Novak, 2000 p. A 131). Human adaptation is aimed at supporting human-system integration. Human adaptation can be achieved with selection and training, artificial adaptation, and natural exaptation.

1. Selection and training: Astronauts are integrated into the system through selection and training on the basis of the human-system integration.
2. Artificial adaptation: The body is designed and adapted to support human needs in an extreme environment.
3. Natural exaptation: The astronaut's body naturally reacts to the new psycho-physiological constraints following the exaptation process on the basis of the human-environment integration.

These three dimensions support the task operation and are strictly related to the human anthropological evolution. It took humans 4 million years to evolve on Earth to where they are today. And that is nothing should the counting start from the "gravitational adaptation" to the vertical environment exactly at a Lemur-like evolutionary stage which, according to the hypothesis of Delattre (1960) and Napier (1967), took 60 million years! To live in space, humans again need to adapt and evolve with completely different environmental conditions. "In the theory of evolution, Darwin posed the question of how organisms could afford new environmental conditions. This occurs when a species or population has characteristics that are suited for conditions which have not yet arisen" (Masali, 2010 p. 156, 7). "Adaptation means evolution," explains Prof.

Masali, an expert on the application of anthropology and anthropology to space. "The adaptation mechanism requires extremely long periods; it involves the architecture of the whole organism, even when it acts on a specific character". He then declares, "in extraterrestrial adaptation, there is no time to evolve" (Masali, 2010 p. 156, 7).

Table 2.6: Human Life Evolution in Years

HUMAN LIFE EVOLUTION

13 700 000 000 = Universe
4 540 000 000 = Earth
4 250 000 000 = Moon
4 000 000 000 = Life in water
3 000 000 000 = Oxygen
1 000 000 000 = Multicellular life
600 000 000 = First multicellular animal
500 000 000 = First vertebrates (fish)
300 000 000 = Vertebrates on Earth (reptiles)
200 000 000 = Mammals
150 000 000 = Fly (birds)
130 000 000 = Flowers
65 000 000 = Dinosaur extinction
30 000 000 = Monkeys
15 000 000 = Hominidae
2 300 000 = **Genus *Homo***
2 000 000 = STONE AGE
500 000 = *Homo sapiens*
200 000 = ***Humans***
50 000 = Behavioral modernity
(language and expression of cultural creativity)
3 000 = BRONZE AGE (writing)
1 200 = IRON AGE
0 = *Anno Domini*
400 = MIDDLE AGE
1500 = MODERN AGE
1900 = CONTEMPORARY AGE
1957 = SPACE AGE "*Homo sapiens spatialis"*
2000 = Today

Astronaut Selection and Training

Astronauts are selected on the basis of their characteristic ability to best react toward the psycho-physiological constraints in space and are trained to improve their potentiality to be productive under those constraints. In the SSP50005C, selection and training are part of the human-system integration study so as "to form an effective Human-Machine System" (AA.VV., 1999).

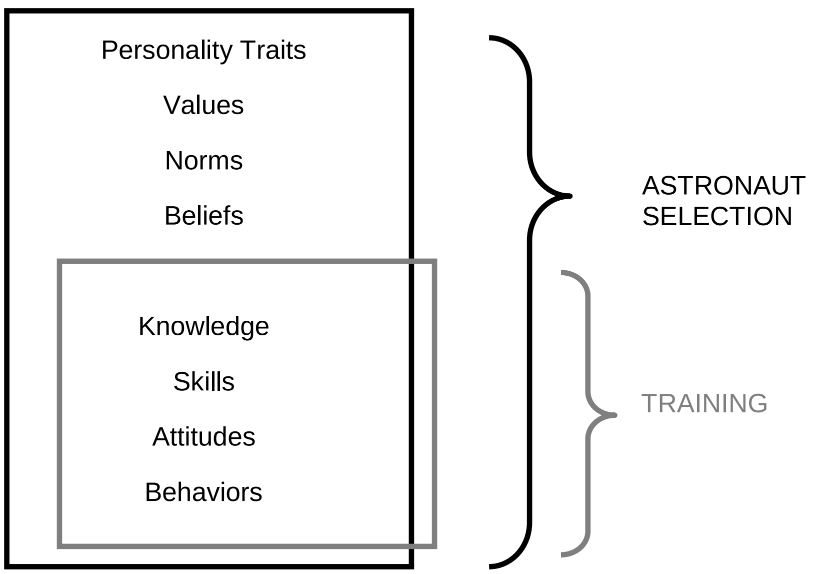


Figure 2.22: Selection and training of astronauts' psychological features (Sonja Ongaro, 2005)

Selection and training are particularly important for astronauts and apply both on the physical and psychological levels. For example, as explained by Sonya Ongaro, the main focus of the psychological training should be on self-management, leadership and teamwork, and group living. Those aspects affect habitability, particularly at the social level.

In the past 50 years of the Space Age, selection has been based on aptitude. The *Fédération Aéronautique Internationale* (FAI) defines spaceflight as any flight beyond 100 km from the Earth's surface. Following this definition, up to the present, we have only had 520 astronauts in total, only 24 of whom have traveled beyond low Earth orbit and of whom 12 have walked on the Moon. 6 of the 520 were space tourists and 2 were commercial astronauts (private spacecraft) (Anikeev, 2011). This means that only 2 of the 520 astronauts were outside of the agencies' aptitude-based selection. In the future, with the amelioration of the space conditions and the increased involvement of private spacecraft, more and more humans will go to space without aptitude-based selection.

In training for long duration space missions, like Earth orbit and Moon or Mars missions, the creative process is a fundamental contribution to mission success. As mentioned by Martius, creativity stimulates the learning process and self-awareness in relation to the environment (Martius et al., 2008). Creative expression may extensively contribute to psychological stability and to astronaut safety. Music, poetry, and painting are art mediums that can be used in space for self-expression or for expressing ideas, adding also a new dimension to knowledge. As the psychologist Csikszentmihalyi (1996) explains, "creativity …leaves an outcome that adds to the richness and complexity of the future" (Schlacht & Ono, 2009).

Artificial Adaptation

How can these humans adapt to the extreme environment of space without attitudinal selection?

One option would see the physical integration of technology with the human body to approach extreme environmental conditions, in order to create a new cyborg identity that transcends the boundary of "the relationship between 'inner space' to 'outer space'" (Halacy, 1965 p. 1). This concept is based on the cybernetic idea of a powered exoskin to survive in extreme environments, which is nothing other than the space suits (as shown in *Figure 2.23*). Indeed, a cyborg, or a human being with an integrated machine, was intended by Clynes and Kline (1960) to support extra-terrestrial exploration (1960): "Altering man's bodily functions to meet the requirements of extra-terrestrial environments would be more logical than providing an earthly environment for him in space" (1960 p. 26). One hypothesis discussed within the space industry is that smaller humans fit better on space stations, and considering that legs are practically not used, genetic or body manipulation has also been considered (personal communications with space employees in November 2005). However, ethical constraints must also be obeyed since astronauts need to represent humanity in its integrity, as underlined by Prof. Messerschmid (personal communication, Stuttgart 2009).

If the human being is "taking an active part in his own biological evolution" (Clynes & Kline, 1960 p. 26), allowing himself to be artificially modified or manipulated with genetic engineering to fit in with the extraterrestrial environment, then this will obviously end up in a new species, which may be called *homo sapiens cyborg-spatialis*.

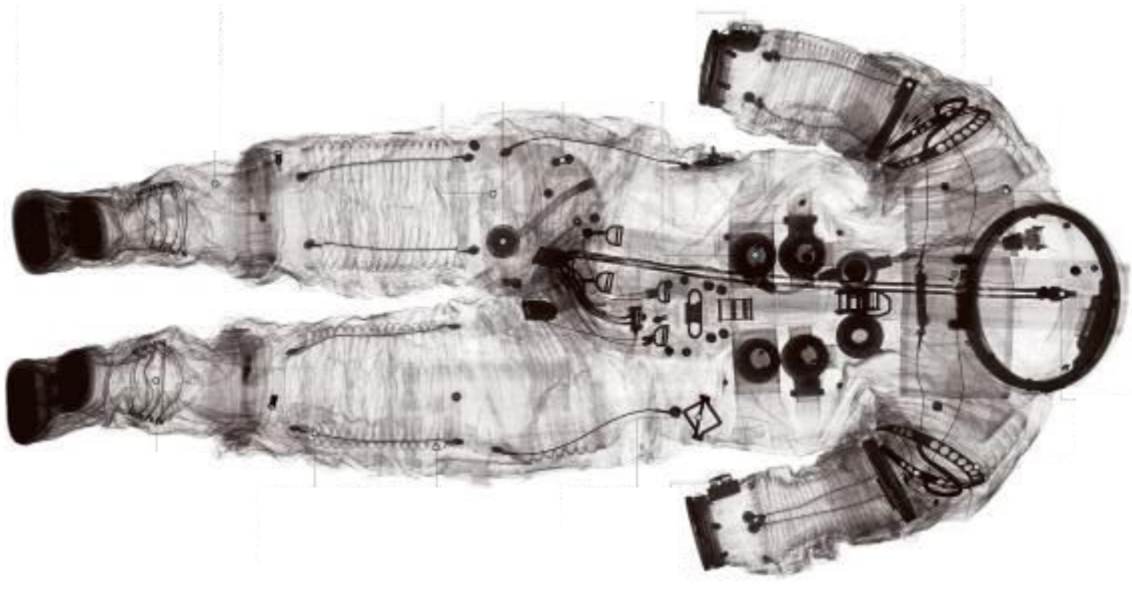


Figure 2.23: Space suit as a skin-tight habitat system.
(X-ray of Alan B. Shepard's space suit, 1971 Apollo 14; © New York Times, 2010)

Natural Exaptation

In summary, to live in the space environment, a different process of evolution needs to be applied, one being the aptitude-based selection and training applied by the agencies, another being the adaptation of the environment to support human life in the effort to create a sustainable and Earth-autonomous habitat. In cases where the environment cannot be adapted, there is a third possibility: exaptation. Exaptation, first proposed by Gould and Vrba, means that the 'archetypal' structures developed by an organism for a specific need are co-opted by the new environment to evolve into new functions (Gould & Vrba, 1982; and Gould, 1991). It is similar to certain types of dinosaurs with small dimensions, which with natural selection developed feathers as features to protect themselves in an increasingly cold environment. This same feature was then already available and allowed them to fly as they evolved into birds. With the exaptation mechanism, "different adaptive patterns may derive from unusual environmental conditions. This approach may be the challenge for extraterrestrial adaptation of Earthly organisms" (Masali, 2010 p. 156, 7). One example is the capacity of humans to move and coordinate themselves in the absence of gravity, as hypothesized. It will be thanks to the same exaptation, which introduced the 'archetypal' structures developed by Lemurs in order to jump ballistically from tree to tree, that the new astronauts will be able to move in the absence of gravity (Masali, 2010).

2.3.2 Machine (Space Habitat System)

The astronauts in space interact and live in a very complex habitat, which is now far away from the architecture concept based on solidity, utility, and beauty (Vitruvius, 29-23 a.c. vol.1-2). The Oxford Dictionary (2011) defines habitat as "the natural home or environment of an animal, plant, or other organism" and habitable as "suitable or good enough to live in". Living environments for astronauts, however, are currently called "habitation" at ESA, which the Oxford Dictionary defines as "the fact of living in a particular place", to which it might well be appropriate to add "congenial to human needs" as described by ESA space designer Manuela Aguzzi (2005

p. 4). Habitat is also defined as the Architecture that *Marcus Vitruvius Pollio* defined in De Architectura, consisting of order, arrangement, proportion and symmetry, décor, and distribution (Vitruvius, 29-23 a.c. vol.1, Chapter 2).

This section presents an overview of the main space station relevant for this research. As an example of a deep analysis, the current space station – the ISS – is reported in *0*.

Space Stations

Space habitats are composed of different systems and subsystems aimed at supporting their physiological needs. Defining the machine as a multiplicity of elements that control a technical process for the realization of material (e.g., oxygen), energy (e.g., power system), and information (e.g., control system), the complex space station can be considered more as a machine than a habitat (Rötting, 2011; Schlacht et al., 2010).

- Apollo, Salyut, Skylab, Space Shuttle, Mir, and the ISS are the space habitat systems that have been built until now. Other stations, like the Mars Desert Research Station (MDRS) or the Mars 500, are simulation environments built on Earth to research the optimal mission strategy. The most relevant habitats are presented below.

- Mir was a Russian spacecraft that flew in low orbit from 1986 to 2001, with 350 m^3 of pressurized area, accessed by astronauts from different nations, including Europe. It was serviced by Soyuz and Progress spacecraft as well as by shuttles. Inside the Mir, the longest mission in space was accomplished by Valeri Polyakov, lasting 437 days.

- Mars 500 is a Mars mission simulation of 500 days conducted by a crew of five in a station of 550m^3 by the State Scientific Center of the Russian Federation. Constraints like differences in gravity and radiation do not affect the crew. The main part is a series of experiments on long-term isolation of the crew in conditions of the specially built ground-based experiment facility (Mars500, 2011).

- The Space Shuttle is a reusable spacecraft designed in an airplane shape that is able to dock at the Mir and the ISS. The Space Lab is the pressurized experiment module mounted on 22 Space Shuttle missions. The Shuttle launches like a rocket, maneuvers in Earth orbit like a spacecraft, and lands like an airplane. The Space Shuttles were operative and flying from 1979 to 2011 with five models: Columbia (1979-2003), Challenger (1983-1986), Discovery (1984-2011), Atlantis (1985-2011), and Endeavour (1992-2011). The longest Shuttle mission was 17.5 days on mission STS-80 in November 1996. Normally, missions may be planned with a crew of six for 5 to 16 days in duration and can be considered mostly as short duration missions. The shuttles have a forward fuselage pressurized crew area of 71.5m^2 (Wilson, 2006; NASA, 2011 and 2011d; Reichl, 2009).

- ISS is the current low orbit space station of 837m^3; detailed descriptions have been extensively presented in the previous chapters. The functional infrastructure related to the ISS environment is called ISS flight system. “The ISS flight systems consist of Habitation; the Crew Health Care System (CHeCS); Extravehicular Activity (EVA); the Environmental Control and Life Support System (ECLSS); Computers and Data Management; Propulsion; Guidance, Navigation, and Control; Communications; the Thermal Control System (TCS); and the Electrical Power System (EPS)” (NASA, 2010 p. 21 pdf, print 47). Payloads, hardware, software, and crew support items on the ISS work within these systems.

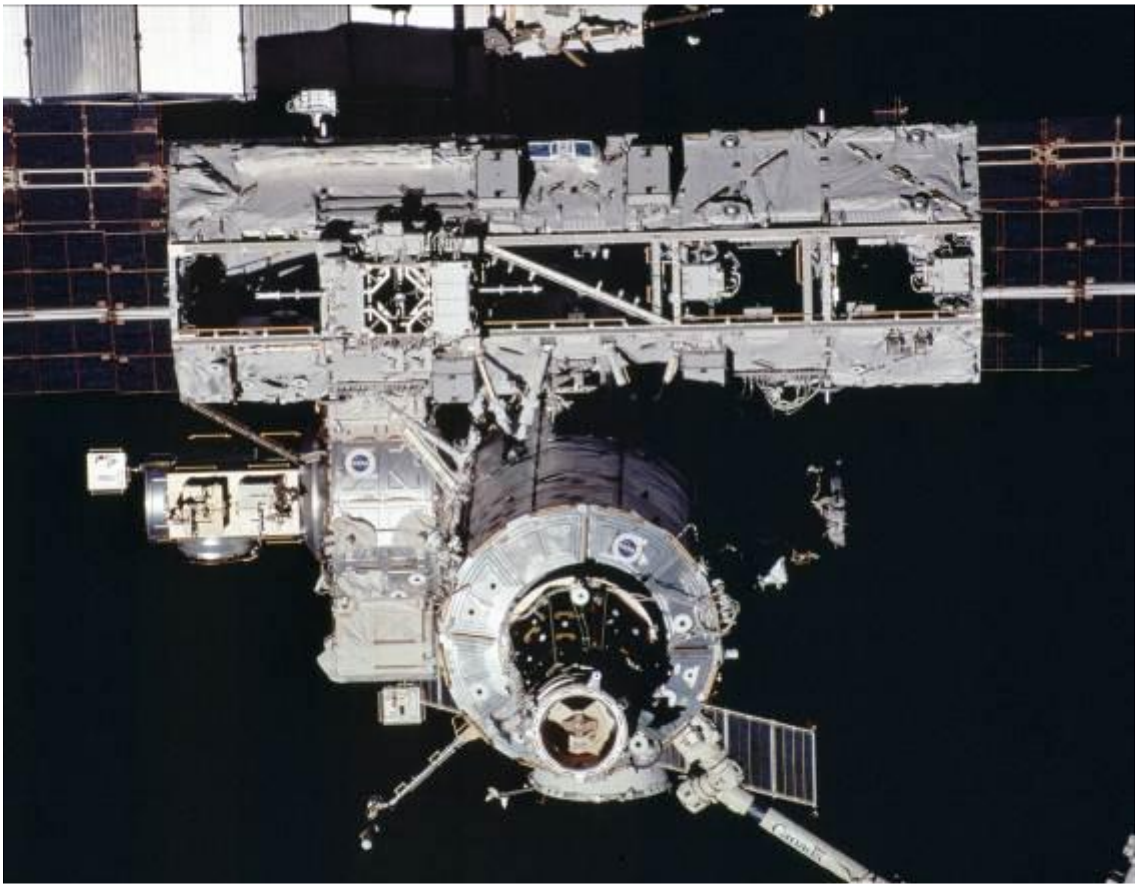


Figure 2.24: ISS habitat system (Foto STS110-729-055 © NASA 2002, http://spaceflight1.nasa.gov/gallery/images/shuttle/sts-110/html/sts110-729-055.html)

ISS Habitat System

The focal points of interest related to the ISS habitat system are:

- Habitation and Pressurized Module
- Health and Safety
- Life Support
- Odor
- Noise and Music
- Temperature
- Power
- Light and Colors
- Interiors Décor

These points are analyzed and described in .

2.3.3 Environment (Outer Space)

Space is an extreme environment. Kanas and Manzey (2008) defined an extreme environment as "any environment to which humans are not naturally suited, and which demands complex processes of physiological and psychological adaptation" (p. 15). In other words, an extreme environment is defined as such by its extremely low level of suitability as a place for human beings to live. Of the various extreme environments that human beings have been able to reach, space is the most extreme. Extreme environments include: submarine vessels, underground, high mountains, underwater laboratories, dwelling stations in desert and Antarctic areas, radioactive areas, offshore drilling rigs and, of course, space environments. Extreme environments are characterized by adverse environmental conditions particularly unfriendly to humans, such as extreme temperatures and pressure, lack of oxygen, and the presence of radiation. In space, we have all these environmental conditions plus other factors such as a wholly different level of gravitational force, meteorites, vacuum, and other effects, such as the very sharp contrasts between light and dark or severe temperature changes. At the environmental level in space, the most important matters are the following (detailed information about these topics can be found in *Appendix C*):

- Extreme Temperatures
- Radiations
- Microgravity (and Difference in Gravity)
- Lack of Oxygen and Difference in Pressure
- Altered Dark-Light Cycle

These environmental factors mainly affect humans at the physiological level; however, they are not the only ones that affect the definition of the level of suitability of a place for human beings; as a matter of fact, operational factors (e.g., workload), physical factors (e.g., danger), psychological factors (e.g., monotony), and social factors (e.g., social isolation) also have a strong relevance *(*cf. *subchapter 2.2)*, as shown in *Table 2.7.*

Table 2.7: Evaluation of various types of extreme environments considering different stressors

Extreme Environment	Physical Danger	Work load	Social isolation	Spatial confinement	Temporal confinement	Environmental isolation	Monotony	Earth out of view
Prison	light gray	light gray	dark gray	dark gray	dark gray	neutral gray	dark gray	
Cloistered Convents		light gray	dark gray	neutral gray	dark gray	light gray	light gray	
Nursing Homes			neutral gray	neutral gray	neutral gray	light gray	neutral gray	
Desert			neutral gray			neutral gray	neutral gray	
Submarines	neutral gray	neutral gray	dark gray	dark gray	dark gray	dark gray	neutral gray	
Antarctica Laboratories	light gray	neutral gray	dark gray	dark gray	dark gray	dark gray	neutral gray	
Underground Laboratories	light gray	neutral gray	neutral gray	neutral gray		dark gray	neutral gray	
High Mountains	neutral gray	neutral gray	neutral gray				neutral gray	
Space Missions	very dark gray	very dark gray	very dark gray	very dark gray	very dark gray	very dark gray	very dark gray	very dark gray

Legend: level of suitability of a place for the human being
Slightly unsuitable (light gray), Fairly unsuitable (neutral gray), Strongly unsuitable (dark gray), Extremely unsuitable (very dark gray)

2.3.4 Mission (Destinations)

Today, there are five main options being considered for future human space missions: Earth Orbits, Lagrange points, Moon, Mars, and NEOs.

Earth Orbits

The ISS is the only currently active and the first international habitat structure built for Earth orbit. This structure cost 100 billion euros and weighs 450 metric tons. With the deployment and activation of the first habitat module on November 20, 1998, an international crew has been living in microgravity in low Earth orbit (LEO) at an average distance of 400 km from Earth. The addition of the PMM (Permanent Multipurpose Module) saw the ISS being completed in 2011, with more than 1200 cubic meters of pressurized space comprising storage, experiments, racks and habitable volume (ESA, 2008b; Ryba, 2011). At a speed of 28,000 km/h, it makes a complete Earth orbit in 90 minutes.

There are two ways for a person to reach the station: on board the Space Shuttle or in a Soyuz spacecraft. The mission duration on the ISS varies from two weeks aboard the shuttle to six months aboard the ISS. After a launch with Soyuz, it takes eight minutes to reach orbit and then usually two days and one hour to dock with the ISS. If arriving in a Soyuz aircraft, the astronauts have to wait another three hours after docking before the hatches open and the astronauts can access the station. The return mission takes between one and three hours from the time of undocking to landing (Zak, 2010; Gerzer, 2010). The main difference to the Shuttle missions is the hypergravity:

Shuttle: 3 Gx Start, 3 Gx Landing;

Soyuz: 4 Gx Start, 7 Gx Landing (Gerzer, 2010).

Lagrange Points

Lagrange points are locations in space where gravitational forces and the orbital motion of a body balance each other out. These points are also considered to be possible positions in space to locate a spacecraft and potential places for refueling or building points for deep space human missions. There are five Lagrangian points in the Sun-Earth system, and such points also exist in the Earth-Moon system. A spacecraft at L1, L2, or L3 is ‘meta-stable’, like a ball sitting on top of a hill. A little push or bump will make it move away. A spacecraft at one of these points has to use frequent rocket firings or other means to remain in the same place. Orbits around these points are called 'halo orbits'. But at L4 or L5, a spacecraft is truly stable, like a ball in a bowl: when gently pushed away, it orbits the Lagrange point without drifting farther away, and without the need for frequent stabilizing rocket firings. L1 is a very good position from which to monitor the Sun; however, for a human mission L2 is considered, as it provides a stable viewpoint for the observation of the universe. L2 is located 1.5 million kilometers directly 'behind' the Earth as viewed from the Sun. It is about four times further away from the Earth than the Moon. L2 is a great place from which to observe the larger universe (ESA, 2009).

Moon

The moon is a natural satellite of the Earth and is 384 000 kilometers from it.

Reached during human missions Apollo 11, 12, 14, 15, 16, and 17 between 20 July 1969 and 1972, it has to this day not seen the establishment of a proper station on it. Only the Lunar Module with 6.7m^3 of habitable volume supporting a crew of two has ever been deployed on it (Smith, 2010; Barry, 2010).

Due to the parameters of the Moon's orbit, 2% of the area of the South Pole is permanently illuminated. According to the Moon researcher Eckart, this is a suitable location for the installation of a base due to the constant presence of solar energy (1999). The temperature on the surface ranges from 114° C to -180° C, depending on the levels of solar illumination. The Moon has an equatorial gravity of 1.62 m/s^2 (1/6 of Earth), which has an obvious impact on human movement and on the design of structures.

The Moon has essentially no atmosphere and no magnetic field. Due to the lack of protection attributable to such lack, the habitat alone must protect human beings from Galactic Cosmic Radiation and Solar Particle Events. In addition, the habitat must be capable of protecting human beings from meteoroids (circa 1 micron) that hit the surface with a velocity of 15 km/s, and also from the effects of lunar dust (Eckart, 1999).

Figure 2.25: Lunar farside (Crater Tsiolkovsky, © NASA 1970, AS13-60-8659 http://spaceflight1.nasa.gov/gallery/images/apollo/apollo13/html/as13-60-8659.html)

Mars

Mars is the 4th planet from the Sun. Like the Earth, it has an atmosphere and is orbited by two satellites of its own: Phobos and Deimos. The tilt of the planet is almost identical to Earth's, meaning Mars has four distinct seasons just like Earth. A day on Mars lasts 24.6 hours and due to its long orbit, one Martian year is nearly twice as long as the Earth's. The Martian atmosphere is composed of carbon dioxide (95.32% CO_2); nitrogen (2.7% N_2), argon (1.6% Ar), oxygen (0.13% O_2), carbon monoxide (0.08% CO), and as a minor component, water (210ppm H_2O). It has a pressure of 6.35 mb at its main radius. The temperature on the surface during the day ranges from -89° C to -31° C depending on the distance from the sun. It has different kinds of winds: 2-7 m/s (summer), 5-10 m/s (fall), 17-30 m/s (dust storm). The two satellites have an orbital period of 0.3 days for Phobos and 1.2 days for Deimos. Unlike Earth, Mars has no global magnetic field (Williams, 2010; Houben, 2010). The distance between Mars and Earth varies from 55.7 million kilometers to 401.3 million km, with an average of 227.9 million km. This distance has strong repercussions on human health due to radiation exposure as well as the physical adaptation to microgravity; in addition, the Earth as seen from the surface of Mars will be less visible than Venus is from Earth, with a resultant high psychological impact due to isolation. This distance may be traversed using current technology in 230 days; however, it will vary with the mission profile in relation to the orbital window selected:

Profile	Short	Long	Middle
Outbound	224	224	150
Stay	30	458	619
Return	291	237	110
Total	545	919	879

(Williams, 2004)

NEOs

Near-Earth Objects (NEOs) consist of two groups of objects: comets (NECs) and asteroids (NEAs), whose orbit of perihelion distance q is less than 1.3 AU (around 200 million km), which puts them in the Earth's neighborhood. Composed mostly of water ice with embedded dust particles, comets were originally formed in the cold outer planetary system, while most of the rocky asteroids were formed in the warmer inner solar system between the orbits of Mars and Jupiter. The scientific interest in comets and asteroids is due largely to their status as the relatively unchanged remnant debris from the solar system formation process some 4.6 billion years ago. Scientists believe comets and asteroids have slammed into Earth in the past, playing a major role in the evolution of our planet. One theory suggests that comets brought some of the water and a variety of organic molecules to the early Earth (Yeomans, 2011; Watanabe, 2011). While comets and asteroids are potentially the most hazardous because they can closely approach the Earth, they are also the objects that could be most easily exploited for their raw materials. Whereas asteroids are rich in the mineral raw materials required to build structures in space, comets are rich resources for water and carbon-based molecules necessary to sustain life. It seems likely that in the next century when humans begin to colonize the inner solar system, the metals and minerals found on asteroids will provide the raw materials for space structures while comets will become the watering holes and gas stations for interplanetary spacecraft (Lewis, 1996).

In conclusion, missions to comets and asteroids help explain the composition and structure of these bodies. Findings from such missions may help us to better understand the formation of the solar system, the potential use of asteroids and comets in future interplanetary exploration, and the best methods for deterring objects with potentially hazardous orbit paths (Watanabe, 2011).

In a personal e-mail communication (3 February 2011), Dr. Donald K. Yeomans, NASA's Near-Earth Object Program Office Manager, explained that "President Obama has set a goal for 2025 as the first human exploration of a near-Earth asteroid". However, other specialists put this goal into the long-term future (Barbara Imhof personal communiocation 2011). Indeed, it has been considered as one of several possible mission destinations.

2.4 DESIGN PROCESS

This subchapter is dedicated to the state of the art of the design process applied to the design of habitability factors. It focuses in particular on the concept phase of the project, both in the context of generic human factors and in the context of human space missions.

The design process is the lifecycle of a project. According to Messerschmid & Bertrand (1999) the term "project" is defined as "all the activities necessary for the realization of a technical system, ranging from the initial ideas to operation to final use" (p. 329). A project is a unique and acyclic sequence of events with a defined beginning and end point. In space, the term mission refers to a state-of-the-art project driven by "political or scientific objectives" (Messerschmid & Bertrand, 1999 p. 331).

2.4.1 Space Design Processes

Habitability is defined by all the system elements that surround the astronauts. These elements are defined during the design of a space mission. The different design strategies and processes utilized in the design of space missions are analyzed in this chapter. Consideration has also been given to the various agencies. Different processes occur in the evaluation of the quality of mission design, including the habitability of the space station. One of these processes is the feasibility assessment; others include the walk-through and the design report. The walk-through is a particularly relevant process at ESA, and utilizes user evaluation in its execution. Two astronauts are asked to "walk through" a mock-up of the habitat and write a report in which they evaluate and comment on the level of habitability. The most relevant process is the concurrent design, which has a special place in this dissertation because it sets up the basis for the development of the overall mission.

Space Agencies' Methodologies

The methodologies utilized by the various agencies are similar, yet different. Most of the ESA standards are based on those of NASA, resulting in a strong connection between these two sets. As a consequence, the ESA and NASA norms are the same. RKA has different norms and the standards used are difficult to access, not only because of the language barrier but also because of the politics of competition that make sharing documents more difficult. JAXA also has difficulties in sharing documents because of the language; however, it also follows most of NASA's standards. ESA (from 1975; ex ELDO created in 1960) and JAXA (from 2003; ex NASDA created in 1969) had their entry into the space industry relatively late in comparison to RKA (from 1992; ex-Soviet space program from 1930) and NASA (from 1958; ex NACA founded in

1915). It is easy to see how RKA has had a strong philosophy of researching psychological factors, design, and artistic application from the beginning of space research. In particular, choreographers, psychologists, and physiologists of the 1960s and 1970s were involved in studying the effect of color in the interior of the spacecraft. JAXA has also had its own artistic program applied to its Kibo module. NASA, too, has had an artistic program, but with strongly debated funding cuts every year, and the results have not been applied at all to the ISS, only in a general broadening of education.

Mission Design Process

Although five decedes have passed since the first human spaceflight, progress in the spaceflight design process has not been as extensive as expected during the first period of competition-driven space exploration, or as fast as could be hoped when comparing it with other advanced technological fields. This is due to the high risks and cost factors, long project schedules, low production quantities, and physical and political challenges associated with spaceflight projects (Osburg, 2002). Designing a space mission is a complex and multidisciplinary task because at each level of development, several parties (sponsors, operators, customers, developers) and subsystems (power, thermal, data, etc.) are simultaneously involved in the project. The development of a human space mission project is a linear process (Aguzzi, 2005). To explain this process is easy. An example can be taken from NASA or ESA; indeed, as shown in *Table 2.8*, although the "lifecycles" used by NASA, ESA, and DoD (Department of Defense) are distinct, they have the same basic concept (Messerschmid & Bertrand, 1999).

Table 2.8: Program development phases for a crewed space system. Dr. Reinhold Bertrand, Space System Institute, University of Stuttgart (Larson and Pranke, 1999)

ESA	0 Mission Analysis, Needs Identified	A Feasibility	B Preliminary Definition	C Detailed Definition	D Production/ Ground Qualification Testing	E Utilization	F Dis-posal
NASA	Advanced Studies	Preliminary Analysis	Definition	Design	Development	Operations	
DoD	Pre-Milestone 0	0 Concept Exploration Needs Analysis, Concept Development	I Demon-stration and Validation	II Engineering and Manufacturing Development	III Production and Deployment	Operations and Support	

In the next part, the mission design process applied by NASA is described as an example.

The phases of the mission design process include:

0. Advanced Study: This phase comprises advanced concepts investigation in new technologies, mission analysis, new propulsion systems, etc.

1. Preliminary Analysis: This is the initial study phase, which results in a broad definition of the space mission and its systems and approaches.
2. Definition Concept and Architecture: This results in a level of design necessary to support a preliminary design review.
3. Design: This is the formal design phase, which leads to a detailed definition of the system components and the development of test hardware or software that can support a critical design review.
4. Development: This is the construction of the ground and space-based systems necessary for launch and operations.
5. Operations: This is the day-to-day operation of the ground- and space-based systems, their maintenance, support, and logistical replenishment.
6. Disposal Phase: This is the disposal of the physical and functional elements at the end of the mission life cycle.

(Larson and Pranke, 1999)

The first step of the mission lifecycle is the preliminary analysis, in which a broad definition of the space mission is given. It defines the space mission's objectives; mission requirements and constraints such as performance, duration, logistics, survivability, and cost; mission concepts and architectures (how the mission will work to meet the objectives). When different concepts have been developed, a trade-off is performed, generally taking into account cost, performance, and crew safety (Aguzzi, 2005).

The output of this process is the definition of a baseline mission concept and architecture. Each space mission is composed of a series of elements that constitute the space mission architecture. Each of the elements influences the others. For example, the focus of the industrial designers' and architects' activities are the crew and surface elements wherein human beings live, work, and operate (Aguzzi, 2005). However, their work has to consider its influence on and correlation with all the elements of the mission architecture.

Mission Concept Phase

The system concept is the phase on which this thesis focuses, which is why it is here presented in detail. The conceptual design at the system level takes place at the start of the design project and involves the design of the configuration and the technical parameters, including the integration of "performance, producibility, reliability, maintainability, manability, supportability, and other speciality" (Blanchard & Fabrycky, 1990). This refers to the NASA mission design process phase 2: Concept and architecture (Osburg, 2002). A widely accepted approach to system engineering that is tailored to the design of robotic and human space systems defines the mission architecture as the set of physical and functional requirements and their interrelationships that design a space system (Larson & Pranke, 1999).

The main elements of the mission architecture are:

- Orbit and trajectory influence every element of the mission. They determine the mission duration, which is crucial data for the design of a space habitat. Depending on the trajectory, the crew can be exposed to different types of radiation; this therefore influences the design of radiation protection of both the transportation vehicle and the habitat vehicle on the surface.

- The space elements consist of the orbiting space vehicle, transportation vehicles, and vehicles for entry, descent, landing, and ascent. Characteristics of the space elements can influence mission duration and crew size.
- The transportation elements include launch facilities, launch systems, and propulsion systems that place the elements in orbit or land and return it from the surface. This component puts constraints in terms of mass, volume and costs on the overall mission.
- Mission operations include the people involved on the ground and space elements. The aim is command, control, and communication from/to Earth of the activity in space.
- People and surface elements are the real focus of industrial designers. (Larson and Pranke, 1999)

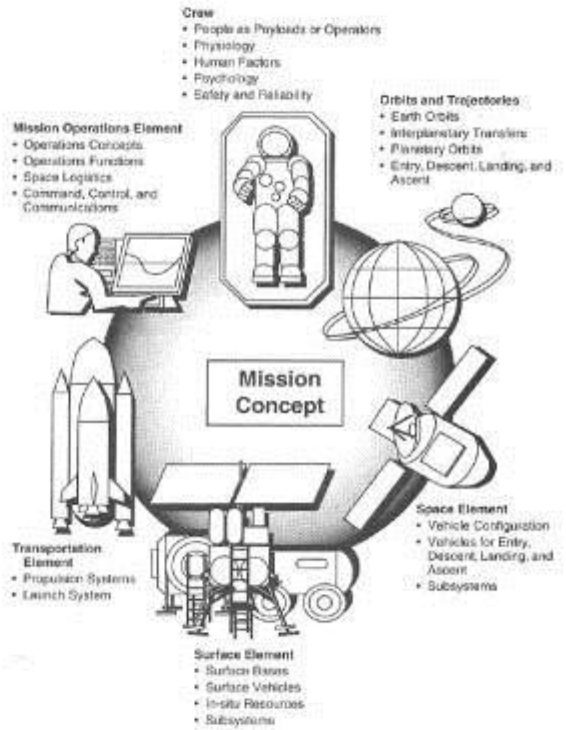


Figure 2.26: Architectural elements of crewed space missions (Larson and Pranke, 1999)

Robotic Mission Concurrent Design

The concurrent design strategy is presently used by EADS, ESA, DLR, NASA, and other groups in the field of space. It has already demonstrated its validity in the sharing of data and knowledge during the design process starting from the concept phase, with a relevant reduction in time and cost.

The definition of Concurrent Design that ESA has adopted for its facility is the following: “Concurrent Engineering is a systematic approach to integrated product development that emphasizes the response to customer expectations. It embodies team values of co-operation, trust and sharing in such a manner that decision-making is by consensus, involving all perspectives in parallel, from the beginning of the product life-cycle” (ESA, 2008).

The Concurrent Design Facility is usually a room (as shown in *Figure 2.27*) where a team of specialists work intensively together on a project, sharing the data of the project with an internal network.

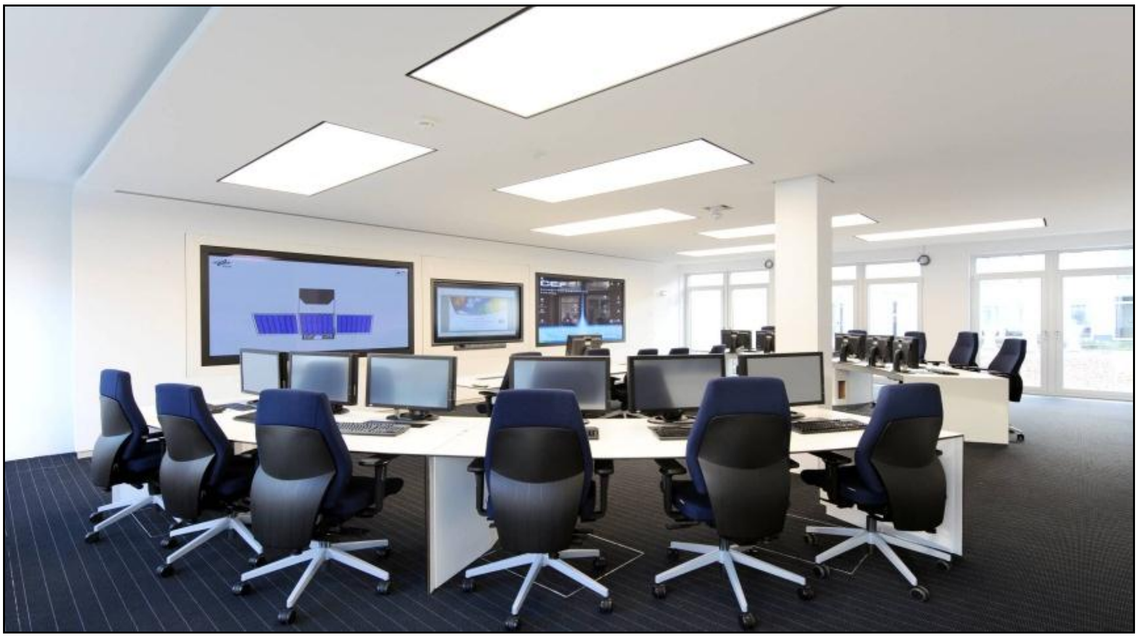


Figure 2.27: Concurrent Engineering Facility interior, DLR Bremen (DLR, 2011)

The key multidisciplinary experts involved in the team are:

- CDF Manager (responsible for the interaction with the customers and for running the facility)
- Team Leader (is in charge of the study progress throughout the whole process)
- Technical Author (takes care of the technical documentation, the user manual, and also the final report)
- Systems Engineer (runs session to make sure that the specialists and the mission design converge correctly, updates the CDF model)
- Assistant Systems Engineer (updates data in the IDM so that it can be accessed by the other disciplines)
- Technical disciplines vary depending on the study, but a few typical positions are:

  systems, instruments, mission analysis, propulsion, attitude and orbit control, structure, configuration, mechanisms, pyrotechnics, thermal control, power, command and data handling, communications, ground systems and operations, simulation, cost analysis, risk assessment and programmatic (ESA, 2007; Bandecchi et al., 2000).

"The System Engineering approach used by the Concurrent Design Facility is model based, and the software infrastructure currently used is called the Integrated Design Model. It consists of a number of domain specific tools and databases interlinked by means of several MS Excel® workbooks" (Johansson, 2010 p. i). "The main advantage of the Integrated Design Model is that parameters are linked between the workbooks and can directly be shared with all the other disciplines" (Johansson, 2010 p. 2). The Concurrent Design Facility at ESA in ESTEC is based on the application of Concurrent Engineering as a methodology to design future space missions. It has been utilized until now mainly for robotic missions, and for this reason it is currently not a human-based design.

Human Mission Concurrent Design

The Concurrent Design Facility at ESA currently does not support human mission design. In order to increase the effectiveness of this facility by also including the designing of human missions, various studies have been supported. In a study carried out during an internship at ESA by Master's student Johansson, proposals were put forward for the creation of a new discipline called "Human Systems Integration" aimed at supporting the human integration of the system. As Johansson reports: "More than 130 missions have been assessed in the Concurrent Design Facility in the last ten years, of which only a small percentage are dedicated to Human Space Flights. For this reason the model has not yet been fully developed and exploited for human missions" (Johansson, 2010 p. i). Johansson's project focuses on the integration of HF in the system: "In order to enhance the Concurrent Design Facility's capability in designing human space missions a new system level discipline is created that deals with Human Systems Integration (HSI)" (Johansson, 2010 p. i). But integrating the human as the last part of a system based on machine-centered design is no easy goal and many problems can occur. For example, as reported by Johansson, "The Human Systems Integration is not a direct quantitative domain, many requirements are difficult to define in numbers and the limits on the human body and the constraints it puts on the spacecraft design cannot always be given in concrete variables" (Johansson, 2010 p. 2). However, the same author at the end of her report concluded: "The Human Systems Integration discipline is a parametric workbook within the Integrated Design Model to be used by the Human Systems Integration specialist during a pre-Phase A study" (Johansson, 2010 p. 71).

The main point is that in the Integrated Design Model proposed in this dissertation, each worksheet contains "the requirements that can be given and numbers are checked and verified in the calculation worksheets by comparing estimated results from the other domains with specified limits" (Johansson, 2010 p. 2). So the requirements that have no quantitative variables are not supposed to be sent to the other subsystems and shared through worksheets in the concurrent design process. However, "the requirements that cannot be sent to the other subsystems via the Data Exchange can be shared in the sessions via presentations or discussions" (Johansson, 2010 p. 2). This draws attention to a relevant matter: there is not a real procedure to share non-quantitative values in the worksheet. However, "the ESTEC CDF system is flexible enough that if there is a need to pass on a non-numerical value, this can be done" (Scott Hovland, courtesy of personal communication, 8 March 2011).

To conclude, concurrent design has proven to reduce costs and time to market by speeding up the process of design. This system has been adopted to manage the innovation of complex products, avoiding the level of cost attributable to the sequential process of design in the case of failures (Aguzzi, 2005). However, the system has been designed for robotic missions, and in the case of human missions, a HF discipline still has to be integrated into the system facility.

2.4.2 User-Centered Approach

User-centered approach means focusing the design process on the user (Norman & Draper, 1986). It is imperative that the design requirement specifications of products and systems be based on the user, the environment, and the intended use of the product. Product design requirements become increasingly critical for extreme environments because the lack of proper product design may affect human performance, thus resulting in safety risks. The user-centered design methodology is based on physical design, industrial design, cognitive design, and user experience design components to ensure that all aspects affecting the user are incorporated into the product design (Meza & Crumpton-Young, 2010).

Participatory Design

User-centered design is performed "primarily by adequately determining user needs and by involving the user in all the stages of the design process" (Wickens et al., 2004 p. 35).

The tasks of the HF designer are:

- Study the user's job or task performance
- Elicit the user's needs and preferences
- Ask the user for insights and design ideas
- Ask the user for design solutions

The goal is "to find a system design that supports the user´s needs rather than making a system to which the users must adapt" (Wickens et al., 2004 p. 35).

User-centered design belongs to the sub-field of usability engineering (Gould & Lewis, 1985; Nielson, 1993; Rubin, 1994; Wiklund, 1994 after Wickens et al., 2004).

Usability is based on four steps (Wickens et al., 2004):

1. Early focus on the user
2. Empirical measurement (questionnaire and usability study on the user)
3. Interactive design (prototype and interface interaction)
4. Participatory design (directly involving the user as part of the design team)

In these four steps, the focus needs to be on (Meza & Crumpton-Young, 2010):

- Physical Design
- Cognitive Design
- Industrial Design
- User Experience

User Experience

User experience, in particular, relates more than the others to the qualitative dimensions from Figure 2.28.

Feeling, intuition, and instinct are part of a subjective social and cultural experience. These are unpredictable and intangible humanistic parts of the human-machine system that contribute to the overall system performance and safety (Schlacht et al., 2010).

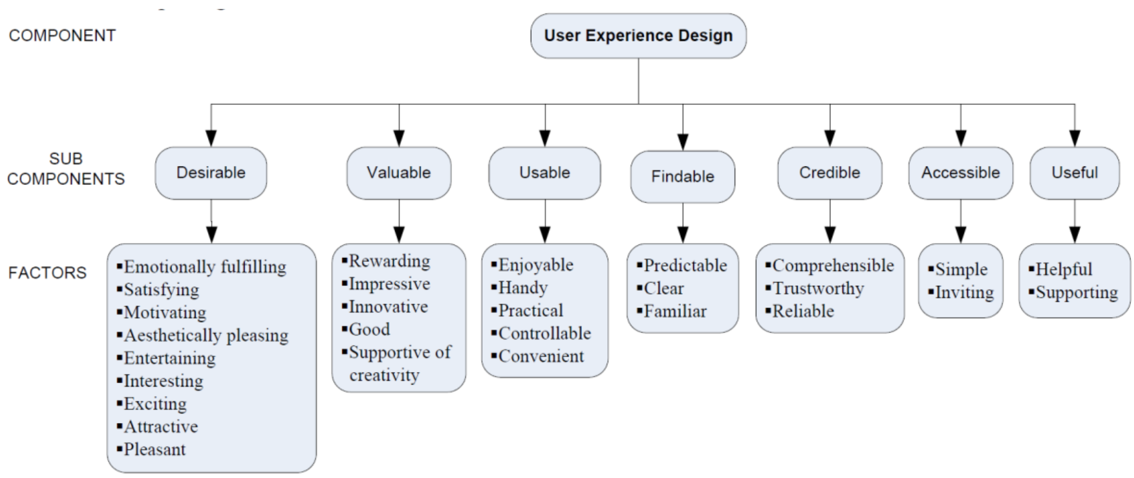


Figure 2.28: User Experience Design (Meza & Crumpton-Young, 2010)

Human emotions need to be considered as a part of the project. It is not as easy as merely inserting the human as one of the physical system elements. The human-system relation is physical from the system perspective, but from the human perspective it can be psychological, cultural, emotional, and even affective. People also experience sentimental affection with machines. Some people talk and even give names to technical devices as they will do with other humans. A recent survey by a U.S. insurance company (Progressive, 2000 cited after Luczak et al., 2001) showed that 32% percent of the respondents name their car and 12% would even buy a gift for their car for Valentine's Day. The phenomenon of people "attributing human characteristics to nonhuman phenomena" (Guthrie, 1993) is common and is known as anthropomorphization. The anthropomorphization context is related to emotion at work and the usability of technical devices. The results of a study done by Aachen University of Technology on 103 subjects – presented and awarded by the International Conference on Affective Human Factors Design in 2001 – revealed that most people frequently talk with their computer (64%). Over half of the people (52.4%) talk to the device in order to motivate it if they have to wait for the device. The most common form of interaction is cursing if the device is not functioning. 78.6% of the respondents agree with this statement. 72.8% scold the device if it is not functioning, and the same number of people agree that they do it to "discharge pressure" (Luczak et al., 2001).

In space, this kind of attitude is not taken into account. The phenomenon of discharging pressure is repressed and, if activated, might endanger the astronaut's life. Also, when the astronaut is highly trained and selected, considering the need for experiencing feelings, emotions, and affection may be crucial for user safety. In order to clarify this concept, Prof. Messerschmid (astronaut and head of ESA's Astronaut Center from 2000 to 2004) explained during a lecture for the Space Station Design Workshop held in 2008 that during an EVA (Extra Vehicular Activity) of the Mercury 7 NASA mission, an astronaut made an unplanned maneuver using manual altitude control jets, thus making the return nearly impossible (2008). Why did a highly trained flight pilot risk his life with an unplanned maneuver? The reason was: He wanted to get pictures of the beautiful sunset! This sheds a light on how emotions, aesthetics, and cultural experiences play a role in human needs and, as a consequence, in overall system safety and mission success.

As explained by Yong-Kyu Chi (expert in industrial design for outer space and director of the Korea Design Science Institute), user experience is indeed particularly relevant to people who live in space for a long time, enduring physical and psychological stress due to standardized spaces and tools designed without a detailed analysis of the human body, emotion, and instinct. "Informal design" is a design method that considers functional and emotional life in extreme environments using a different combination of spaces and tools, the coexistence of hidden functions and expressed design, and the combination of moment and permanence. One example might be to give astronauts the possibility of free movement and emotional expression, or the possibility of dance. Considering free movement in patterns of space behavior, we could combine freedom of action in formal spaces, developing it from formal to informal (Schlacht et al., 2010).

Subjective emotions like pleasantness and satisfaction are key factors in the interaction between humans and systems, as in space systems. As a matter of fact, satisfaction is considered an attribute of usability along with efficiency and effectiveness by the International Standard Organization (ISO DIS 9241-11, 1998). Following this concept, many relevant researchers have integrated emotions into design methodology, for example D.A. Norman (2004) with "Emotional Design". In "Kansei Engineering", M. Nagamachi (1995) considers subjective sensations and reactions; P.W. Jordan (1997) studied "The Four Pleasures", a design research methodology, while L. Bandini Buti (2008) proposes a "Sensorial Quality Assessment Method" (SEQUAM). These studies combine a scientific approach with aesthetic judgment to shape holistic design solutions (Bandini Buti, 2008).

Human experience is a very complex process. Perhaps the best-known explanation is the notion used by William James: "The content of consciousness is experience" (James, 1890). If the content of consciousness is experience, in order to gain new knowledge in space we need conscious humans and a human-centered design to support them.

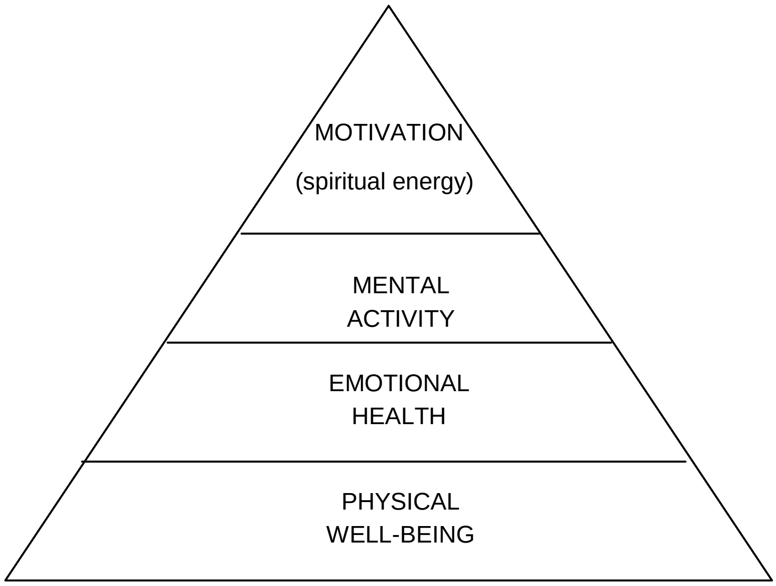


Figure 2.29: Pyramid Performance of Human Beings (Loehr & Schwartz, 2001 cited from Imhof, 2004)

User Experience and Performance

User experience is tightly interconnected with performance. The experience can be identified with "the soft, non-quantifiable, intangible issues that play a vital role in the crew well-being and mission success" (Imhof, et al. 2004, p. 134).

To explain the relations between experiences related to performance, the Performance pyramid is presented here (cf. previous image), where the physiological performances are at the bottom and the mental and visceral ones are at the top. For instance, “vigorous exercise can produce a sense of emotional well-being, clearing the way for peak mental performance” (Loehr & Schwartz, 2001 cited from Imhof, 2004).

Emphatetic Design

To fully support the user experience, mood and feeling, “the design process needs to start with an understanding of the user situation” (Greenbaum & Kyng, M., 1991). “To be able to design for positive future experiences, the designer has to understand potential users as well as their physical and social contexts. This means widening the scope from task focused usability to taking into account contexts, actions, feelings, attitudes and expectations” (Mattelmäki and Battarbee, 2002).

Empathy is “the ability to understand and share the feelings of another” (Oxford, 2011). Empathic design is a User-centered design approach that pays attention to the user's feelings toward a product (McDonagh and Lebbon, 2000; Fulton-Suri, 2003; Crossley 2003 – original source not available – cited after Straub, 2009). Empathic design assesses the needs of a potential user by examining it from the user’s perspective (Rayport and Leonard-Barton 1997). Emphatic design is different from Emphatetic design. With Empathetic Design, the designer should actually spend a day living as the user (Sweeney, 2007). The Emphatetic design definition, unlike the Emphatic design definition, is new and not widespread in the field (Ladwehr, 2007). However, the application is a common methodology for investigation. For example, “aging simulation activities often help younger people understand the physical limitations that frustrate elderly people” (Reichert, 2011), but at the same time it gives a designer the opportunity to understand the user’s needs, based on the Emphatetic design principle.

2.4.3 Holistic Methodology

In order to support human space exploration, HF design is proposed here with a holistic approach (όλος, holos, a Greek word meaning all, whole, entire, total). It focuses on objective and numerical parameters, but also on subjective sensations and reactions related to descriptive parameters, combining scientific and humanistic disciplines with a multidisciplinary methodology (Schlacht et al., 2010). Holistic HF design is meant to support space missions as a complete experience, by integrating different multidisciplinary scientific and humanistic perspectives into the entire mission lifecycle, such as aesthetics, emotions, instinct, creativity, and cultural development, which are all considered to be relevant aspects of space missions (Schlacht et al., 2010).

Indeed, it is not sufficient to support each single element of the space system; invisible and subtle connections may be missed. The holistic methodology is intended to support the entire complex system characterized by the interactions between the parts. As Aristotle (384 BC-322 BC) already explained back in 300 B.C.: The whole is more than the sum of its parts (Rötting, 2011).

The following sections about concurrent design, human-machine-environment interaction, and multidisciplinary methodology have been selected as methodologies that are related to the proposed holistic methodology.

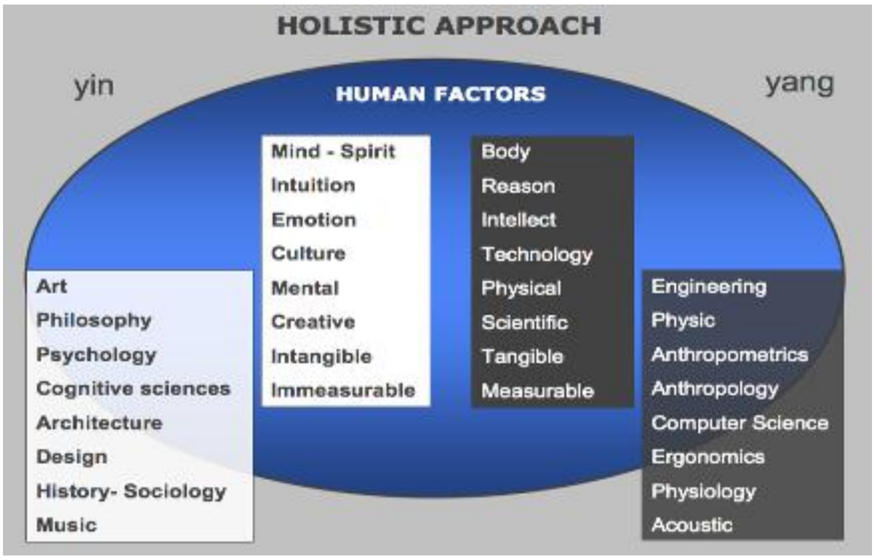


Figure 2.30: Multidisciplinary characteristic of the holistic methodology (Schlacht presentation for the SSDW, 2009)

Concurrent Design

Concurrent design is a methodology that is already used in the space environment, as explained in *subchapter 2.4.1* part *Robotic Mission Concurrent Design* and *Human Mission Concurrent Design*.

Generically, in all fields, concurrent engineering refers to a project methodology that considers concurrently or simultaneously "all the life-cycle phases of a product (i.e., development, production, distribution, usage, and disposal/recycling) …from the conceptual stage through the detailed design phase" (Kusiak, 1993 p. ix). As explained by Prof. Andrew Kusiak in one of the main publications on the topic, concurrent engineering "address the entire life cycle of the products and include not only its primary functionality but also producibility, assemblability, testability, serviceability, and even recyclability" (Kusiak, 1993 p. ix).

The concept of concurrent engineering was initially proposed as a means for optimizing product development time. Since then, many interpretations of the concept have emerged in the literature (Winner, 1998; CALS, 1991). Today, concurrent design is applied in many facilities in Europe, either as concurrent design facility (CDF) or concurrent engineering facility (CED), mostly in the area of space research. The Team X facility from NASA at JPL (NASA) installed in 1994 was the first ever used, followed by ESA-CDF (Dominik Quantius from DLR personal communication 2011; Romberg et al., 2008).

In long duration missions, this concept is fundamental because the space station must be as autonomous as possible and products have to be designed in direct relation to the environmental closed loop. Indeed, Kusiak explains that this technique is really effective as it allows for the valuation of each factor. For example, "when focusing on the environmental issues, the criteria elements must ensure that the product can be produced, distributed, used, and disposed/recycled without harm to the environment in any of these phases. Therefore alternative technical solutions will have to be assessed in each of the life-cycle phases and evaluated in these individually as well as in all phases seen as whole" (Kusiak, 1993 p. 5).

Table 2.9: Concurrent Design Facilities (courtesy information Dominik Quantius, DLR, 2011)

Kontinent	Land	Stadt	Name	Dachverband	U/I/A
Europa	Frankreich	Cannes	CDF	TAS-F	Industrie
		Strasbourg	CDF	ISU University	Universität
		Toulouse	PASO	CNES	Agency
		Toulouse	SDO	EADS Astrium	Industrie
	Deutschland	Bremen	CEF	DLR	Agency
		Friedrichshafen	SDO	EADS Astrium	Industrie
	Italien	Rom	ISDEC	TAS-I	Industrie
		Rom	CEF	ASI	Agency
		Rom	CDF	La Sapienza	Universität
		Turin	COSE Centre	TAS-I	Industrie
	Netherlands	Noordwijk	CDF	ESA	Agency
		Noordwijk	CDS	JAQAR	Industrie
	Portugal	Lisbon	CDF	IST	Universität
	Schweiz	Lausanne	CDF	EPFL	Universität
	UK	Glasgow	CDF	Strathclyde University	Universität
		Stevenage	SDO	EADS Astrium	Industrie
		Southhampton	CDF	Southampton University	Universität
		Harwell Institute	CDF	Oxford	Agency
Andere	USA		TEAM X	NASA/JPL	Agency
			IDC	NASA	Agency
		Baltimore	ACE	John Hopkins University	Universität

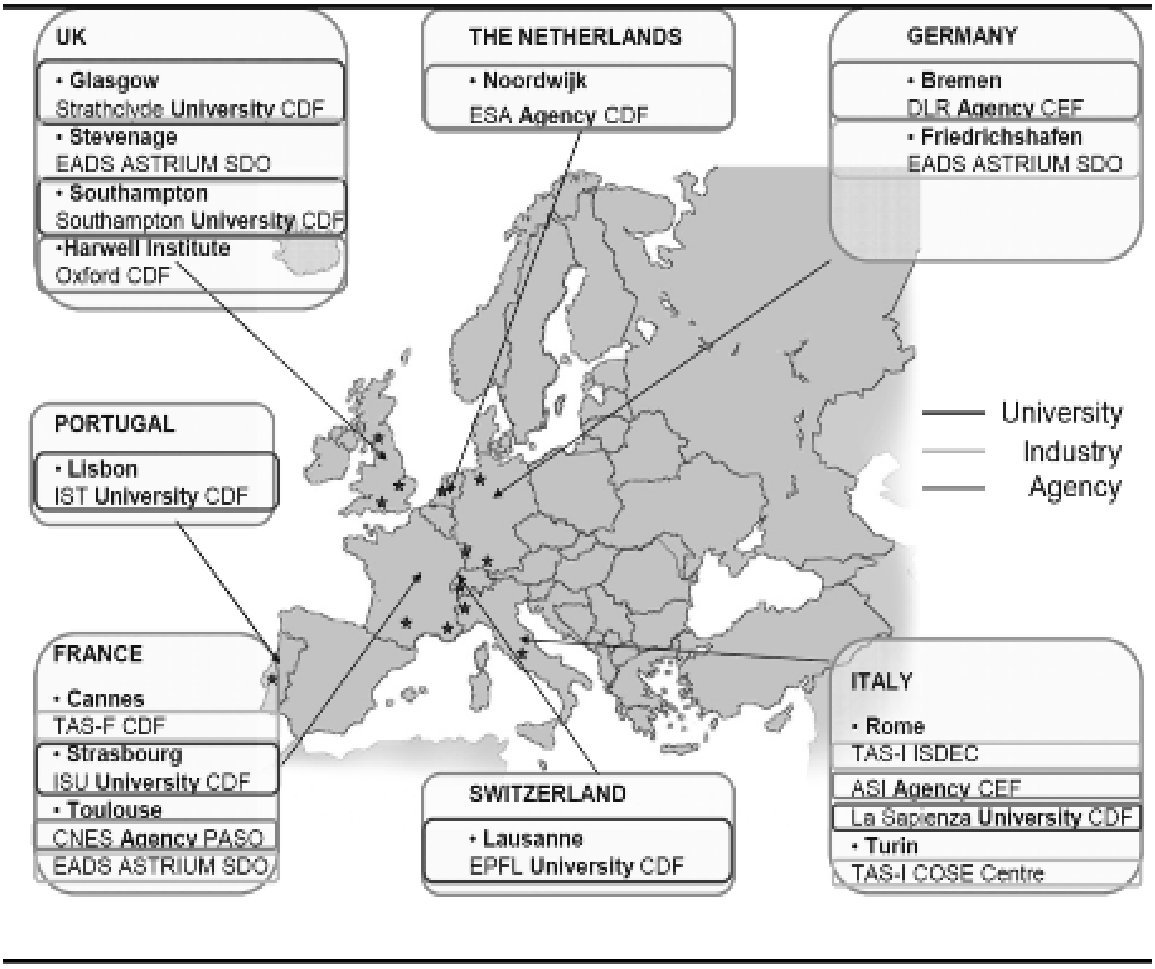


Figure 2.31: Concurrent design facilities in europe (ESA, 2011b p. 20)

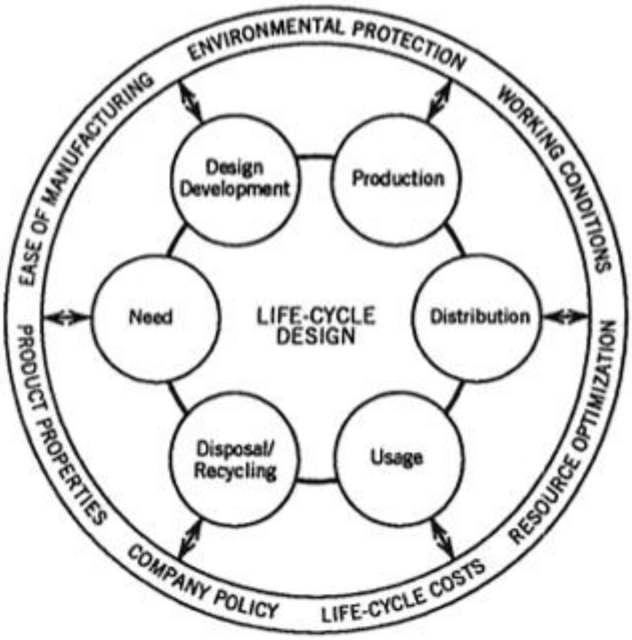


Figure 2.32: The lifecycle concept of product design (Kusiak, 1993 p. 4). (Image utilization courtesy of permission by e-mail from Andrew Kusiak, 21.02.2011)

Human-Machine-Environment System

Habitability is not a single variable, but an element influenced by the system of which it is a part; indeed, it is a result of "human-machine-environment-mission interactions" (Fraser, 1968 p. V). The consideration of all the system elements and their relations is called holistic design (Bandini, 2008).

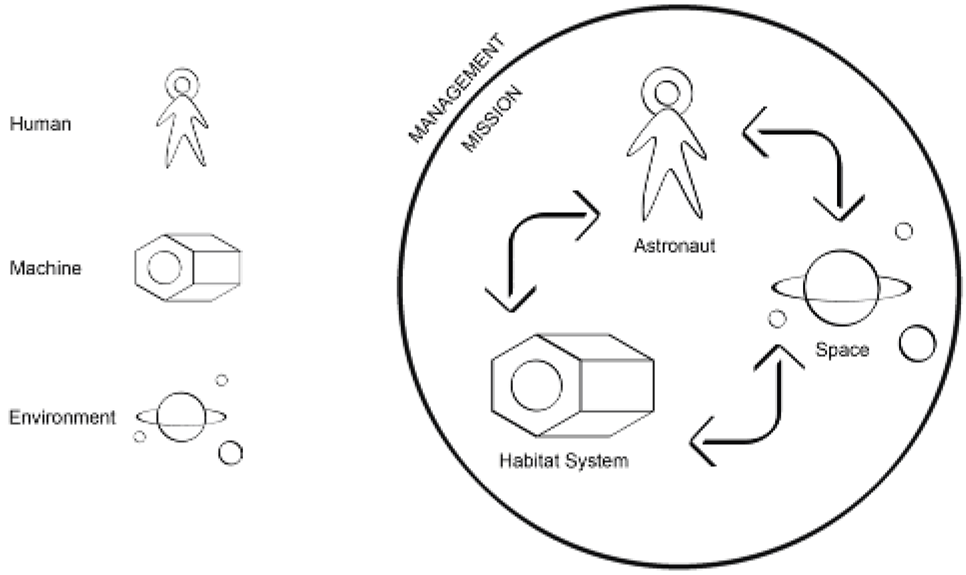


Figure 2.33: Human-machine-environment interactions in space missions

Quoting the ergonomist and designer Prof. Bandini Buti (Bandini, 2008; Schlacht et al., 2010), holistic design is the result of all aspects and relations of three fundamental components:

- Human (user)
- Machine (artificial component)

- Environment (natural component)

Humans have to be considered as the central element of interaction following the human-centered design approach, supporting physical and psychological as well as cultural needs. The environment is related to the interaction with the natural condition that affects the final product or service. Machines encompass the multitude of elements that control a technical process in order to produce a product or service, as well as the machine involved in the process of production of the multitude of elements. In this case, the machine is the habitat (Bandini, 2008; Rotting, 2011; Schlacht et al., 2010).

Considering the environment as the natural condition that surrounds the product or service, the environmental control system as an artificial system becomes part of the final product: the habitat machine.

The interaction of the HME and the technology available deeply influences the design of space habitats. To understand this principle, some concrete examples are given below (Aguzzi, 2005):

- Launchers: The technology available for launchers dictates the available volume into which the habitat structure must fit.
- Power system: Different power generation systems can influence the design of the habitat: photovoltaic arrays, fuel cells, and nuclear reactors.
- Thermal control system: passive or active thermal control for internal and external environments (cold plates, radiators, pumps).
- Radiation protection: Different materials such as plastic, metal, or regolith are under evaluation.
- Life support system: The choice between closed or open loop; physico-chemical or bio-regenerative systems can influence the design of the habitat, as they require different volumes, mass, and infrastructures.

It can thus be concluded that as underlined by Aguzzi (2005), the final "space habitat system" will be influenced by all the technologies involved in achieving it. Moreover, to design a human habitat also means comparing the design solution with the current and near-term technologies available (Eckart, 1999).

Multidisciplinary Methodology

Multidisciplinary research applied to human-machine interaction started "in the early 1900s, as the Industrial Revolution got into motion, there was some concern with the design of tools, but engineers often tried to solve these problems without the help of psychologists. During World War II, as the design of machines became increasingly complex and selection and training of operators reached their limits, the military decided to ask those who knew about human behavior—psychologists—about the capabilities and limitations of the human operator. Although there was little research at the time on these issues in psychology, a group of psychologists found these problems interesting and founded an area called engineering psychology. Today, many psychologists are doing research into human-machine issues and applying their findings to design. The design of computerized systems accounts for the sharp recent growth in the number of psychologists who specialize in consumer industries. The interdisciplinary term for those who work in human-machine-environment design is human factors or, sometimes, ergonomics.

Although psychologists working in ergonomics are called engineering psychologists, those from industrial engineering are often called human factors engineers. There is also some overlap of ergonomics with physiology, anthropology, sociology, archaeology, and even geography" (Martin, 2006, p. 127).

Unlike psychologists and engineers, industrial designers consider HF and ergonomics as a part of their fields. Indeed, HF and ergonomics feature multidisciplinarity.

While in the past, space was a pioneering field for architects and industrial designers, in the last decade they have been involved in projects related to habitability conditions on board the ISS. Today, in the context of the ISS, industrial designers, architects, and psychologists are working on improving the working and living conditions to counter problems due to the lack of gravity and isolation (Ferraris, 2005; Vogler, 2002).

In 2008, Extreme-Design formed an international group applying multidisciplinary fields to the space environment with the aim of achieving a positive impact on the quality of life for people living in extreme environments (Extreme-Design, 2008).

The Extreme-Design team is an evolving structure open to experts operating in advanced contemporary fields or completely new fields related to outer space. Each member of the group is specialized in the new branches and focuses on extreme environment living contexts. Each branch is supported by internal and external specialists. The disciplines are defined below (from Schlacht & Masali, 2008):

- Extreme Design: branch of design that intends to increase quality of life in extreme habitats at the limits of human survival, to find project solutions, and to support cultural expression.
- Space Ergonomics: the application of "human factors" concerning the human-machine interface using scientific knowledge in the design of products, systems, and environments meant for human use in outer space.
- Space Anthropology: study of exaptations (Latin: ex = from and aptus = adapt. [2]), potentialities, or archetypes of the functions now needed within the new environment, pre-existing in the human species, that allow physical and cultural adaptability to outer space as an aspect of ongoing human evolution and cultural development.
- Space Design: discipline that aims to contribute to the process of improving living and working conditions in outer space, considering – at the design stage – all the human factors that are essential in creating a personnel-friendly environment that must be comfortable, pleasant, and efficient.
- Space Art: "Contemporary art which relies on space activity for its implementation" (Malina, 2002). In the space habitat, art is able to interact with the feelings and the mood of the inhabitants, opening their minds and increasing their well-being.
- Space Visual Design: design related to visual perception applied to outer space habitats. It aims to increase the user's well-being and user experience utilizing instinctive reactions and intuitive communication. It is closely related to human factors and cultural expressions.
- Space Psychology: as a specific topic of Applied Psychology, it "addresses the impact of living and working conditions in space and during space flight on human behavior,

> performance, mood, and behavioral health. It includes basic issues of human adaptation to the extreme conditions in space as well as operational issues of selection, training, and support of astronauts" (Manzey, June 2007, courtesy personal communication).

Space may reflect the needs and the society of Earth, which is why all the different disciplines may have an application in this new and young field.

2.5 CONCLUSION

Having analyzed the concept, factors, and design process related to habitability, both as applied to space systems and in human factors research, some obvious challenges emerged, which will be critically analyzed in the following chapter.

Habitability is defined by the NASA Operational Habitability Team as "the usability of the environment" (Blume, 2000), and internationally by different space agencies as "the quality of life in an environment" (AA.VV, 1999). In space missions, human factors design aims to support habitability and overall system performance. In long duration missions, many human factors problems affect the habitability level. On the International Space Station, for example, these include issues such as small habitable volume without recreational space, crowdedness due to all kinds of equipment, lack of storage resulting in difficulties finding stuff, an absence of standardization regarding interfaces, lack of privacy, absence of variability, and many other factors. In the difficult conditions of space missions, the habitat needs to fully support human performance and well-being by reducing or avoiding potential psycho-physiological problems with sound and dedicated design.

"Considerate la vostra semenza:
fatti non foste a viver come bruti,
ma per seguir virtute e canoscenza"

"Consider your origin;
you were not born to live like brutes,
but to follow virtue and knowledge".

(Dante Alighieri, 1555, Canto XXVI, lines 118-120)

3. PROBLEM: CRITICAL ANALYSIS OF HABITABILITY CHALLENGES

Based on the state of the art of the current habitability scenario presented in the previous chapter, this chapter critically analyzes the scenario challenges, both on the level of current habitability conditions and looking at the roots from the perspective of the project process. The analysis of the problems and their causes is a mandatory step on which the subsequent chapter on problem solutions is based.

In adverse environmental conditions, psycho-physiological effects cause significant challenges to space habitability. With machine-centered procedures derived from the military approach, the space habitat does not allocate HF to mission design. "Therefore, although great efforts have been made in order to offers astronauts a comfortable stay in space, the first requirement of manned spacecraft's have always inevitably been oriented towards the crew´s survival so that, at the moment life on board is possible but very tough" (Ferraris, 2004, p. 21). The current low habitability has repercussions on human performance and reliability, increasing the possibility of human error and, as a consequence, jeopardizing mission success. Moreover, the habitat should also provide support for the cultural application of space, giving the astronauts the opportunity to increase the knowledge of humankind both from the scientific and the artistic perspective.

Following the analysis of the different models in the state-of-the-art section, four factors were selected as key elements for the debriefing analysis, namely, the operational, physiological, environmental, psychological, and psycho-social factors. In light of the fact that physiological and environmental factors are both physical factors, these are reported under physical factors.

To investigate the system problems, a concise step-by-step research approach has been applied with two main phases:

1. Problem analysis:
   1.1 Definition of the problem fields
   1.2 Hypothesis of the current problems
   1.3 Investigation of the user perspective
   1.4 Verification of the hypothesis
2. Problem root
   2.1 Understanding of the problem in the system
   2.2 Research of the problem causes
   2.3 Focus on the key elements in order to offer a solution

In this section, the result of the first phase is reported.

3.1 HABITABILITY CHALLENGES

In order to identify the challenges, this subchapter analyzes habitability problems in current and future scenarios, based on user analysis, post-mission debriefings of astronauts, and pertinent publications from this field.

What are the problems related to habitability? This is the first question that needs to be approached in the problem analysis.

With current technology, a mission to Mars would take around three years. This is what is known as a long duration mission. The problems related to long duration missions are manifold: galactic cosmic radiation, debris, meteorite impacts, microgravity effects, cargo capacity, isolation… The research takes into account those environmental constraints in order to focus on designing a habitat capable of supporting the active acquisition of knowledge.

In long duration missions, habitability is an extremely relevant matter. One problem is that in many publications, habitability is restricted mainly to life support systems and habitat characteristics. Morphew, for example, addresses habitability only in terms of hygiene, vibration, noise, illumination, privacy, and isolation from support systems; however, in his stressors table, close to all of the habitability parameters are mentioned, but under separate fields (cf. *Table 3.1*). As explained in *section 2.1.2,* physical, psychological, and social factors are part of the functions of habitability. At the same time, habitability is part of HF and focuses not only on the habitat but also on system usability, as well as on well-being, motivation, satisfaction, psychological stability, performance, and clear and active mental activity. All these factors are fundamental for the quality of life.

Table 3.1: Stressors of Long Duration Spaceflight (Morphew, 2001 p. 75)

Physiological/Physical	Psychological	Psychosocial	Human Factors	Habitability
Radiation	Isolation & confinement	High team coordination demands	High & low levels of workload	Limited hygiene
Absence of natural time parameters	Limited possibility for abort/rescue	Interpersonal tension between crew/ground	Limited exchange of info/comms with external environment	Chronic exposure to vibration and noise
Altered circadian rhythms	High-risk conditions & potential for loss of life	Family life disruption	Limited equipment, facilities and supplies	Limited sleep facilities
Decrease in exposure to sunlight	System & mission complexity	Enforced interpersonal contact	Mission danger & risk associated with: equipment failure, malfunction, or damage	Lighting & illumination
Adaptation to micro-gravity	Hostile external environment	Crew factors (i.e., gender, size, personality, etc.)	Adaptation to the artificially engineered environment	Lack of privacy
Sensory/perceptual deprivation of varied natural sources	Alterations in sensory stimuli	Mulitcultural issues	Food restrictions/ limitations	Isolation from support systems
Sleep disturbance	Disruptions in sleep (readjustment with crew changeovers)	"Host-Guest" phenomenon	Technology-interface challenges	
Space Adaptation Sickness (SAS)	Limited habitability (e.g., limited hygiene)	Social conflict	Use of equipment in microgravity conditions	

3.1.1 User Analysis

To create the basis for habitability design according to the human-centered design philosophy, first of all we need to discover what the astronauts' needs are.

To investigate the problem of quality of life in the space system, the user-centered approach suggests focusing on the user. The user analysis needs to be performed "before any other analysis is conducted", "for each stage of the system lifecycle" (Wickens et al., 2004 p. 37). The purpose of this analysis is to answer the following questions (Wickens et al., 2004):

1. Who are the system's/product's users?
   (including people who dispense, maintain, repair, monitor, and dispose of the system).
2. What task must be performed?
3. Under which environmental conditions?
4. What is the user's preference or requirement for the system/product?

To answer these questions, the astronaut is here defined as the user, who directly uses and dispenses, maintains, repairs, monitors, and disposes of the system, with the purpose of living and working under outer space environmental conditions. To answer the fourth question, the user needs to be directly involved.

Target Analysis

Astronauts are particularly rare users if we compare them to the average of the population. The overall number of former astronauts that have been in space is 551 (until September 2011) – approximately 2/4 Americans, 1/4 Russians, and 1/4 astronauts from other countries (Harwood & Navias, 2010; NASA 2011f, 2011g).

However, the number of astronauts who are active today is less than one third of this number and includes:

- 60 astronauts from NASA (Dismukes, 2011)
- 44 cosmonauts from Roskosmos (RKA) (Dismukes, 2011b)
- 15 (maybe 14) taikonauts from CNSA (China National Space Administration) (Space-facts 2011; Quine, 2010)
- 14 astronauts from ESA (ESA 2011)
- 8 astronauts from CSA (CSA, 2009)
- 6 astronauts from JAXA (JAXA, 2010)
- 2 commercial astronauts.

Methodology

Performing a user analysis is something quite complex, considering that you will rarely meet all astronauts together and that they are quite busy people. Sponsoring a user analysis is too expensive for PhD research. For these reasons, the author was able to collect user data only thanks to the kind voluntary participation of various astronauts and thanks to the great interest that they exhibited towards the author's research. Astronauts were interviewed during conferences, meetings, exhibitions, or in the course of private appointments in different parts of Europe and the USA.

Figure 3.1: DLR Astronaut Day, Joint Space Pavilion ESA, ILA 11 June 2010, Berlin. From left to right: Ernst Messerschmid, Ulf Merbold, Léopold Eyharts, Gerhard Thiele, Frank De Winne and Hans Schlegel

The astronauts interviewed were selected from the CSA, ESA, JAXA, and NASA agencies. Between 2005 and 2010, the author was able to interact with 20 astronauts, collecting data from a total of 14 astronauts. It is important to underline that in light of the 88 astronauts currently active in CSA, ESA, JAXA and NASA, the research performed on 14 astronauts may be considered as a representative number. The astronauts were of both genders.

The goal defined at the start of the research was to improve habitability, well-being, and performance of the astronauts in long duration missions (Schlacht et. al., 2005). One problem that occurred during the investigation was the definition of habitability: Many astronauts associate with this term only physical qualities of the habitat, like the air, and if is breathable, they report that there is high habitability. For example, after the astronaut Thagard reported on Mir habitability problems related to standardization, cooking hazards, food preferences impacting health, noise, and communications, he said: "I would rate habitability on the Mir Station as high. The air is clean" (1995).

To avoid misunderstandings, the aim and the methodology of the habitability research were presented. This aim was to discover the needs and potentials of the environment and to improve the habitability, well-being, and productivity of the astronauts for long duration missions. The methodology included evaluating the perception, preferences, and sensitivity of the astronauts, following the logic of 'human-centered design' (Schlacht et. al., 2005).

A specific focus was placed on the visual environment, which was considered to be of particular relevance as previously explained in *section 2.2.4*. The complete results are reported in *Appendix D*. The most important findings are presented in *Table 0.1,* anonymized with alphabetical letters except for public interviews.

Results

The results are divided into two types, those voluntarily discussed by the astronauts and those obtained via focused questions in the context of questionnaires and reported in *0*.

From the table it is possible to conclude that all the astronauts gave their opinion about the relevance of the topic and about the need to improve the habitability conditions.

- 14 out of 14 astronauts consider the topic of habitability as a relevant matter for mission success
- 13 out of 14 astronauts suggested that habitability factors need improvement. Only the astronaut “I” found habitability not to be relevant (X); however, he agreed that in long duration missions, habitability needs to be improved.

The main habitability problems, voluntarily discussed by 14 astronauts during the interviews, are:

- Low habitability, particularly in long duration missions (mentioned 5 times)
- Orientation problem due to visual chaos (4 times)
- Ineffective storage system (3 times)
- Unpleasant interior color (twice)
- Visual monotony (once)
- Physiological effects (coordination, visual focus, sensorial perception) (once)
- Psychological environmental effects (once)
- System maintenance (once)

The main habitability problems selected on the questionnaire were:

- Variability (4 times)
- Privacy (4 times)
- Personalization (3 times)
- Input to avoid monotony of isolation (3 times)
- Open space (twice)
- Quiet (twice)
- Feeling of freshness (once).

Conclusion

Satisfying the astronauts' habitability needs may help to avoid stress, enhance well-being, and increase performance. After consulting 14 astronauts, it became clear that the ISS's habitability could be improved.

Spacecraft are expensive and constrained habitats. To optimize the working µg areas, all the surfaces are completely covered by instruments, which are oriented differently. This condition creates visual bewilderment and orientation difficulties. Taking also into account the fact that the vestibular system becomes silent after three days (Mallowe, 2001), the astronauts can detect head rotation and body acceleration, but have no up and down perception and generally experience orientation difficulties. Furthermore, in a µg environment, the up and down working position is arbitrary. Intuitive visual orientation may be critical in emergency situations. Indeed, considering the NASA Standard, "visual cues shall be provided to allow the crew member to quickly adjust to the orientation of the crew station" (NASA, 1995 STD 3000 p. 8.5.3.4.d).

Referring to the observations of astronaut "I", visual chaos in space habitats is mostly created by the high quantity of labels and electrical cables as well as by storage problems. An interior color scheme that intuitively guides the user's orientation is the best solution, but not practicable in the ISS, in all reality.

Considering that "In µg, orientation is defined primarily through visual cues which are under the control of the system designer" (NASA 1995 STD 3000 p. 8.4.2), the interior design - if applied from the beginning of mission design - can effectively deal with such problems.

It can be concluded that in µg, up and down orientation is achieved mainly by using the environmental configuration and a person's position as a reference. This becomes more difficult in an environment full of visual chaos related to storage problems. Also following the needs analysis, it emerges that the storage system is not working. This is the biggest mismatch of the habitat interface because it contributes to visual chaos, visual orientation problems, as well as difficulties in distinguishing instruments and in performing activities (Schlacht et al., 2008b).

In summary, the most relevant habitability problems are:

- Low habitability (discussed 5 times)
- Orientation problem due to visual chaos (discussed 4 times)
- Ineffective storage system (discussed 3 times)
- Variability (selected 4 times in questionnaire)
- Privacy (selected 4 times in questionnaire)

Habitability and visual interface are relevant factors in long duration missions. As an example, orientation can be improved consistently throughout the system with interior color design and labeling, but also with a good storage system. Variability can be supported with a flexible interior décor, while privacy can be improved with interior layout design. It is interesting to note that these problems are not physical, because they neither affect environmental controls nor physiological health. On the other hand, they affect all the qualities of habitability needed in long duration missions: usability, livability, and flexibility. These aspects need improvement in the current ISS.

Table 3.2: Main Habitability Problems

	Operational	Physical	Psychological	Socio-Cultural
Usability	Storage System: Higher usability		Orientation: Labeling and interior color	
Livability	Visual Chaos: Interior design			Privacy: Interior design
Flexibility			Variability: Flexible interior	

3.1.2 Debriefing Analysis

After a mission, possible challenges and problems are recorded in debriefings and interviews performed with the astronauts. These results are then utilized to improve future missions, and are analyzed here to find potential challenges.

To investigate habitability problems, the architect Sandra Häuplik-Meusburger (2011) recently published a complete space activity analysis based on usability, livability, and flexibility, which the author (Häuplik-Meusburger, 2011 pp. 8-9) defines as follows:

- Usability: “The layout, configuration and design of extra-terrestrial habitats assure efficient, user friendly and trouble-free habitation over a specified or planned period of time”, also defined as the achievement of “effectiveness, efficiency and satisfaction” regarding the use of a product (ISO 9241-11, 1998), e.g., infrastructure, equipment, zoning, space organization, storage.
- Livability: “The habitat provides maximum living space even within a minimal limited and socially isolated volume for the individual and the crew.” This includes territoriality, privacy, sensory perception, interactions with the habitat, and relations with the environment.
- Flexibility: “The habitat allows adjustments according to the requirements of the users, to changing mission tasks as well as unforeseen social and mission related changes”. This includes environmental variability, flexible usage, and personalization.

To investigate habitability, the problems reported by the astronauts have been evaluated with respect to safety hazards and the usability, livability, and flexibility levels.

As examples of habitability problems in short duration missions such as Apollo, Mercury 7, Soyuz, Space Shuttle, and in long duration missions, episodes are reported that were described by astronauts on the Mir, based on 3-month flights; on the ISS, based on 6-month flights; in Mars 500, based on a 1-year mission; and in the Biosphere, based on a 2-year mission (Lucid, 1996; Mars 500, 2011). It is interesting to note that the difference in gravity and the duration of the mission have a high impact on the problems reported.

The problems are derived from an analysis of different publications (Behar, 2006; Häuplik-Meusburger, 2011; Lucid, 1996; Mars 500, 2011; Messerschmid, 2008; Musser Shiner, 2006; Thagard, 1995); details are reported in *Appendix E*.

The problems reported here are divided according to the following selected factors:

- Operational factors
- Physical factors
- Psychological factors
- Socio-cultural factors

The results of the analysis are given for each factor. This analysis shows how all the factors are important for preventing safety hazards. In particular, operational and physical factors are essential for the entire mission typology, whereas psychological factors become more relevant with increasing mission distance and duration, and socio-cultural problems are a key element for safety in long duration missions. In conclusion, a combined long range and long duration mission such as the Mars mission needs to prevent and consider all the different kinds of factors (as shown in *Figure 3.2*).

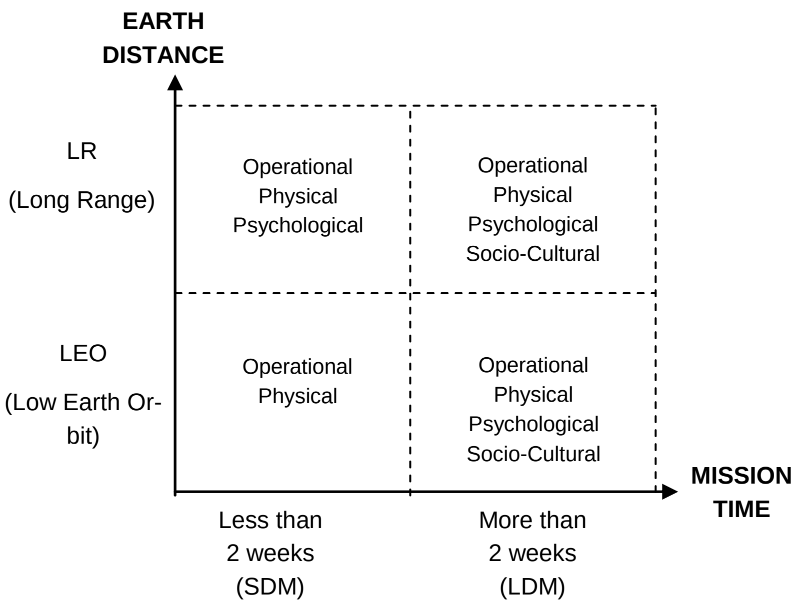


Figure 3.2: Possible human factors related to hazards in relation to mission duration and distance (Behar, 2006; Häuplik-Meusburger, 2011; Lucid, 1996; Mars 500, 2011; Messerschmid, 2008; Musser Shiner, 2006; Thagard, 1995)

Operational Problems

Operational problems are mainly related to the usability level. The topic is very relevant for mission safety, from LEO (Low Earth Orbit) missions to all other kinds of missions.

- Operational problem: low usability
- Need for storage: Mir, ISS

- Maintenance: Mir, ISS
- Standardization: Mir, ISS

The complete analysis is reported in *Appendix E, Table 0.8*.

Physical Problems

Physical problems are related to the livability and flexibility levels. This topic is very relevant in both short and long duration missions. The complete analysis is reported in *Appendix E*.

- Physical problem: low livability and flexibility
- Uncontrollability of environmental control: Mir, ISS
- Noise: Mir, ISS
- Low motivation for physiological exercise: Mir, ISS

The complete analysis is reported in *Appendix E, Table 0.9*.

Psychological Problems

Psychological problems are mainly related to the livability level. The topic is very relevant for safety in long duration missions, but also in long range missions, such as the simulations with Mars 500 or Biosphere 2.

- Psychological problem: low livability
- Communication and privacy: Mir
- Motivation: Mars 500
- Boredom: Mars 500, ISS

The complete analysis is reported in *Appendix E*, *Table 0.10.*

Socio-Cultural Problems

Socio-cultural problems are mainly related to the flexibility level. This topic is very relevant for safety in long duration missions, such as the mission to Mars, but also in LEO long duration missions.

- Socio-cultural problem: low flexibility
- Cultural preferences: Mir, Mars 500
- Social isolation: Mir, ISS, Mars 500

The complete analysis is reported in *Appendix E*, *Table 0.11*.

3.1.3 Habitability Challenges

The problems reported all have the same root, the lack of HF (Lucid, 1996). Each single problem is connected to another one, creating a kind of snowball effect. But what will happen in the future when long duration missions will also be long range missions? We do not know, but we can use the current data to speculate about what the snowball effect will entail.

Snowball Effect

The snowball effect refers to the concept that a small snowball rolling down from the top of a mountain may become a big avalanche at the bottom of the mountain. In a space mission, a small problem may become an avalanche of problems in long duration and long range missions (as illustrated in *Figure 3.3*). This concept may be used to hypothesize about the presence of a never experienced problem in the context of a long range/duration mission, which is currently unknown.

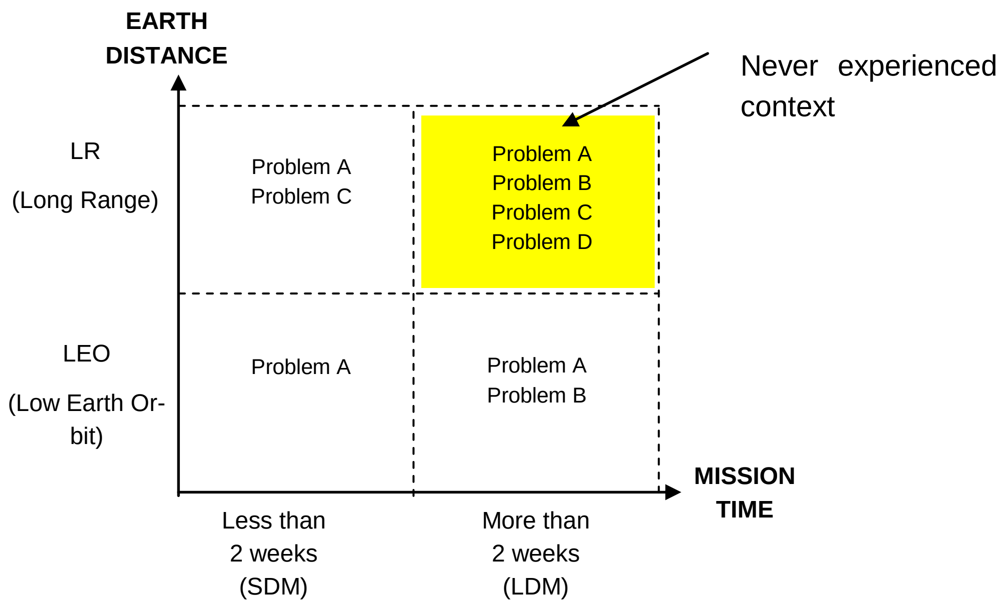


Figure 3.3: Examples of the snowball effect of habitability problems

Current Problems Applicable to Future Missions

To better understand this effect, some selected problems are analyzed in this section, not individually, but in relation to the context.

Examples of system problems and snowball effects:

Storage: Objects crowded → passage crowded → difficulties moving → risk of injuries

Location: Visual chaos → long time spent on object finding → object gets lost

Trash: Trash → place for disposal too small → trash accumulation → crowded

In the following, special attention is paid to Storage System, Orientation, Autonomy, and Isolation and Monotony.

- Storage System

There are many problems associated with habitability in an isolated and completely artificial habitat. One of these is the difficulty of storing all the equipment, and another is to find where you stored it. It is evident that having many types of equipment crammed into a small and crowded place leads to visual confusion and reduces the amount of otherwise usable habitable space as well as the room for free movement. "Spacecraft interiors are complex, with all kinds of hiding places" (Jones, 2010, p. 1). Another problem related to the storage system is the accumulation of discarded items; the trash is mostly collected in a small spacecraft (inside Progress spacecraft during the Mir missions and inside the Soyuz spacecraft during the ISS missions). When these are full, they are launched from the space station towards direction and burn in the atmosphere. However, the Progress and Soyuz spacecraft are not sufficient to collect all the trash, causing accumulation in the storage place of the space station.

Table 3.3: Concrete examples of storage problems reported by astronauts

PLACE	PROBLEM	REFERENCE
ISS	Visual chaos	
	(Anonymous, ISS mission 1991)	(Astronaut's personal courtesy communication, ILA, Berlin 2008, Mission 1991)
ISS SS SL	Small object in the filters	
	(Tom Jones, 4 shuttle missions)	(Jones, 2010, p. 1)
MIR	Finding small objects was better before ISS	
	(Thagard, Mir mission 1995).	(Thagard, 1995)
ISS	Incongruence on lost-and-found system	
	(Tom Jones, 4 shuttle missions)	(Jones, 2010, p. 2)
MIR	Object finding and bad visibility with impact on safety and performance	
	(Lucid, Mir mission 1996)	(Lucid, 1996)
MIR	Unorganized storage, no detailed location code	
	(Thagard, Mir mission 1995)	(Thagard, 1995)
MIR	Too small trash system led to accumulation of trash materials onboard	
	(Lucid, Mir mission 1996)	(Lucid, 1996).
MIR	Trash accumulation:	
	(Thagard, Mir mission 1995).	(Thagard, 1995)
STS (Space Transportation System): Space Shuttle; SL: Space Lab;		

It is interesting to note that storage was basically a major problem that occurred later in the ISS, particularly with regard to finding small items, whereas on the Mir, there had been a facility to store small items: "Were there enough small spaces for any small items that you had? Oh yeah. There was this little sort of cloth thing which had the added capacity of being basically like pile Velcro®, but it had little pockets in it, and I would put deodorant, for instance, would wedge in the pocket, the shaver would wedge in one of the pockets, the toothbrush and toothpaste would, the comb would, so I had this nice little arrangement. It was already there when I got there. These things have been in use for a while, and people have gotten them to the point where they are very convenient for personal use" (Thagard, 1995).

- Orientation and Locating of Objects

The storage system and the crowdedness are also related to another problem: the difficulties of orientation. Orientation problems are found both regarding the position of an object in a room, which is really difficult with visual crowding, and regarding the position of oneself in the room, which is also extremely difficult in surroundings where one has no congruent up and down orientation. As the astronaut Prof. Ernst W. Messerschmid, (personal courtesy communication, Stuttgart 2009) reported: “When you look through the windows at the Earth, you don't recognize the landscape until you turn your body with the head towards the Earth’s north. After a few days you can read the beautiful landscape also upside down. It will, maybe, be applicable in reading labels.” “The orientation is really important, and is made through the habitat design, for example in SpaceLab (30.10.-06.11.1985, Spacelab Mission D1) it was really efficient, because you have in the ceiling illumination and different corner configurations in respect to the floor”. The relevance of orientation and object finding is also underlined by Chiaki Mukai, (courtesy personal communication, Strasburg 2006): “Visual elements like colors are really important for the orientation in space. For example I had a personal color through which all the things referring to me were labeled”.

Hypothetical New Problems in Future Missions

The next space exploration mission scenarios will be those related to long duration Moon missions, Mars missions, and Near Earth Objects (NEOs) missions, as shown in *Figure 3.4*, which also considers the next space tourism missions. Even though this research focuses on space exploration and not on space tourism, the latter will also be part of future missions. The first space tourism flight was in 2004 with Space Ship One. The flight was a sub-orbital flight and did not reach Low Earth Orbit; for this reason, it is not mentioned in the following figure. However, space tourism is one of the main areas of growth for future missions. Taking into account the new user typology and new goals related to space tourism, other dimensions, such as user experience, may become the focal points.

Coming back to the Next Space Exploration Scenario, as in the context of the Moon LDM, Mars or NEOs mission scenarios (*Figure 3.4*), the problems will not only include the ones experienced until now, but new problems will also arise, such as user autonomy, isolation, and monotony. These problems will be analyzed in detail in the next paragraph. Experiments are currently underway at simulation facilities to understand which kinds of problems will emerge. However, as Kanas and Manzey mention in their publication, the only completely effective test for space is space (Kanas and Manzey, 2008).

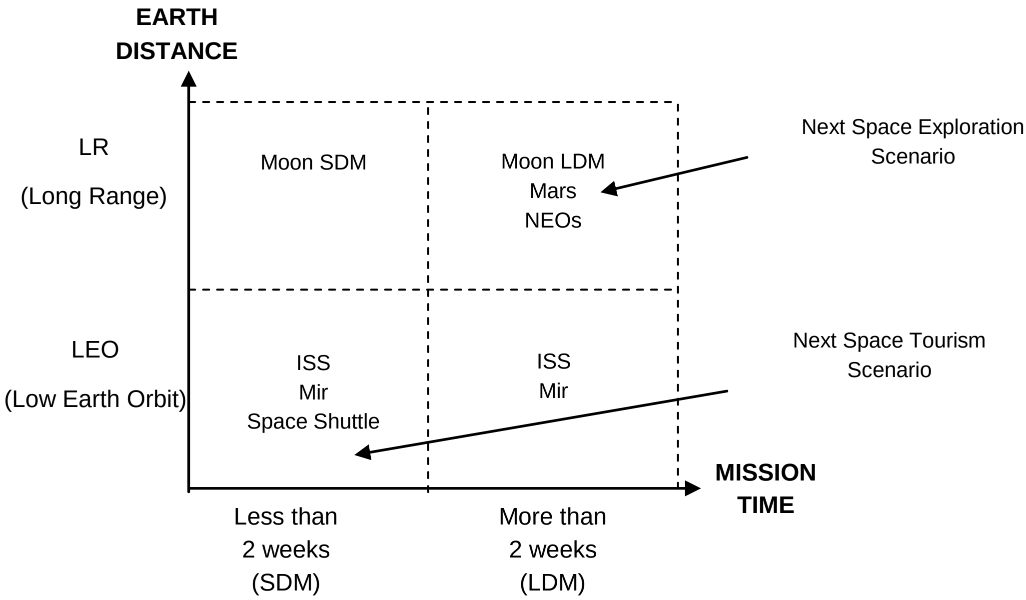


Figure 3.4: Past and future mission scenarios

- User Autonomy

One relevant problem in long range missions is system automation and standardization, which are needed to control the habitat. In particular in long duration missions, where the crew needs to have more autonomy from ground support, human automation and automated decisions will become a crucial issue (Korsmeyer, 2009).“High autonomy” means very long periods of time (one week in this case) when the crew draws up their daily schedule by themselves and also makes decisions regarding the realization of experimental programs. High autonomy is likely to occur during interplanetary flights; it might be caused, for example, by physical factors (for example, solar flares can induce rather long-term full interruption of crew-Earth communications). Undoubtedly, this is a very serious stress factor and its investigation in the context of the “Mars 500” project is ongoing and really significant for science. It was shown in the studies of Grigoriev et al. (2004) that high autonomy could be a factor that positively influences operative activities, the mood of the crewmembers, as well as the volition to make decisions independently and to input some proposals. At the same time, communication issues between the crew and the mission control center are not well-understood. In particular, one can imagine that in the event of a longer interruption of communications, the crew will be able to experience a lack of control over the situation; then again, they might also breathe more freely because of this lack of control (Mars 500, 2011 section 25.04.2011). Onboard autonomy is a fundamental part of crew training, but is also important for research into new technologies. One example is the research on “software systems that enable the crew to resolve a crisis when lengthy communications delays —in the case of Mars, up to 22 minutes each way, depending on the positions of the planets—make it impossible to talk to the ground in real time” (Behar, 2006, p. 4). Indeed there is a strong delay that changes depending on the positions of the planets. This delay makes it impossible to talk to the ground in real time. “When there’s an onboard fault, it can’t just be a light that turns on. Today, when that light comes on, the guy sitting next to me tells the crew what page of what book to turn to. In the future, the software systems will have to do that for them” (Behar, 2006, p. 4). To support user autonomy, the training of creative solutions may be one of the possible solutions as commented above (cf. s*ection 2.2.1*, part *Creative Performance*; s*ection 2.3.1*, part *Astronaut Selection and Training*).

- Isolation and Monotony vs. Privacy and Variability

As reported by users who have experienced long duration missions in Low Earth Orbit, the absence of privacy and variability may be a problem. The social monotony of a small community and the environmental monotony of the small and artificial habitat are the causes of those problems. But what happens in the scenario of a mission that is both long range and long duration? Isolation and monotony may occur as new problems, particularly at the psychological and socio-cultural levels. Indeed, monotony is a real psychological stressor in long duration missions (Kanas, et al. 2003); if the crew is not in Earth orbit, they will not be able even to visually enjoy Earth's beauty from the windows, and boredom may lead to mental drowsiness and mental inactivity. Taking into account and designing user experience in long duration missions can help to avoid these problems. To maintain active and healthy levels of mental activity, a human needs to experience being stimulated just as in his natural environment. Let us consider a “surprise”: This can be an emotional experience that awakens mental activity. ‘Surprise’ is a typical characteristic of a variable environment (as in nature) and not of artificial environments, e.g., the unexpected changing of the weather. However, randomized “surprises” may be artificially planned and act as an effective defense against boredom. The surprise effect could be, for example, the opportunity to make a birthday gift for somebody. In fact, humans also need to be intellectually active, maintaining the development of learning and discovery processes with constructive and stimulating experiences. Also, cultural involvement of the astronaut may help to avoid boredom and will stimulate mental activity. In addition to this, engagement by the astronauts in the creative arts will support effective communication and help express new knowledge gained. For example, if an astronaut on the ISS were to use his or her free time to learn how to play a new musical instrument, this endeavor might release tension, attract public interest, and result in a new form of knowledge and cultural expression. Cultural and emotional experiences should then be supported in the habitability design in order to stimulate the astronauts as discussed above (cf. s*ection 2.2.4*, part *Countermeasure*).

Problems in Current and Future Missions

In conclusion, the problems in current and future missions are summarized in the following figure. The figure shows how the numbers of problems increase with the increase in mission duration and distance. In particular in the context of long range/duration missions, the hypothesis is the presence of a scenario that includes the problems of storage system, living conditions, privacy, autonomy, and Variability.

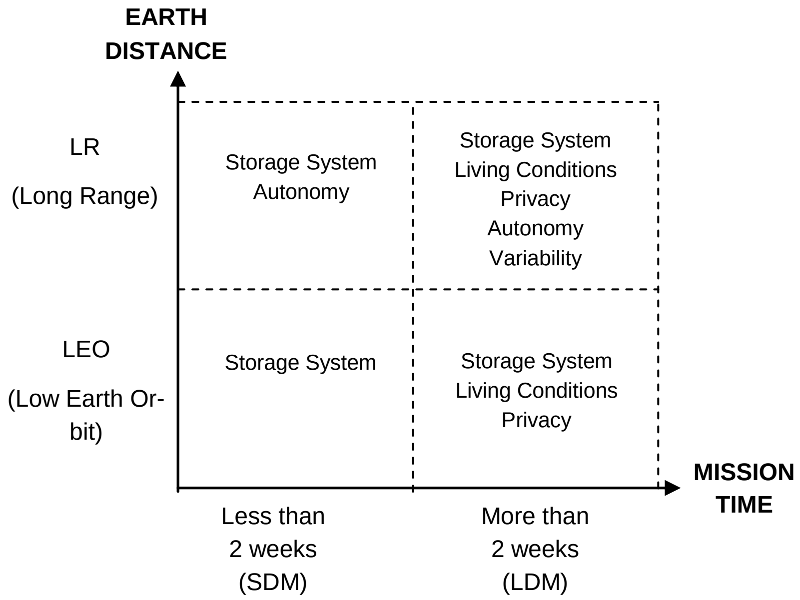


Figure 3.5: Examples of habitability problems

3.1.4 Gaps: Lack of Human Factors

All of these problems are related to HF and, as a consequence, caused by the lack of adequate support for HF. In conclusion, whereas the planning of a mission is a necessary countermeasure against Galactic Cosmic Radiation (GCR) and Solar Particle Events (SPE), the quality of life on board a space habitat is vital for the success of the mission. In other words, the lack of adequate HF support in mission design has a direct effect on the crew's quality of life, performance, and safety. Indeed, in the delicate safety equilibrium of such an extreme environment, low quality of life does not only impact performance, but may also risk the crew's lives.

This section reports on the lack of HF topics in the analysis of problems reported by the astronauts as well as on the repercussions of this lack of HF on the safety of the entire mission. The focus of this section is on the following issues:

- Current Problem Analysis Methodology
- Current Lack of Human Factors in the Methodology

Current Problem Analysis Methodology

The analysis of mission problems is conducted by means of an interview done with the user, which is called a debriefing. It is not focused on HF and habitability in particular, but on all aspects related to the mission. Usually astronaut debriefings are conducted after a mission. The debriefing is a kind of long interview where the astronaut is asked to talk about the working and living activities, illustrating what may have been a problem. There exists no defined structure for such debriefings, and the topics are selected on the basis of the previous debriefing results. If in one mission there was a problem with wet towels, in the next mission the question is asked whether there was any problem with wet towels. However, the analysis is here divided by the author according to habitability factors. Debriefings based on these factors may find results in a more complete and definite analysis, covering all topics of relevance.

The answers to the focus question on Psychological and Socio-Cultural Interactions posed in the user interviews revealed different results than the standard NASA debriefing.

Whereas the storage system and the visual chaos were reported as problems in both cases, problems such as low habitability, privacy, and variability emerged only in the user interviews performed by the author.

Table 3.4: Problem Analysis Strategy

EXAMPLES	NASA DEBRIEFING	AUTHOR USER INTERVIEW	NEEDED FOR FUTURE MISSION
Orientation/ Visual Chaos	Physical	Physical	Physical
Storage System/ Trash	Operational	Operational	Operational
Privacy		Socio-Cultural	Socio-Cultural
Variability		Psychological	Psychological
Habitability		all	all

Current Lack of Human Factors in the Methodology

A shortage of HF may risk the astronaut's life in an extreme case, but is also responsible for losing a lot of time and causes a decrease in performance and motivation. The problems reported are mutually interconnected. The majority of the problems are related to a lack of HF.

For example, the lack of HF prevents correct standardization and, as a consequence, poses a life hazard, as reported by Shannon Lucid: "All that human factor type thing is not present either in the Soyuz or Mir". "The Soyuz was built by engineers, and they never asked for any input from people that were actually going to use it". As a consequence on the Soyuz you have 2 switches with the same name and position with different functions, "the same place and the same letters, and it was so tiny that you could hardly find it. I just found that unbelievable. I think you could kill yourself one way or the other if you use the wrong one. In essence the lack of human factors could be characterized as a safety hazard" (Lucid, 1996).

Another example related to personal needs occurred during the NASA Mercury program when one astronaut decided to follow his personal feelings, going against the instructions and risking his life to take a picture of his experience. The opportunity to express affective needs should be supported with HF design.

A more current example is the recurring problem of the storage systems. The four-time space shuttle astronaut Tom Jones reports problems with finding objects: "It happens to everyone in space. No matter how well you Velcro your pockets, how carefully you duct-tape an item to the bulkhead, or how tightly you pull the drawstring on your ditty bag, some vital piece of gear will go missing. Will you see it again? It's a toss-up" (Jones, 2010, p. 1). "The dozen or so High-Efficiency Particulate-Absorbing (HEPA) filters built into the baseboards of the ISS modules sometimes trap drifting equipment as they screen circulating cabin air. But sometimes a prayer to St. Anthony, patron saint of lost articles, is more effective".

The consideration of human-machine-environment relations is a fundamental basis for human factors. Exhilaration, the need to personally remember the experience, social conflicts with ground control, the logistics of the storage system, distraction, and stress, are all HF-related problems that involve human-machine-environment relations and have not been considered so far, and which may risk the lives of the crew. Compared to the Mir, some HF have been taken into account in the ISS and Mars 500. However, the current problems are still really too large to guarantee the best performance conditions.

Considering that HF and habitability requirements are derived from mission duration and distance (cf. *section 2.3.1*, part *Mission Duration* and part *Mission Distance*), a fact that is also supported by the hypothesis of the increase in problems (previously explained as snowball effect in *section 3.1.3*, part *Snowball Effect*), it is clear that habitability factors and qualities will also be of increasing relevance in long distance and long range missions as shown in *Figure 3.6*.

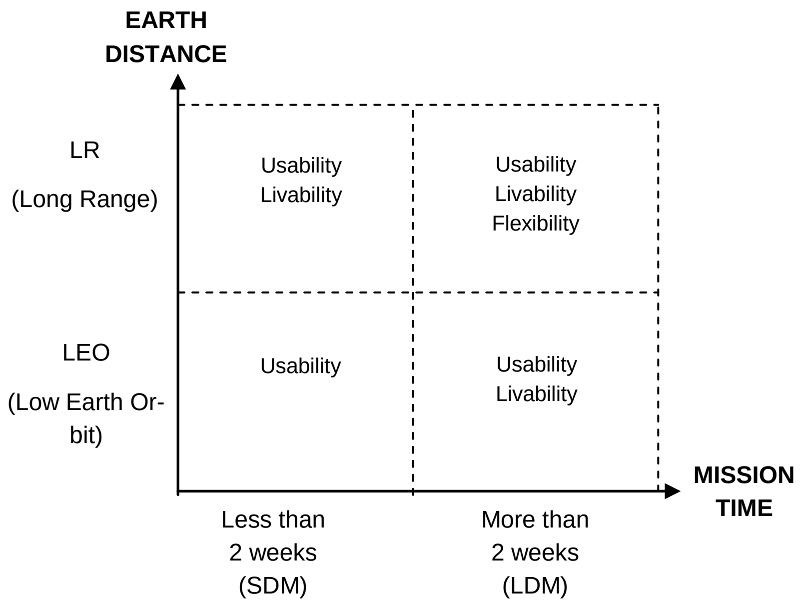


Figure 3.6: Increasing relevance of habitability qualities with increase in mission duration and distance

In conclusion, the final part of a NASA post-mission debriefing is given here, which refers to problems related to habitability and HF: "In essence the lack of human factors could be characterized as a safety hazard" (Lucid, 1996).

3.2 ROOT CAUSE OF THE CHALLENGES

This subchapter aims to identify the root causes of low habitability, which is a major step towards clarifying where a problem solution is needed. Ultimately, the root is identified as being in the mission design process. In particular, the focus is on a human-centered approach, a holistic methodology, and interdisciplinary principles as the main gaps. These principles are common strategies used by industrial designers and architects.

Considering the lack of human factors identified in the previous section (cf. *section 3.1.4*), it emerges that the root causes of these gaps are to be found in the design process. Indeed, the design process neither includes human factors design nor the basic principles applied to human factors and design disciplines, such as a human-centered approach, a holistic methodology, and interdisciplinary design principles. These principles have been explained in the state of the art (cf. *section 2.1.3, section 2.4.2, section 2.4.3*).

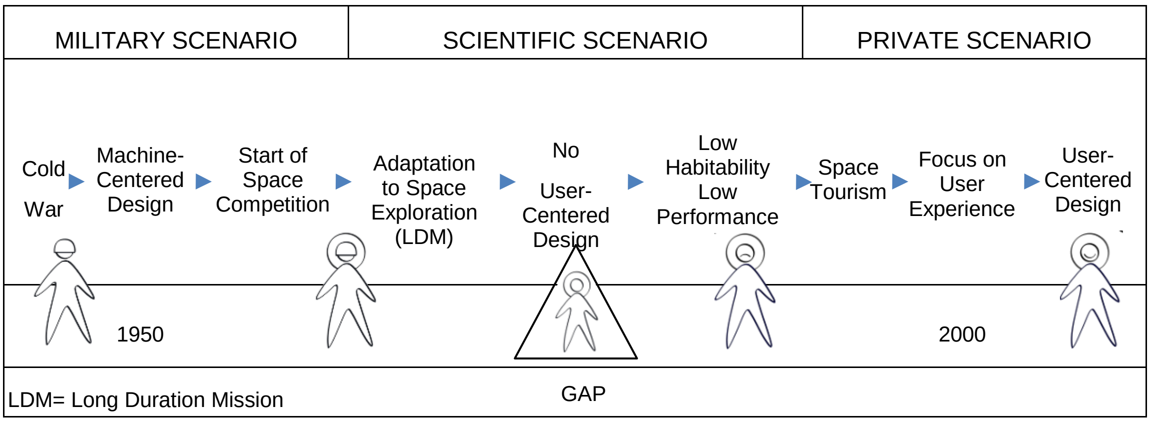
3.2.1 Need for a User-Centered Approach

In the previous section a user analysis and literature review were used to identify and demonstrate that low habitability in long duration missions is a problem because it has an impact on user performance and mission success (cf. *subchapter 3.1*). The need for an increase in habitability comes from the basic absence in system design of a structure capable of supporting human beings, as the structures and the experts used to design robotic space systems are the same as those that are used to design human missions. Moreover, the initial concept was designed for military purposes, utilizing men who were able and willing to sacrifice much more than their comfort or safety: their lives. This precedent is not sufficient to justify contemporary low habitability conditions, where not only military pilots, but also scientists and private citizens are experiencing space travel. Many of these conditions are problems arising from, and the consequence of, the prior conditions dictated by the Russian and American Cold War scenario, where working conditions were considered to be like those experienced in war.

Machine-Centered Design

To understand the importance of implementing a user-centered approach (cf. *section 2.4.2*) in the space mission design process, we need to look at the history of space exploration as summarized in the following table.

Table 3.5: Development of the habitability gap. As shown in the table, the missing user-centered design results in a decrease in performance in long duration missions. The increased focus on human-centered design is also due to the emerging private scenario resulting from space tourism.



The development of space activities started after World War II, when Russia and the United States rushed to recruit the best engineers and scientists working in Germany under the Hitler regime. After the defeat of Germany, many of the most brilliant German scientists and engineers went voluntarily or were taken by force to work for either the U.S. or the Soviet government

(Messerschmid & Bertrand, 1999; Hentschel, 1996 p.xciii). In Russia for example, during the 1946, “the movement of 7000 German specialists from various disciplines from Germany to the USSR” was accomplished in only two weeks (Sobolev & Khazanov, 2001). In the late 1950s, as a part of the Russian-American Cold War, they were all employed in the so-called “Space Race.” This period comprised the launch of the first satellite, Sputnik (October 4, 1957), the first human in space, Jury Gagarin (April 12, 1961), the first human on the Moon, Neil Armstrong (July 21, 1969), the first Russian-American coalition with the Apollo–Soyuz Test Project (ASTP, in 1975), and can be considered the birth phase of human spaceflight history (Messerschmid & Bertrand, 1999).

Consequently, the German engineers working during the Cold War created the basis for space exploration; their goal was the success of their country, not the fulfillment of user needs. This is why the first space ships emerged from a military logic. The goal of space habitat design was to accommodate astronauts who were trained to be sacrificed for the primacy of their country (Messerschmid & Bertrand, 1999). Space history continued to develop based on this approach. The USSR generated a series of Salyut Space Stations and the Mir Orbital Base, while the United States developed the Skylab Orbital Station and Europe developed the necessary know-how with the Spacelab program in the 1980s (Messerschmid & Bertrand, 1999).

Need for Better Living Conditions

As mentioned in the Skylab history book by NASA, “For the most part, astronauts accepted whatever discomforts were inherent in their spacecraft, unless they interfered with performance; what mattered was accomplishing the missions. Quite a lot of minor inconvenience could be tolerated by a human on his way to the moon” (Compton and Benson, 1983, p. 131). Space was the primary project of engineers and scientists, but with the utilization of orbital stations for long duration missions, astronauts started to express the need for better living conditions. Quality of life in space started to became a topic for projects. With mission duration lengthening, the involvement of industrial designers, architects, and psychologists in habitability design became more and more relevant. The industrial designer Raymond Loewy, who worked at NASA on the definition of crew quarters in the orbital base Skylab, is one of the first examples of designer involvement in a space mission (Caprara, 1998). However, the final design applied to the station (probably even different from the final configuration proposed by Loewy) did not support countermeasures against the psychological stress experienced by the astronauts living on the station, who decided to protest against the low habitability conditions and the bicolor, monotonous surrounding (Schlacht, 2007). While during the 1960s, the Russians were undertaking a major research effort related to better living conditions, studying the psychological and physical implications of the mission for humans, NASA was still maintaining a military approach, which had no place for multidisciplinary efforts. The relation between designers and engineers remained one between two separate worlds.

Need for Architect and Designer

At the 1965 hearings on the paper “Skylab Experiment M487, Habitability/Crew Quarters,” presented with NASA authorization at the 20th American Astronautical Society Meeting in 1974, the habitability issue was clearly discussed: “Habitability, livability – or whatever name is given to the suitability of the environment for daily living – is, as one NASA designer remarked, '*a nebulous term at best*, one not usually found in the engineer's vocabulary.' Besides factors within the engineer's usual responsibilities, such as the composition and temperature of the atmosphere and the levels of light and noise, habitability also encompasses the ease of keeping house, the convenience of attending to personal hygiene, and the provision for exercise and off-duty relaxation… Experience and intuition both suggested that habitability factors would become more important as missions grew longer" (Johnson, 1974, p. 141). In the paper, Johnson points out the importance of considering as habitability factors house-keeping, personal hygiene, exercise, and off-duty time; however, today we know that the habitability concept is much more complex. In a space station, habitability encompasses a great variety of factors. "Some of these factors were intangible, but they were no less important for that," writes Fred A. Payne in Work and Living Space Requirements for Manned Space Stations, which was presented at the International Conference on Environmental Systems (Payne, 1969, pp. 100-03). Intangible factors are rather complex to understand in the concrete, tangible, and quantitative world of engineering. Intangible factors are typically dealt with in humanities disciplines, and the image of the designer is usually something in between the two worlds. The designer as a multidisciplinary team coordinator can be the mediator between engineers and humanities experts. George Mueller, Skylab and Shuttle Engineer Designer and NASA Associate Administrator for Manned Spaceflight, has explained to congressional committees more than once the relevance of communication with designers: "NASA designers needed basic information on these problems of living in space," but only with a multidisciplinary team made up of both engineers and designers cooperating on a space station design project can the basic trust to support the flow of information exchange be optimal (Johnson, 1974, p. 141).

We had to wait until the end of the Cold War to see the first example of international and multidisciplinary collaboration materialized in the ISS International Space Station, the base orbiting around Earth with permanent human presence on board (Messerschmid & Bertrand, 1999). To work on the habitability conditions of the ISS, architects, designers, and psychologists became part of the design process. For example, industrial designers developed operational scenarios and equipment (body restraints, equipment restraints, clothing…) to improve working and living conditions, countering problems due to the lack of gravity and isolation (Ferraris, 2005; Vogler, 2002). However, most of the habitability projects proposed were cancelled due to budget limitations. Indeed, even today, the contribution of human factors, architect, and designer are still not allocated from the start of the mission design, but only at the end, when the available budget is almost gone.

Today crews on the ISS rotate missions every six months. The future exploration of the Moon and Mars will require even longer mission durations and much higher isolation from the home planet. For this reason the quality of habitability conditions is an essential issue for the success of human exploration missions. Hence, the involvement of architects and industrial designers from the early phases of mission development has been quite beneficial. They should be involved from the beginning, together with aerospace engineers, medical doctors, physiologists, psychologists, geologists, and space scientists, but also with all the experts who can provide significant contributions in defining the design of human missions (Aguzzi, 2005), such as humanities experts from the disciplines of history, fine arts, social science, and anthropology. Cultural experience, humanities, intangible factors, non-functional elements – these will support the human mission, like a break of space and time, like the place between the walls, like the pause in a conversation, or in one word that summarizes all these concepts, like the "ma" from Japanese culture. More than just space societies, agencies, or companies, the astronauts themselves need the humanities while performing their activities in order to fully reach the objective of space exploration, namely, the gain of further knowledge.

3.2.2 Need for a Holistic Methodology

It is not possible to build a system to support human work in space and not consider human life in space. Neither is it possible to support the physical and functional elements of a human mission without also supporting the psychological and socio-cultural aspects. This calls for the consideration of all factors, in other words, for a holistic methodology (cf. *section 2.4.3*).

Working is also Living

Today on the ISS, where the average astronaut mission duration is up to six months, this concept of associating work with low habitability conditions is still clearly present. In the design of habitability in space, activities and zones are divided into living and working, as commented on by Ferraris (2004): It is as if working was not an activity that belongs to living, too, "a semantic error that emerged early in the US Space Station program—the distinction between the "habitability module" and the "laboratory module." In short, the laboratory must also be habitable to provide a safe, supportive and productive working environment for the scientific mission and payload specialists who work in it" (Cohen, 2001 cited after Ferraris, 2004 p. 71).

As described in the section on the state of the art (cf. *section 2.1.1*), Messerschmid (2008) defines *habitability* as the living conditions that concern both work and domestic environments. "Equipment designed for working should be as comfortable as all the others designed for living"; however, we should not forgot that "certain qualities are necessarily specific and related to each specific use" as Ferraris explains (2004). "They might be as different as a chair for a dining table is to a chair for an office table in a terrestrial environment" (p. 71). To summarize, the design concept cannot be adapted from an robotic or military based one, or even adapted from Earth-based logic. Everything must be rethought and optimized from the start. Indeed, considering the many different conditions that exist in space in comparison to those on Earth, in space design it is of primary importance that the specific space environment logic is included right from the start of the project.

> And because we are working with the future, we have to reconsider our whole concept of mission structure, composition and the single crew members personality and qualifications. Space mission designs, both on the technological and the HF side are bound in a very conservative tradition, based on a high skill engineering and a personnel structure taken from the air force due to historical reasons as astronauts and cosmonauts were recruited from the corps of military test pilots. Principles for a good design, giving respects to the comfort of the crew, without compromising on mission agenda or safety have been done before. Human space flight until now has been a general success with focus on safety and technical compliance. Now the next step will be to develop both the human capability to handle the new missions and to create habitats for living more than surviving (Jorgensen, 2010 p. 257). And we do not need to reinvent these principles. It has been done before in our history at the time of early polar explorations. Leadership by men such as Shackleton has shown that the democratic leader can function even in dangerous situations and can combine his own leadership with the knowledge of the crew in a mutual responsibility. Another example is the principles in designing the

> schooner *Fram* in late 1800s by Fridjof Nansen and Roald Amundsen. With a strong focus on both the capability to perform the polar trips in heavy ice and weather, and to manage the 2-year-long overwintering in the ice, they gave maximal comfort to the crew aboard. *Fram* had room for social and cultural life, work and voluntary solitude aboard the ship. The crew consisted of persons with multiple, both formal and informal, skills and personalities. And in opposition to space crews, an artist was seen as important for the expedition for documentations of all the non-technical and emotional matters. Let this be an argument for including a diversity of professionals in designing the Moon base and investigating human factors in a broad frame. We need historians, sociologists, psychologists, artists, doctors, engineers, information technologist specialists and all the others who can give their learnt views to the mission design procedure. Seen from a space psychological and sociological perspective, future long term missions to the Moon will be very important as an understanding of the human factor problems related to longer interplanetary missions out in the solar system. (Jorgensen, 2010 p. 258).

Rebuilding space design from the start, we will then integrate a multidisciplinary approach capable of supporting humans in every sector.

In particular, a better approach to social and psychological barriers, for example “more qualitative and anthropologically founded and neuropsychological research will give further knowledge on human coping, interpersonal cooperation and new models for conflict resolution” (Jorgensen, 2010, p. 257).

3.2.3 Need for an Interdisciplinary Habitability Design

Form as a Function

In this thesis, human factors are considered a design discipline (cf. 2.1.1). Design is the project discipline that implements architectonic-artistic disciplines with technological and management ones. In other words, it is the conjunction between creativity and rationality (Dell´Acqua Bellavitis in: Bandini Buti, 2008), art and science, form and function, “chance and necessity”. It is aesthetic because unlike the principle of Louis Sullivan that “form follows function”, this dissertation is based on the principle that form has a function!

Because of the increase in mission duration, the new targets of human exploration, namely, Moon, Mars, and NEOs (Korsmeyer, 2009), require deeper investigation of issues related to habitability and HF in space. This requires engineering disciplines to be integrated into multidisciplinary teams, and raises issues surrounding the definition of an interdisciplinary process that can allow people from different disciplines to work together to achieve the same goal (Aguzzi, 2005).

Gap: Human Factors Design

Silvia D. Ferraris, researcher and Industrial Designer from Space Lab at *Politecnico di Milano* University, explains in her essay the relevance of an HF interdisciplinary approach to the increase in the level of habitability in the habitat design processes. In this process, she points out HF as part of the Industrial Design discipline based on interdisciplinary integration.

She explains: "In the aerospace field, scientific research is highly developed in the engineering disciplines and in all sciences relating to space environment – ranging from astronomy, physic, chemistry, biology, Earth science – to life sciences – medicine, psychology and sociology. In this context Industrial Design enters crosswise cooperating with all kinds of scientists by introducing innovative issues though its typical interdisciplinary approach. In this perspective this essay collaborates in researching design solutions for a better life for crewmembers in outer space, proposing the industrial design discipline as a promising integration for the future implementation of space projects" (Ferraris, 2004, p. 21). In the design process of this complex human-machine system, the collaboration of designers, architects, psychologists, ergonomists, and HF specialists was added only at the end of the project when the investment capabilities were exhausted. That was an application of the "form follows function" theory to apparently allow less investment.

This way of proceeding was nonsense. Ergonomics had already been used during World War II in the British Army to increase the efficiency of the human-machine system (Bandini Buti, 2008 p. 13) and is now an unambiguous heritage of any industrial structure.

And finally today, there is an important remark in the 2008 European Space Standard: "The customer's total cost of ownership will be dramatically reduced if HFE (HF Engineering) practices are well integrated into all project phases, from the very beginning" (ECSS, 2008, p. 8). What is now missing is how to define a way to realistically apply this principle in the space industry.

Gap: Interdisciplinary Design

In order to get a complete range of different perspectives and various kinds of expertise regarding mission design (cf. *section 2.1.3*), a interdisciplinary methodology should not only involve scientific and engineering disciplines, but also humanities. Experts from humanities disciplines, such as artists and cultural theorists, but also architects and designers have been involved in a new type of space research: the cultural utilization of space. As mentioned by Arts Catalyst, an art and science organization that has been cooperating with ESA, "Space exploration is a cultural activity and therefore cultural utilisation programmes just broaden the scope" (2006 p. 6). The need for cultural utilization is highly beneficial in different dimensions of space exploration as discussed above (cf. *section 2.3.1,* part *Astronaut Selection and Training* and *section 2.2.4*, part *Countermeasure*). In this section, we analyze the potentiality for the cultural utilization of space for:

- Humanities: to expand the gaining of knowledge in space
- Astronauts: to increase the astronauts' well-being and performance
- Awareness: to communicate with the entire population and attract public interest

Gap: Humanities Contribution

This part analyzes the potentialities of integrating humanities into space mission design and is based on the publication "Creative Process to Improve Astronaut Reliability" (Schlacht & Ono, 2009).

Humanities are disciplines that are strongly related with creativity; however, creativity is also applied by scientific disciplines. Creative expression is the result of the creative process used to solve a concrete problem, related to scientific disciplines or humanities. It can be artistic expression when finalized to self-expression through the use of art mediums such as music, poetry, and painting. Although many different opinions are reported, artistic expressions are not considered as art, but can be conducive to art. Artistic expression is the “objective expression of subjective impressions” (Maksim Gor’kij in Munari, 1966), and, consequently, part of the humanities.

To understand the potentiality of the application of humanities in space, different field specialists were interviewed and various field publications were analyzed to answer the question: How to get artistic expression into space missions?

- Life improvement

The space dwelling is an artificial high-tech environment, where monotony, boredom, and repression of instincts (like sexual or emotional ones) can “enhance stress with effect on the immune system” and as a consequence impair an astronaut’s health (Le Scienze Scientific American, 1998). The creative process improves the astronauts’ well-being and safety in three ways. First, it activates the lateral thinking mechanism, which is needed for astronauts to face unanticipated problems. Second, it supports artistic expression in order to guarantee psychological stability in isolation (e.g., it sublimates repressed impulses via creative expression.) Third, art such as music, painting, poetry, or even imagination are stimuli against the sensory deprivation in a synthetic habitat. In creative expression, emotions, feelings, instincts, and memories, come out – through the sublimation process (cf. *section 2.2.4,* part *Countermeasures*) – in the artistic product, as real and concrete proof of our existence and our experience (Rubano, 2005). Creative expression is a medium of communication between the artist and the world. The artistic communication of astronauts’ experience will attract public interest. Moreover, space is a place for us to apply our cultural heritage, adding a new dimension to human knowledge. Quoting Csikszentmihalyi (1996), “Creativity leaves an outcome that adds to the complexity of the future.” As Malina states in the definition of Space Art, "The creation of contemporary art is inextricably tied to the process of creating human civilization. Within this perspective, art making will occur as a part of Space exploration, and in fact art making must be encouraged in Space as one of the ways without which, in the long run, human use of Space will be incomplete and unsuccessful” (Malina, 1989 in Woods, 2001).

In conclusion, in the context of outer space, the capacity to implement the creative process is a psychological countermeasure. It can effectively support a mission’s success as a complete human experience. Buzzoni (2007) says, “Let me express a wish: may a new place of cultural synergy come into being…”

- Cultural application of space

Replying to the question “What brings artistic expression into the space mission?”, Dr. Bernard Foing, scientist of ESA and ILEWG and poly-instrument performer and composer, said in a courtesy personal communication (Potsdam, September 2009): “Art in Space will give a new dimension to the artistic production expanding human culture. Through artistic production the international crew of Space missions -- bringing their original local culture -- will be interacting with the new heritage of universe.” Foing underlines the importance of space as a place for cultural application. He points out that the crew is international, each member bringing the culture of his homeland that will be expressed in a new dimension: the Universal.

"Of course culture!" Roger Malina said in response to the same question. He is an astrophysicist, Space Art expert, editor and director of the "Leonardo Journal of Art, Science and Technology"; he expressed his opinion in a courtesy personal communication (e-mail, 16 September 2009). "After more than fifty years of Space exploration we have failed as a society to build a "Space culture." Space professionals need to admit that they are not experts by the side of developing Culture; they must work in collaboration with professionals in the arts and humanities if we wish to continue human expansion and exploration of Space. Just as the Chinese emperor burned his fleet of ships to focus on the internal affairs of his empire, so we on earth must find ways to build a sustainable society on the planet. If Space culture is to be part of the solution, we have urgent work to do with professionals in the arts and humanities to make sure that it is not five hundred years before humans again step on another celestial body. We must explore all possible ways of involving professionals from the arts and humanities in all aspects of Space activities."

- Quality of Life

Artistic expression is a way to bring inner emotions outside. This process helps to feel, understand, learn about, and control our inner experience. It is a challenge to expand us. "People who learn to control inner experience, will be able to determine the quality of their life, which is as close as any of us can come to being happy" (Csikszentmihalyi, 1990, p. 2). Optimal experience is when people report a feeling of concentration and deep enjoyment, and "depends on the ability to consciously control what happens moment by moment, each person has to achieve it on the basis of his own individual effort and creativity" (Csikszentmihalyi, 1990, p. 5). The creative process is part of what Csikszentmihalyi (1990) defines as flow; it is a moment of concentration to pursue a goal, where the person momentarily forgets everything else. "The periods of struggling to overcome challenges are what people find to be the most enjoyable times of their life" (p. 6): "it's fun, a great fun, to come upon something new" (Csikszentmihalyi, 1996, p. 4)

To get an idea of the joy, risk, and hardship involved in creative endeavors, we all know that when we are involved in creativity, we feel that we are more satisfied than during the rest of our life. The excitement of the artist at the easel or the scientist in the lab comes close to the ideal fulfillment that all of us hope to get from life, and so rarely do. Perhaps only sex, sports, music, and religious ecstasy – even when these experiences are satisfied and leave no traces – provide as profound a sense of being part of an entity greater than ourselves. But creativity also leaves an outcome that adds richness and complexity to the future (Csikszentmihalyi, 1996, p. 2). Prof. Mihaly Csikszentmihalyi is a positive psychologist, former chairman of the department of psychology at the University of Chicago. Famous for his research on flow state and creativity, he supports Aristotle's theory that "more than anything else men and women seek happiness" (Csikszentmihalyi, 1990, p. 1).

Gap: Humanities Application

The potential for photographers, filmmakers, painters, sculptors, theater makers, choreographers, writers, and musicians to draw inspiration from space facilities to add to world culture is enormous (Arts Catalyst, 2006). Since prehistory, art has always been an element of human expression to communicate with the external world (Rubano, 2005). Art can be applied to record the mission and communicate it not only to the space specialist, but also to the world community. Including humanities experts in mission design will provide the opportunity to effectively support not only the gain, but also the communication of knowledge from multiple perspectives.

NASA has had its own art program since 1962, and in 2004 had an artist in residence for two years: Laurie Anderson, American experimental performance artist and musician. The artist was able to work in direct contact with the NASA engineers and scientists, fully filling the idea of multidisciplinarity with contributions from the humanities. Bertram Ulrich, curator of the NASA Art Program, said in a telephone interview that “her mind works very much the same way a scientist’s would. They're both reaching out to try to understand what's unknown" (Gross, 2004). "Art is what's left behind of history," said Ulrich, "It's a way to document something for future generations" (Hull, 2004). NASA’s goal is perhaps far from the cultural utilization of space, but aims mainly to achieve educational and promotional purposes; in fact, “artistic and cultural activities relating to space are an important way of strengthening public engagement” (Arts Catalyst, 2006, p. 2).

In 2004, NASA’s investment in art represented $50,000 out of a total budget of $15 billion. These costs were highly criticized and there was no follow-up to the art in residence program. However, one solution could be to work “with contracted companies to seek external funding and sponsorship for cultural utilization” (Arts Catalyst, 2006, p. 7) of space, as suggested by Arts Catalyst for ESA.

ESA had experience with an artist in residence in ESTEC in 2006-7, hosting Ayako Ono, a Space Artist, graduate in Fine Arts and Music and currently a researcher in the field of behavioral medicine at Tohoku University in Japan. ESA, differently from NASA, tries to conciliate different goals, integrating cultural utilization of space, educational and promotional purposes, as well as using art to improve the astronauts’ living conditions. “If suitable art can be created for a weightless environment, it will not only improve the mental health of astronauts, but also inspire people to learn about the universe and space exploration”, explains Ayako Ono (ESA, 2006).

In the context of the cultural utilization of the ISS, JAXA has provided a variety of different art experiments and ways of cultural utilization for the Kibo module. The goal is to “make new discovery through artistic expression”, to “lead productive lives in space”, but not only there (JAXA, 2010 p. 1). The JAXA philosophy, which supports the application of Space Art, is reported in the “Pilot Mission of Utilization for Culture/Humanities and Social Sciences”:

> Human beings have looked up at the starry sky, been moved by it and achieved evolution driven by curiosity since our earliest days. Even in modern society we have extended the range of our activities to space, many space-related areas remain uncovered. One of the objectives of the ISS is to introduce impressions that humans beings have never experienced and to expand the wisdom of human beings by exploring the space environment. JAXA has long considered the significance of space exploration in the field of culture/humanities and social sciences. At last, the opportunity aboard Kibo…of artistic expressions that utilize the microgravity environment, and lead to the creation of social values on the ISS (JAXA, approx. 2010 p. 1)

Interviews with astronauts were performed on these topics (courtesy of Ayako Ono at the author’s request in July 2011) and are provided in the following:

ESA Astronaut:

1. Do you think that cultural activities (e.g. poetry, music and painting) may add a cultural dimension to space exploration? Yes. It is very important and part of exploration to translate experience. I tried to relate to people on the Earth. Will they remember the ISS? Astronaut's print on the Moon will be remembered.

2. Do you think that cultural activities may improve astronaut quality of life and performance? (Summary) If you would ask this question to my friend Bob Thirsk (CSA Robert Thirsk), he will say yes. For me music was really helpful, every evening one crew member bring his culture choosing the music to play, I play Flemish rock music because this is what I like. That exposes you to different environments culture, and I really like that. For the rest I´m not a scientist and I´m not an artist person. Having been obliged to something that is art – I´m not saying it is something part of the program, so to execute it – so to be exposed to it and to have to look into it, will annoy terribly, because this is something I´m not relating to on Earth so why should I relate to it in space. But that is a very personal opinion, but other people like Bob that enjoy going to museums and enjoying art, I´m sure that they will like to be exposed to art in space. We are ordinary people, with all kinds of variety, different tastes and interests.

One of the JAXA astronauts interviewed thinks that cultural activities (e.g., poetry, music, and painting) may add a cultural dimension to space exploration. However, regarding the question of whether cultural activities may improve the astronauts' quality of life and performance, the reply was: "It depends on the persons, doesn't it? If you give a cultural activity as an obligation, then it gives a stress. There are many astronauts like physical training, and such type of people may feel stress when they need to write a poem and to paint a picture. If it was passively received, may not be good, but would be good as one choice. So, when a person is interested in the trial of art, then positive opinions will support what they did. Therefore, preparing various kinds of choices would be good".

Indeed, being given the opportunity to perform art is beneficial if the astronaut likes this kind of activity, as the psychologist Csikszentmihalyi explains: "People that spend their time in an activity that they like may experience happiness, increasing the quality of life" (Csikszentmihalyi, 1990, p. 4).

In conclusion:

- Cultural activities should be one possible choice to improve an astronaut's life. It should be supported, but should not be obligatory.
- Artistic training and selection may improve the choice of activities to perform in space, giving more variety.
- Artistic activities may increase the chances for knowledge communication.

As explained by Ayako, "JAXA's art projects are a part of the educational project. If the art project has the impact to know space environments, it could be the education for general public, and children will have more interest about science including outer space. As another reason point, the art may be helpful for astronauts to make their mood better. Some artists' idea is that artistic activities are not only for relaxation but also the stimulation to have new viewpoints. JAXA's consideration vision is that cultural artistic activities are a part of human beings, when the human being expands the area place where he lives and works in from earth to outer space, he will expand the activities area and cultural activities will also be part of the life."

Another aspect is public interest. Public interest is a key element for any industry because it brings support and sponsors. The public is attracted to things that everyone can do, like painting or playing, facts of everyday life, experience and emotions, and things that can be easily apprehended as visual art (Schlacht & Ono, 2009). The Space Art expert Roger Malina points out that the work of some of the most important illustrators not only “anticipated some of the results of Space exploration, but in some senses made Space exploration possible by generating public interest and support as well as helping scientists to plan and illustrate their experiments” (Woods, 2001).

To gain public interest, astronauts must be able to communicate their personal experiences to the general public. As shown by Rubano (c.f. paragraph about Art Therapy), visual representation was used from prehistory to communicate man’s experience (Schlacht & Ono, 2009). Visualizing personal experience through artistic expression brings astronauts knowledge of their emotional dimension and at the same time helps them to communicate it to the public (Rubano, 2005).

Art as a cultural heritage was used in the past as advertising because it attracts public interest. Music has been sent into space aboard the Voyager mission (NASA Voyager, 2009). Also in the Cassini mission, music was sent to Saturn’s moon Titan. ESA explains that it was “aiming to leave a trace of our humanity in the unknown and to build awareness about this adventure, especially among young people” (ESA, 2009).

Figure 3.7: Problem of storace inside the ISS (© NASA)
http://spaceflight.nasa.gov/gallery/images/shuttle/sts-116/hires/iss014e09446.jpg

Figure 3.8: Measuring the mass of a crewmember in space is difficult because mass does not equal weight in the absence of gravity. © NASA ISS012E12635 - www.nasa.gov/mission_pages/station/research/experiments/Clinical_Nutrition_Assessment.html

3.3 CONCLUSION

From the critical analysis of habitability problems and design process challenges, the conclusion has been drawn in this chapter that in order to support the success of long duration and long range missions, it is of primary importance to solve these problems with a new methodology that integrates human factors design right from the start of the project.

Until now, human factors have not been taken into account appropriately and, as a consequence, the level of habitability on space stations, from the Mir to the current International Space Station, has been low. This situation is caused by two gaps. The first gap lies in the military approach that forms the basis of human space flight development. This approach does not consider the human side of the user, such as his or her sensory, affective, and cultural needs. The lack of application of these dimensions could become problematic in view of prolonged mission duration and the opening up of space missions to the general public as in space tourism. The second gap is found in the application of the same procedures for human and robotic missions, which even today do not include human factors from the preliminary and conceptual design phase. Indeed, the conceptual design of a system poses a significant challenge to the traditional design approach used for robotic or short duration missions (Osburg, 2002).

In the interviews done by the author, 13 of the 14 astronauts interviewed suggested that habitability needs improvement, particularly in anticipation of long duration missions. As a result of the analysis of user interviews, mission debriefing reports, and space agency standards, it emerged that with increasing mission duration and distance from the Earth, the effect of the problems related to habitability and human factors grows so strongly that, if not adequately dealt with from the first phase of mission design, it will impact user performance and become a safety hazard for astronauts' lives. In particular, psychological and socio-cultural factors, which were identified as not being adequately considered in the current project methodology, are of increasing importance in the context of long duration/range missions. However, along with the psychological and socio-cultural factors, problems related to operational and physical factors were also identified as fundamental factors that have to be considered to ensure mission success and safety. In detail, stowage systems, living conditions, privacy, autonomy, and variability were identified as fundamental needs that have to be considered to ensure long duration/range mission success and safety.

As a consequence of denying human factors in the project, the current "man in a can" design (referring to the shape of the space station's habitat module) does not allow the performance, safety, and well-being of humans in space needed for the success of long distance/range missions. Only the application of sound human factors principles from the start of the design project will assure a level of habitability that will ensure mission success in long distance/range missions.

The customer's total cost of ownership
will be dramatically reduced if HFE
practices are well integrated into all project phases,
from the very beginning.
(Enrico Gaia, ECSS-E-ST-10-11C 31 July 2008, p. 8)

4. SOLUTION: INTEGRATED DESIGN PROCESS

As described in the previous chapter on habitability challenges, there is a need for a new design process that integrates human factors and interdisciplinary design starting from the preliminary design phase. This section presents the Integrated Design Process (IDP) as a concept model that is capable of fulfilling this need.

The habitability challenges analyzed in *subchapter 3.1* have been identified as being caused by the lack of HF design. Experience has shown that a lack of HF and low habitability affect performance and safety in long duration missions, and that high habitability may support the gain of cultural knowledge. Requirements oriented more towards the crew´s survival than towards its quality of life have been identified as the main cause of low habitability in space missions. To change the orientation of spacecraft design, this chapter presents a new design process that integrates HF: the Integrated Design Process (IDP). The role of HF in the IDP is to contribute, from the very beginning, principles of design structure aimed at optimizing quality of life and overall system performance in human long duration missions. In short, when it comes to increasing habitability in long duration missions, IDP has been identified as a methodology that integrates HF design within its application by combining the following principles, which constitute the basis of every good design project:

- Interdisciplinary human factors design
- User-centered approach
- Holistic methodology

4.1 IDP SYSTEM DESIGN

This subchapter explains in detail each individual principle on which the IDP is based: interdisciplinary human factors design, user-centered approach, and holistic methodology.

Considering the previous challenges analysis, the IDP has been created as a new design model that integrates human factors to increase habitability in all phases of the design process. Indeed, as explained in the ESA standard, HF must be integrated from the very beginning into all project phases of the habitat design process (Enrico Gaia, ECSS-E-ST-10-11C 31 July 2008, p. 8).

Unlike the classical quantitative orientation used in previous spacecraft requirements, this process also supports the qualitative and cultural dimensions of habitability, such as the cultural utilization of space.

Considering the needs of interdisciplinary habitability design (cf. *section 3.2.3*), user-centered approach (cf. *section 3.2.1*) and hoplistic methodology (cf. *section 3.2.2*); to increase quality of life in long duration missions, IDP is based on the following three principles.

The first principle is given by the interdisciplinary habitability design (cf. *section 2.1.3*). Human factors and habitability (cf. *subchapter 2.1*) are based on the interdisciplinary design of four different factors:

- Operational factors, physical factors, psychological factor, and socio-cultural factors.

The second principle is the user-centered approach (cf. *section 2.4.2*). This integrates the support of user needs into the design process as an active part of the human-machine-environment mission system. This principle is based on the contribution of:

- Participatory Design: designing together with the user
- User Experience: designing the experience of the user
- Empathetic Design: designing as the user (by identifying oneself with the user)

The third principle is the holistic methodology (cf. *section 2.4.3*), which is based on three main interrelated and connected focal points:

- Human-machine-environment system: What is the subject of the project?
- Multidisciplinary team: Who is involved in the project?
- Concurrent design: How is the project developed?

With the IDP, habitability is effectively increased with the concurrent contribution of these three principles that support the qualitative dimension in all design phases. The concept of the design model, which combines these three principles, is represented in the next figure.

In the figure, the first principle illustrated – interdisciplinary design – is designed as the contribution made by human factors, and is represented by one large arrow with the letters HF inside and four small arrows around the central human, who is designed as an astronaut. These four arrows represent the operational factors, the physical factors, the psychological factors, and the socio-cultural factors, while the arrow with the letters HF represents the presence of the HF specialist on the team. The second principle, the user-centered approach, is represented by the human positioned in the center of the overall model. The third principle, the holistic methodology, is represented by the other parts of the figure. In particular, the human-machine-environment system is represented by the design of the three small elements (astronaut, space station, and space environment) around the central human, which are interconnected with each other by three arrows. The multidisciplinary team is represented by all the large arrows that are in the circle around all the figures, covering all the different perspectives of the central image. Finally, the concurrent design is represented by the circular arrow that merges all the large arrows in the circle, connecting all the different perspectives of the multidisciplinary team.

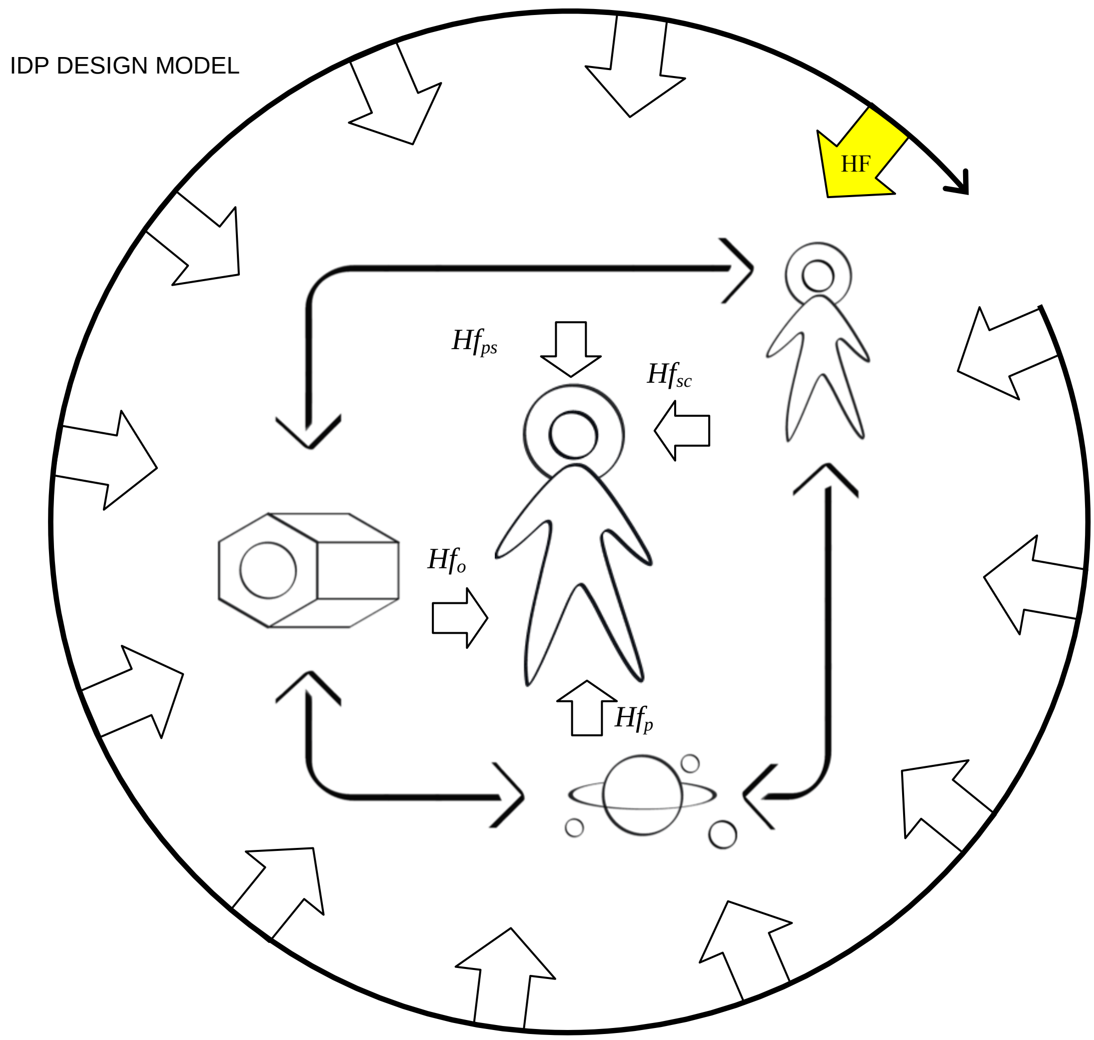


Figure 4.1: IDP integrates qualitative HF dimensions into the preliminary mission design to support the habitability factors (Hf) aimed at increasing quality of life in long duration missions

4.1.1 IDP Habitability Factors

Habitability is the quality of life given by the interaction between humans and the system, and composed of operational (f_o), physical (f_p), psychological (f_{ps}), and socio-cultural (f_{sc}) factors (cf. *section 2.1.3*). It can be defined using the following function:

Habitability = $f_o + f_p + f_{ps} + f_{sc}$

Habitability = Quality of life in a system

= System usability

= Performance

Where:

- Operational factors (f_o) are all the factors related to the task, task management, and task support, e.g., training, mission support, equipment, interface, software, hardware instruments and equipment, and time schedule.

- Physical factors (f_p) are all the natural and artificial environmental factors (f_e) – related to the environmental conditions outside the habitat and the environmental controls inside the habitat – and all the factors related to the human physiology (f_{ph}), e.g., external, habitat, and body temperature.
- Psychological factors (f_{ps}) are all the factors related to mental well-being, e.g., mood, feeling, emotions, and motivations.
- Socio-cultural factors (f_{sc}) are psychosocial and cultural factors related to the interactions among humans, e.g., crew relations, religion, and art.

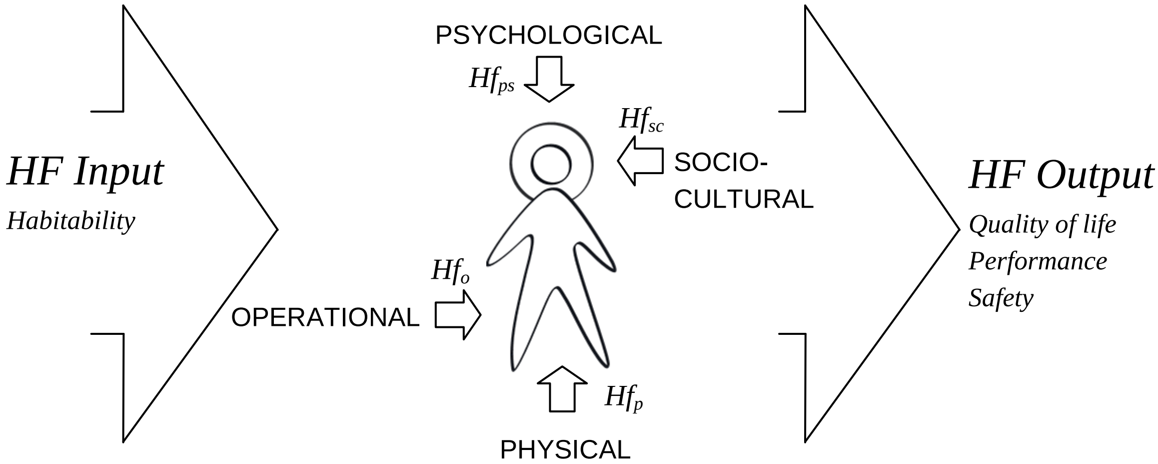


Figure 4.2: HF designs intended to contribute to the habitability factors (Hf) supporting quality of life, and increasing performance and safety.

Table 4.1: Examples of habitability factors

EXAMPLES OF HABITABILITY FACTORS (*Hf*)	
HABITABILITY FACTORS	EXAMPLES
Hf_o (Operational Factors)	Schedule, tasks, interface, instruments, performance.
Hf_p (Physical Factors)	Health, environmental conditions, environmental control, physiological conditiona, sensory monotony.
Hf_{ps} (Psychological Factors)	Motivation, mood, emotions, perception.
Hf_{sc} (Socio-Cultural Factors)	Personality and personal development, communication, rituals, social relations, art, religion.

Increases in habitability correspond to increases in quality of life and performance. Both are driven by the same factors. However, the former is mainly relevant for long duration missions, the latter for short duration missions. These factors are related to each other and are not completely separate fields; all of them together come into play for the quality of life and the performance of the human-machine-environment system. It is wrong to define habitability only in terms of the physical factors related to habitation, like noise, temperature, or light. Territoriality, workload, or privacy are strictly related to quality of life in a habitat and are interconnected to physical, psychological, social, and operational factors.

HIGH HABITABILITY

Increases: safety, performance, productivity, efficiency, satisfaction, comfort, life quality.
Decreases: human errors, human effort, stress, frustration.

↓

HABITABILITY FACTORS

Applied to: IVA (intra-vehicular activities)
EVA (extra-vehicular activities)

↓

HABITABILITY ELEMENTS – EXAMPLES

A. System interfaces (e.g., temperature control)
B. Environmental elements (e.g., dust)
C. Working and living condition (e.g., time schedule, territoriality, workload, or privacy)
D. System work maintenance (time spent on making the system work: e.g., repairing)
E. Adaptability (skills needed to adapt to new conditions, e.g., jetlag and isolation problems)

Figure 4.3: Habitability factors schema of the MDRS crew debriefing by Schlacht (Blume Novak, 2000; Whitmore et al., 2000; Yamaguchi, 2000; Messerschmid, 2008)

In synthesis, for short duration or short distance missions, the habitability factors can be interrelated to a gain in performance, while for long duration or long distance missions, they need to be interrelated to a gain in the quality of life, which can support performance.

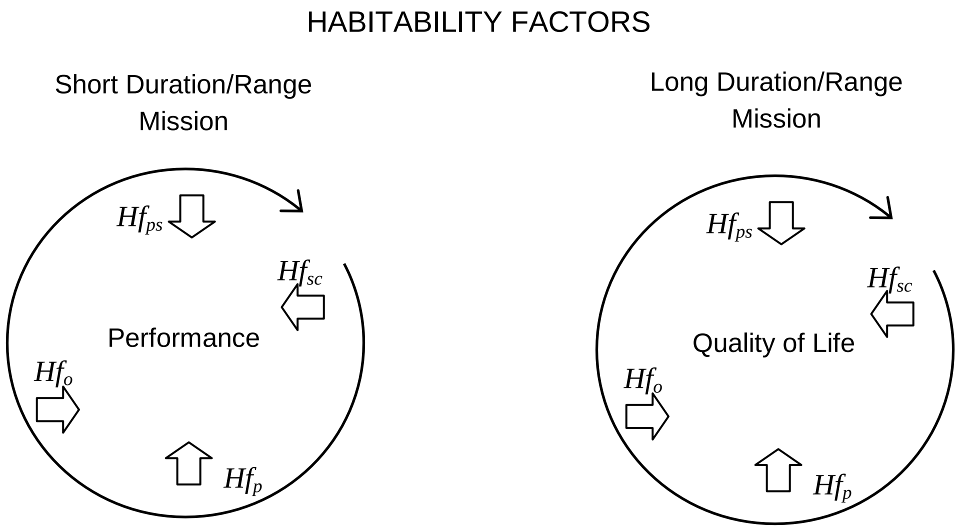


Figure 4.4: Habitability factors approach correlated with mission duration and distance.

4.1.2 IDP User-Centered Design

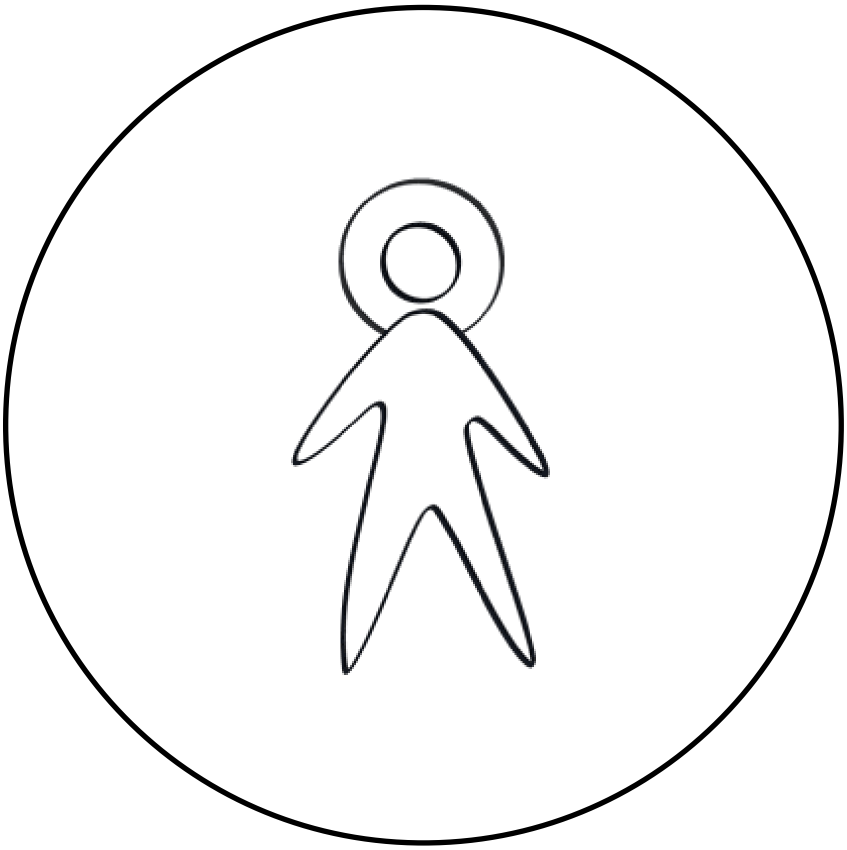


Figure 4.5: User-centered approach

To apply user-centered approach within the IDP, three main design approaches have been selected:

- Participatory design: the user is participate in the design
- User experience: the user experience is supported, including cultural, sensory, and affective user needs.
- Empathetic design: designer experiences the user condition.

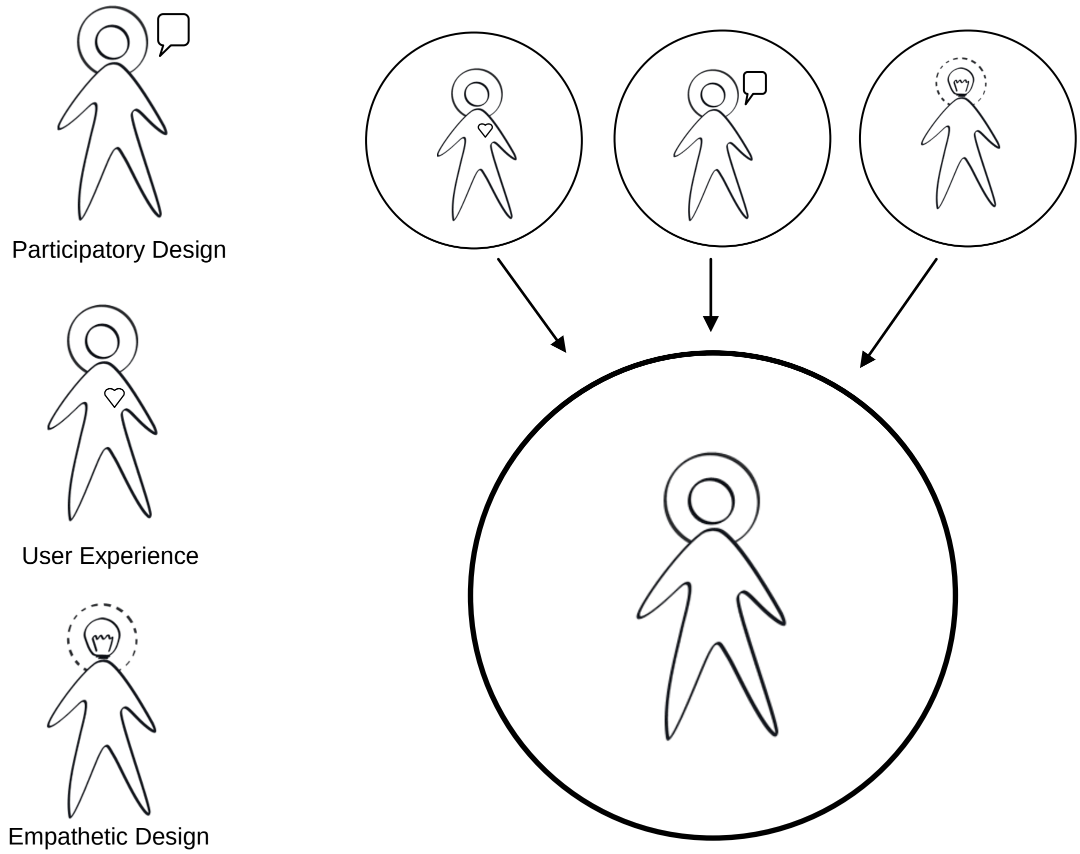


Figure 4.6: User-centered-design. It is based on the contributions of participatory design, user experience, and empathetic design.

IDP Participatory Design

In the IDP, participatory design is aimed at:

- Involving the user in the design process ideas
- Finding qualitative and quantitative user needs
- Finding project solutions together with the user

It is applied together with user experience design and empathetic design to the:

- User-centered approach
- HF design process

IDP User Experience Design

In the IDP, user experience design is aimed at supporting cultural, sensory, and affective user dimensions in order to contribute to a "rich variety of human experiences" (Takatalo et al., 2008). User experience is not only physical, but also includes sensory, cultural, and affective qualities. It approaches the human as an integrated system consisting of mind and body (Imhof et al. 2004). The user experience design focuses on the investigation and support of human interaction experienced sensually, intellectually, and emotionally.

In the IDP, experience design is aimed at:

- Supporting sensory, cultural, and affective user needs
- Integrating both quantitative/numerical dimensions with qualitative/descriptive one

It is applied together with participatory design and empathetic design to the:

- User-centered approach
- HF design process

IDP Empathetic Design

Empathetic design is defined here as a project carried out by a designer who has been able to directly experience, observe, and thoroughly understand the user condition and discover latent user needs (cf. *section 2.4.2*, part *Emphatetic Design*). It can be applied by assuming the role of the user and experiencing the interaction with the system. It is based on learning-by-doing principles. Hypothetically, optimal empathetic design can be applied by a designer who has experienced and observed the user condition; in the case of a space mission, there would be at least one astronaut on the team who is a designer. If this is not feasible, letting the designer directly simulate and observe the user condition may also be a possible solution. For example, during parabolic flights, the author, as team designer, was able to personally perform an experiment in microgravity, while during the mission simulation at the Mars Desert Research Station, she was able to experience and observe user interaction with the space system. At the preliminary study level, this can also be performed with simple media. For example during university team work, the students were observing astronauts living and working in space by watching documentaries, and experienced the user condition through the process of identification, by performing user activities in which they identified themselves with the user in order to understand the user scenario and acquire new knowledge.

Figure 4.7: Empathetic Design apply performing experiments in microgravity (CROMOS Experiment, Airbus A300 parabolic flight, Schlacht I.L., Vince M., © ESA, 2007)

In the IDP, empathetic design is aimed at:

- Personally experiencing the user condition
- Thoroughly understanding the user condition
- Identifying latent user needs

Together with participatory design and user experience design, this contributes to:

- Integrated user-centered approach

4.1.3 IDP Holistic Methodology

Holistic approaches for understanding and evaluating the inner worlds of the users and their complex functionality are required in numerous technological contexts. The holistic nature of the human is being studied systematically using solid approaches. As a result, the psychological understanding of the human experience in space environments increases and benefits the designing of habitability qualities (Takatalo et al., 2008)

IDP Concurrent Design

Concurrent design aims to consider from the first design concept all the lifecycle phases of a product or a service (i.e., development, production, distribution, usage, and disposal/recycling) with the support of multidisciplinary experts. In order to work with a multidisciplinary team, concurrent design must also provide qualitative variables, which cannot be constrained in a prestructured work sheet, typical of the concurrent design facilities in use today. The qualitative variables need to be discussed and developed with visual presentations and materials and then summarized in the final report. Currently, concurrent design is performed at concurrent design/engineering facilities (cf. *section 2.4.3*, part *Concurrent Design*). However, in the conceptual phase, it is not necessary to be constrained to a facility with pre-defined Excel sheets in order to have different team members design in parallel. For example, a concurrent design can even be realized if there is nothing but a table in a room where the people may sit and design together, and if needed, there may also be a computer in the room. Actually, this is the standard way to proceed for designers and architects.

To design concurrently using different computers, the Microsoft operating systems (e.g., Windows Vista or Windows 7) already have simple tools that are able to connect the computers. These tools include Remote Desktop connection and local area networks (LAN). The Remote Desktop connection allows being connected to the monitor of another computer online while this computer is being used by its owner. The monitor can be visualized and the viewer can work on it in real time. Another sharing facility is the Google Documents online program, which supports concurrent writing by different authors, regardless of whether they are located in the same room or in different parts of the world.

The difference between concurrent design and the concurrent design facilities used today is that a facility is based on work sheets, and concurrent design is based on a more open and flexible approach typical of designer environments.

In the IDP, the concurrent design is aimed at:

- Simultaneously designing all lifecycle phases

With multidisciplinarity and human-machine environments it is used to:

- Integrate the scientific and cultural utilization of space
- Support HF to ensure human-centered design

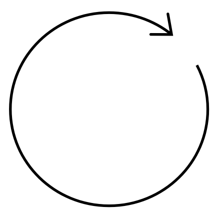


Figure 4.8: Concurrent Design

IDP Human-Machine Environment

A space habitat is meant to be as much as possible a sustainable system, a closed-loop system with autonomy from the Earth. To support human life in such a habitat, each specific element of this complicated system is designed and built artificially considering the relation with human and environment (cf. *subchapter 2.3*). To easily understand the artificial closed-system concept, we can imagine an aquarium where each single element has a direct influence on the equilibrium of the overall system. In the aquarium, the equilibrium between fish, plants, and water is fundamental. Too many fish will eat all the plants, resulting in insufficient oxygen, resulting in water contamination, which will eventually kill the fish. Just as in an aquarium, in a closed system the relationship of a part to the whole is extremely intensified; in this sense, the user's well-being is strictly related to the equilibrium existing within the system. Fostering optimal relations among all the elements that constitute the living system becomes crucial for maintaining a perspective as global as possible when considering each phase of the system's lifecycle.

All the factors are closely interrelated and influence each other. Therefore, a holistic (*holos* = complete) approach is needed that takes into account the system elements and the relations between them. Holistic design applied to human-machine-environment elements focuses not only on the elements themselves, but also on the interaction between these, as explained in the chapter on space habitability (cf. *section 2.1.3*). Today the various human-machine-environment fields are already considered during the design process, but their interaction is not part of deep design. Human-machine-environment interaction supports the habitat system holistically, in its complexity. Indeed, as defined in the field of HF design, human-machine-environment interaction takes into account all aspects, relations, and interactions of three fundamental elements of mission design: human, machine, and environment.

In the IDP, the human-machine environment is the focus of the design, which aims at:

- Supporting a holistic approach

  (System elements and the relations between those)
- Supporting sustainability

Together with multidisciplinarity and concurrent design, it is used to:

- Integrate the scientific and cultural utilization of space
- Support HF to ensure human-centered design

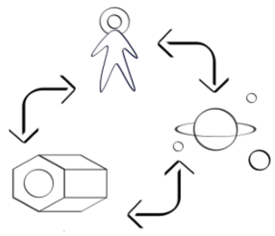


Figure 4.9: Human-machine-environment

IDP Multidisciplinary Team

<u>With the multidisciplinary team, the IDP supports the user both in performing quantitative tasks and in acquiring qualitative experience by integrating cultural, sensory, and affective dimensions (cf. *section 3.2.3*, part *Gap: Interdisciplinary Design*).</u>

At the moment, the interdisciplinarity of the project is based only on different kinds of engineering disciplines that support only the "physical and functional elements" in the project (Larson and Pranke, 1999, cf. *section 3.2.3*). The IDP integrates in the design process a multidisciplinary panel of experts in order to support the mission goal both from a scientific perspective – using the social, natural, and applied science disciplines – , and from a humanities perspective, to enhance the users' cultural experiences. By adding humanities, the qualitative, affective, and cultural experience of the user is also considered and supported, and the cultural utilization of space becomes a fundamental part of space exploration. Following this multidisciplinary logic, art, history, and anthropology, for example, are integrated into the scientific and engineering disciplines of space mission design in order to support humans in experiencing comprehensive and successful space exploration. Until now, space missions have been based on a set of "physical and functional elements" (Larson and Pranke, 1999) – which has allowed humans to survive in space –, but combining these approaches with humanistic disciplines will allow humans to live in space.

In the IDP, multidisciplinary specialists are involved in:

- Integrating scientific disciplines and humanities

Together with human-machine-environments and concurrent design, this is used to:

- Integrate the scientific and cultural utilization of space
- Support HF to ensure human-centered design

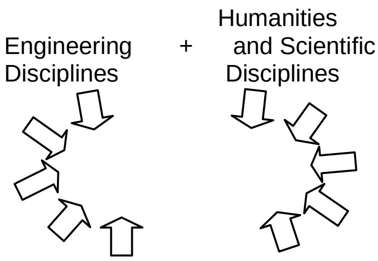


Figure 4.10: Multidisciplinary Team

4.2 IDP PROCESS

This subchapter presents the application and verification process of the model concept, abd then compares it with the actual process currently applied to space mission design.

4.2.1 IDP Application Process

As far as application of the IDP is concerned, the process applies both the holistic methodology and the user-centered approach to HF design. The elements of the methodology are interrelated, just like the elements of the approach. In this way, the application of the process is determined by the interactions of each element, as described in

Figure *4.11*. The relations between the various elements have been described and applied in different projects related to space design. The projects all had different highlights. The application of the integration process must support all of the process elements and their correlations. The application of the process should answer two basic questions: What should be designed?

and How to design it? The three principles presented in this chapter need to be applied in order to answer these questions. In particular, as illustrated in

Table 4.2, all the principles partly answer both questions.

Table 4.2: IDP Design Methodologies

IDP Design Methodology			
IDP COMPONENTS	INTERDISCIPLINARY HF	USER-CENTERED APPROACH	HOLISTIC METHODOLOGY
WHAT	*Habitability Factors: Physical, Operational, Psychological, Socio-Cultural.*	*User Experience*	*Human-Machine-Environment Interaction*
HOW	*HF Design*	*Participatory Design Empathetic Design*	*Multidisciplinary Design Concurrent Design*

The IDP has been applied in different projects related to habitability, with varying foci and team backgrounds. Each project was supported by the complete IDP; however, the projects were applied with flexibility in terms of the type of project to allow supporting an increase in habitability as a common goal. As a matter of fact, although all the elements of the IDP were necessary, the methodologies and the approach were applied with different degrees of relevance. Indeed, the elements that answer the question of what should be designed emerged to be the major focus, compared to the elements that answer the question of how to design.

As a consequence, even though the entire IDP is needed to achieve an increase in habitability, the main core of this process is the connection of:

- Habitability factors
- User experience, defined as the support of the astronauts' qualitative experience
- Human-machine-environment relations, defined as the holistic design of the system elements and their relations.

The IDP is the concept of an interconnected, dynamic, and flexible design model. All possible interconnections are depicted in below, where the relevance and the connections between these three elements are underlined with thick lines. In

Figure *4.11*, the habitability factors are at the top, covering the user-centered approach and the holistic methodology, while the elements of the last principle – interdisciplinary HF – are represented as being dynamically interconnected in a flower-shaped figure.

The successful application of the IDP core is the basic element for succeeding in increasing habitability. The support of human-machine-environment interaction and user experience has been verified in each project. Also, when all possible combinations between all IDP elements were analyzed, the application of the combination of human-machine-environment and user experience turned out to be the most relevant element for an increase in habitability in all projects (as shown in *Appendix F*, *Table 0.16* and *Table 0.17*).

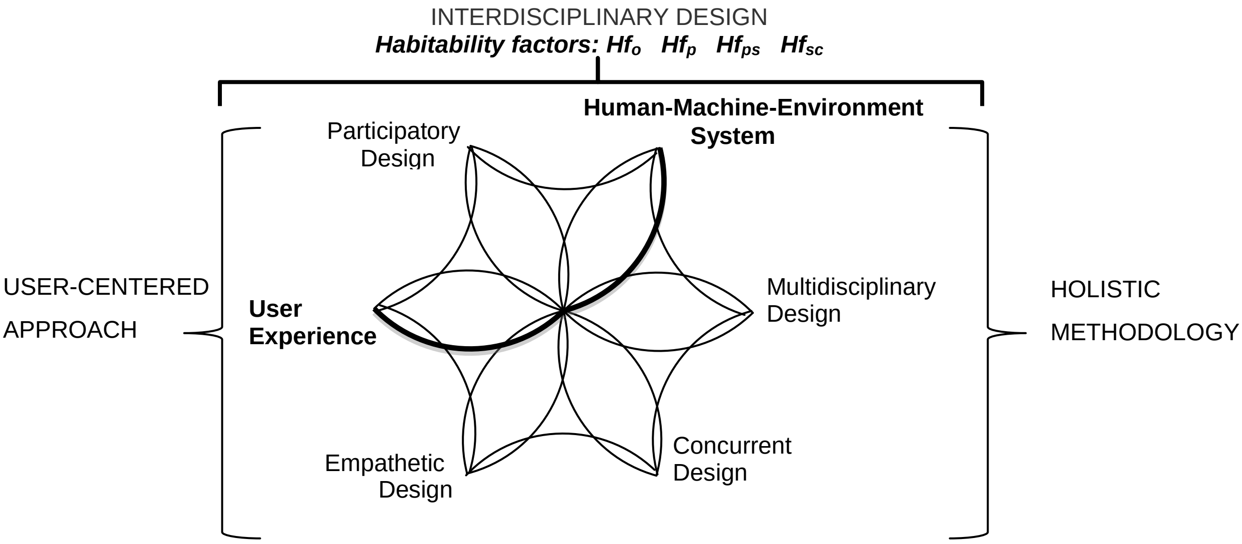


Figure *4.11: IDP elements and their correlations*

4.2.2 Verification Process

In summary, the IDP is the concept of an interconnected, dynamic, and flexible design model that supports human factors with the application of a user-centered approach and a holistic methodology.

Considering the flexibility and dynamism of the model, there is no rigid and linear step structure to follow; rather, different principles can be applied concurrently from the first design steps, in accordance with the principles of design. The main rule of the design model is that each principle of the methodology needs to be applied. In the model, the habitability factors and the qualities are considered "needs", while the user-centered approach and the holistic methodology are used as the methodology. The process of verification is based on a simple checklist methodology, which verifies the fullfillment of each individual principle as shown in the following table.

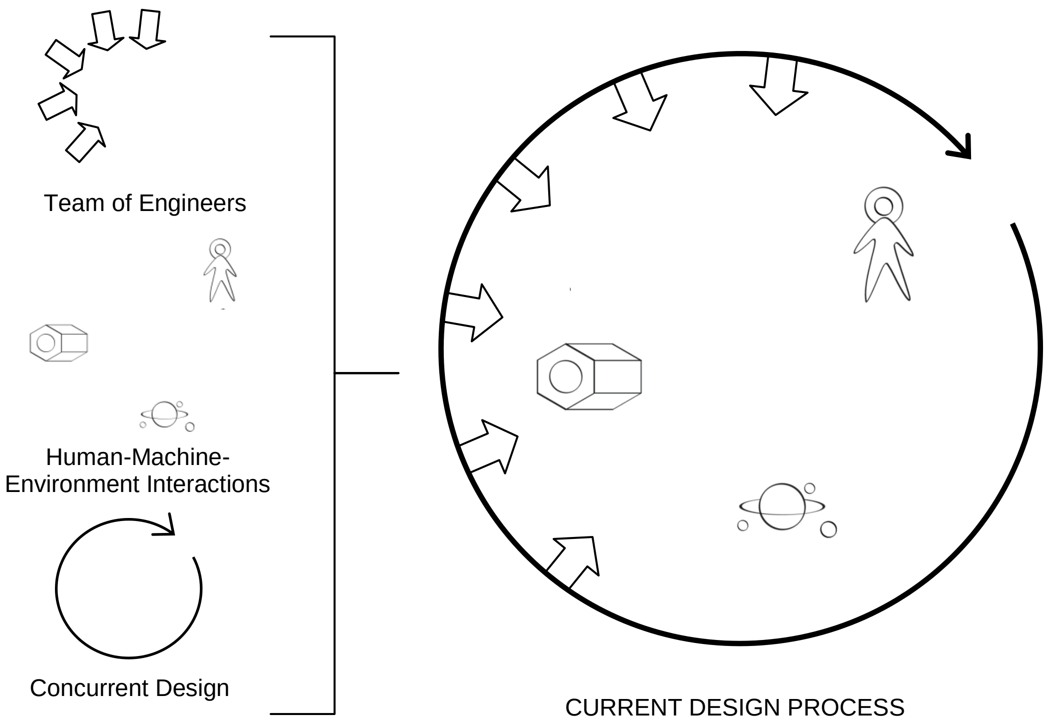
Table 4.3: Design checklist (IDP and current process in comparison)

USER NEEDS IN LONG DURATION MISSIONS	METHODOLOGY APPLIED TO SUPPORT THE NEEDS

	QUALITIES				HF HABITABILITY FACTORS				USER-CENTERED APPROACH			HOLISTIC METHODOLOGY		
	Innovation	Usability	Livability	Flexibility	Operational	Physiological	Psychological	Socio-Cultural	User Experience	Participatory Design	Empathetic Design	Concurrent Design	Multidisciplinary Design	Human-Machine-Environment Interaction
IDP	v	v	v	v	v	v	v	v	v	v	v	v	v	v
State of the art					v	v						v		

4.2.3 IDP vs. the Current Process

Concurrent design is a methodology already applied by ESA as well as by DLR as explained in *subchapter 2.4*. The application of the IDP to concurrent design is compared here with the classical ESA concurrent design configuration. Today's ESA design does not support human-centered design because there is no HF specialist on the team (ESA, 2007; Bandecchi et al. 2000). As a consequence, the activities related to HF are divided between the different engineers.



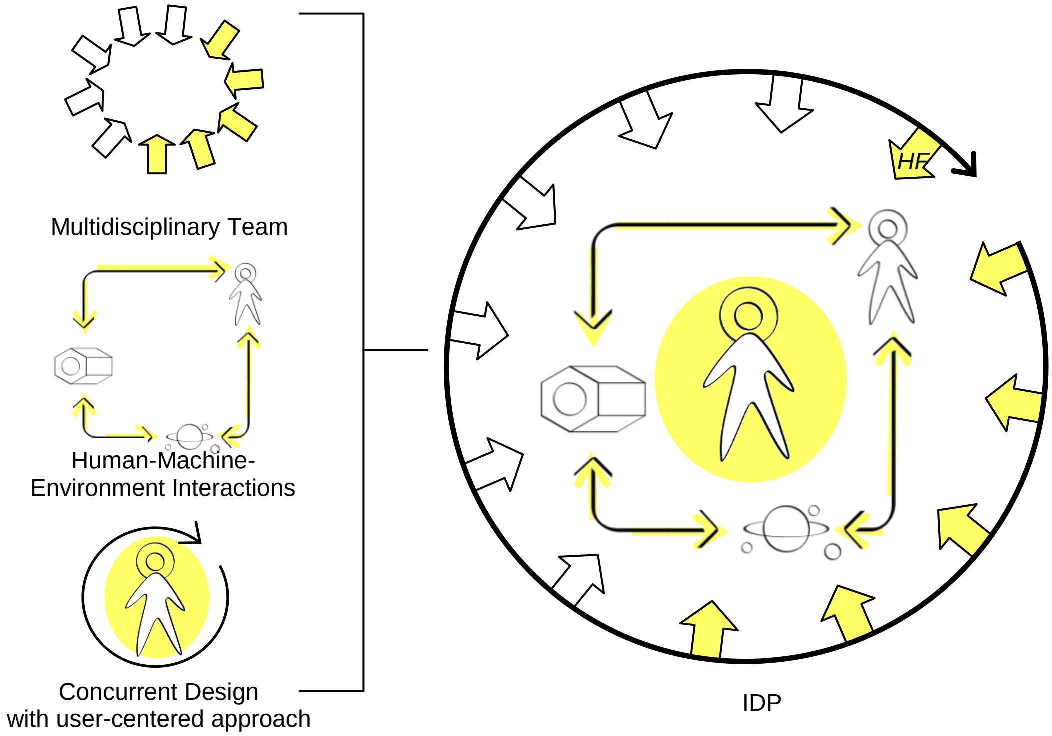


Figure 4.12: Current design process vs. Integrated Design Process (IDP).
Index: yellow parts are not present in the current design process.

Unlike the ESA approach, in the IDP the concurrent design management positions are specifically defined to support human-centered design:

- Concurrent Design Facility Manager: Responsible for the interaction with the customers and for running the facility; should be aware of and informed about the HC design approach.
- Team Leader: Checks that the procedures follow a HC design approach.
- Technical Author: Takes care of technical documentation, user's manual, and final report.
- Systems Specialist: Runs session, making sure that the specialists and the mission designer work in a synchronized manner and follow HC design, updates the Concurrent Design Facility model to support HC design.
- Systems Assistant: Updates data in the system so that it can be accessed by the other disciplines.

Apart from the concurrent design management positions, multidisciplinary experts are on the team. In the Concurrent Design Facility at ESA, these positions may vary depending on the study, but official positions are allocated and people work together with shared Excel sheets. In the ESA Concurrent Design Facility, there is no HF sheet or position. Other Concurrent Design positions (listed in Table 0.12) have been utilized here:

- HMM: ESA Mars Mission Pilot Design (ESA, 2004)
- SSDW: Space Station Design Workshop (SSDW, 2009)
- HSI: ESA Human Integration System (Johansson, 2010)

In the IDP, the concurrent design positions are completely flexible, and the team is formed in relation to the design objective. Each position can be covered by one or more persons with the needed skills (examples are listed in

). Considering the acquisition and communication of new technical and cultural knowledge as the overall space exploration objective, a general panel of possible positions has been selected. This panel contains all the positions utilized by HMM, SSDW and HSI, plus completely new ones that had not been considered before and that were specifically selected to support the overall space exploration objective. These positions are:

- Cultural Theorist (space cultural application)
- Physiologist/psychologist (medicine)
- Science and Physics
- Visibility (PR)
- User: Astronaut

In the IDP, the positions strictly connected with HF are both qualitatively and quantitatively oriented and are supported by multidisciplinary experts from the cultural and scientific worlds. The HF positions are flexible in that numbers follow needs. A possible configuration is given below.

Table 4.4: Example of multidisciplinary skills of IDP positions strongly related to HF

Example of multidisciplinary skills of IDP positions strongly related to HF	
IDP (position that works in close relation with Human Factors)	Possible Skills
Configuration (habitat system)	Architecture, Anthropology, History, User Experience, Philosophy, Zoning, Sociology, Ethnology
Cultural Theorist (space cultural application)	Music, Dance, Visual Art (Sculpture, Land Art, Painting, Drawing…), Literature Arts (Theatre, Literature, Poetry, Music…), Art Therapy
Crew Performance	Engineer Psychology, Human-Machine System, Usability, User Experience
HF/Habitability	Architecture, Industrial Design, Physiology, Behavioral Psychology, Ethnology, Interior Design, Industrial Design, Social Psychology, Environmental Design, User Experience, Affective Design, Industrial Design
Life Support	HF, Physiological Well-Being, Crew Motivation, Art Therapy
Operation	Ergonomics, Human-Machine Systems, Social Science, Usability, User Experience

Physiologist/Psychologist (Medicine)	Medicine, Psychology, Sociology, Cognitive Ergonomics, HF
Structure	Perceptions, Anthropology, History, User Experience
Visibility (PR)	Public Relations, Project Divulgation, Project Visual Representation, Project Concepts Internal Communication.
User: Astronaut	User Experience

To define the project guidelines, the HF design needs to be supported in particular by:

- Team Leader
- Costs
- Resources (in-situ)
- Future Operations and Developments
- Risk/Safety

The introduction of humanities expertise and the human-centered design orientation of the entire process allow habitability to be increased. This strategy also allows the integration of qualitative, cultural, and affective dimensions into mission design.

It should be noted here that the goal of the new positions – such as architecture, cultural application of space, or HF and performance – is not to increase habitability; this can only be achieved as the result of the overall user-centered design process, the IDP.

Figure 4.13: Aquiring new knowledge La Scuola d´Atene, Vaticano. Plato, Aristoteles, Socrates, Pythagoras, Euclid, Ptolemy, Zoroaster, Raphael, Sodoma and Diogenes.(Raffaello 1510)

4.3 CONCLUSION

The Integrated Design Process presented in this section is a conceptual model for the design of long duration space missions that integrates and supports human factors and design quality starting from the preliminary design phase. It improves habitability and thus leads to an increase in human safety, performance, quality of life, and overall mission success.

In 2008, the European Cooperation for Space Standardization underlined the need for integrating human factors into all project phases, starting from the very beginning. This concept is of primary importance for reducing mission costs, but is also necessary for mission success and for the safety of the users; and it becomes fundamental in view of far distances and prolonged mission duration. At the European Space Agency, there currently exists no adequate process for integrating human factors from the preliminary phase of design projects for human missions; this has repercussions on the overall system habitability.

The highlight of this dissertation is the development of a new conceptual model that integrates the design of human factors from the preliminary phase of design process in order to enhance long duration mission habitability. This new conceptual model is labeled the Integrated Design Process (IDP) because it integrates operational, physical, psychological, and socio-cultural habitability factors starting from the conceptual phase of a long duration mission. The IDP effectively supports the quest for knowledge in space missions from multiple and qualitative perspectives, including, beyond the scientific perspective, the cultural gaining of knowledge. This helps the astronauts to not only acquire new knowledge, but also to express it. The IDP is based on a human-centered approach and a holistic methodology. To support the human side of the project, such as cultural and affective dimensions, the human-centered design focuses on three techniques: designing the experience of the user (user experience), designing together with the user (participatory design), and designing by identifying oneself with the user (empathetic design). The holistic methodology aims at supporting the user in relation to the system and is composed of the interrelation among three main qualitative-oriented methods: multidisciplinary team (integrating humanities), concurrent design, and human-machine-environment interactions. The application of the design model in respect to the current methodology increases habitability because it supports usability, livability and flexibility when it comes to designing innovative solutions.

The human race will expand into the solar system,
thereby demonstrating once again that,
while our resources may be limited at any given time,
the human imagination is not.”
(Hans Mark in Lewis, 1996, p. 275)

5. APPLICATIONS: HABITABILITY DESIGN PROJECTS

Following the application of the IDP in four case studies related to the preliminary project phase, this chapter provides evidence that the IDP conceptual model is able to guarantee an increase in habitability, from the equipment to the overall system design.

In the system design process, the introduction of HF to support human-centered design and a qualitative approach allows an increase in habitability. It is not through the work of any individual position or any individual design phase that habitability increases; this can only be achieved as the result of the entire design process, the IDP. Taking into account this preface, this chapter presents the application of the IDP to different projects, varying from the design of the entire habitat to just a single element. In each project, human-centered design and the qualitative approach sustained an increase in habitability, which verifies the validity of the IDP process.

IDP APPLICATION										
	HABITABILITY FACTORS				USER-CENTERED APPROACH			HOLISTIC METHODOLOGY		
	Operational	Physiological	Psychological	Socio-Cultural	User Experience	Participatory Design	Empathetic Design	Concurrent Design	Multidisciplinary Design	Human-Machine-Environment Interaction
IDP	v	v	v	v	v	v	v	v	v	v

5.1 SSDW

The first case study concerned the application of the IDP for the design concept of a Moon Base during the Space Station Design Workshop. When compared to the current methodology, the results support the introduction of highly innovative solutions aimed at increasing habitability in long duration missions by applying new technologies.

Figure 5.1: SSDW held at ESA's Concurrent Design Facility (SSDW, 2010b)

The Space Station Design Workshop (SSDW) "is an environment for the multidisciplinary conceptual design of space stations and other orbital infrastructure" (SSDW, 2010), organized by the Institute of Space Systems (Institut für Raumfahrtsysteme, IRS) of the University of Stuttgart, led from 1999 by Professor (and astronaut) Ernst Messerschmid. The workshop was organized by a team of novice organizers, and the goal was to accomplish a complete space station design phase A0 supported by tutors and experts. This methodology aims to test different design procedures and to gain innovative solutions.

The SSDW was selected as the optimum platform for testing the IDP. The reason for this choice is that the SSDW is based on a pilot multidisciplinary approach that, unlike the ESA Concurrent Design Facility, has an HF position on the concurrent design team. Thanks to the support of the SSDW team during the SSDW 2009, the IDP was introduced by the author to set up the optimum basis for habitability in project phase A0 of the Space Station Design. The results are compared with the ESA process and also with the standard SSDW.

Table 5.1: IDP in comparison with ESA and SSDW (Messerschmid & Bertrand, 1999; ESA, 2007; Bandecchi et al. 2000; SSDW, 2009; Johansson, 2010; Osburg, 2002)

	HF HABITABILITY FACTORS				USER-CENTERED APPROACH			HOLISTIC METHODOLOGY		
	Operational	Physiological	Psychological	Socio-Cultural	User Experience	Participatory Design	Empathetic Design	Concurrent Design	Multidisciplinary Design	Human-Machine-Environment System
SSDW-IDP	v	v	v	v	v	v	v	v	v	v
SSDW	v	v					v	v	v	v
ESA		v						v	v	

5.1.1 SSDW Design Process

The main phases of the SSDW design process are selection, training, and design. In 2009, the IDP elements were applied with the support of the author and the SSDW team to each phase of the SSDW-IDP design process, which is composed of:

1. Selection
    1.1 Multidisciplinary and international call
    1.2 Selection of participant positions
    1.3 Composition of teams
2. Training
    2.1 Acquisition of field knowledge
    2.2 Multidisciplinary learning design
3. Design
    3.1 Space station concurrent design
    3.2 Support with guide line
    3.3 Cooperation with tutors

Team Selection

In 2009, the author took part in the selection process for the HF participants in order to fully support the application of the IDP. A multidisciplinary team was put together with HF as one of the team positions. It should be noted that the presence of HF and a multidisciplinary team were also stipulated by the SSDW guidelines.

In 2009, 32 students were selected to make up two competing teams. The call was sent out internationally via e-mail to different universities, student organizations, and professors from different fields and countries. In 2009, two thirds of the students were from Germany and one third from Russia, Australia, England, Switzerland, Greece, Spain, France, the USA, and Belgium. More than two thirds of the students were aerospace engineers, and one third were studying engineering, architecture, physics, HF, and structural systems. A group of 10 tutors specialized in different fields was present to supervise the contributions of each position.

Figure 5.2: Students and tutors of the SSDW-IDP 2009, IRS Stuttgart (SSDW, 2009)

The positions applied for concurrent design were selected on the basis of the objective presented in the mission statement and the task (details in *Appendix G*). The objective of the SSDW conceptual study was to define an evolutionary space station concept in an international space exploration scenario (SSDW, 2009).

Unlike the ESA approaches, the positions allocated by the SSDW had been studied to support first of all the multidisciplinary approach request to optimize the process (Osburg, 2002). For this reason, nine positions were allocated to the teams that are not considered in the current ESA Concurrent Design and the experimental HMM ESA project. One of these positions was "Human Factors and Crew Performance".

To apply the IDP, the first step is to allocate the HF position to the design process. The SSDW was selected as the most suitable environment for the application of the IDP, particularly considering the allocation of "Human Factors and Crew Performance".

Table 5.2: Absence of HF in the concurrent design position at ESA.
ESA (ESA, 2007; Bandecchi et al. 2000; SSDW, 2009; Johansson, 2010)

Concurrent Design	SSDW IDP	ESA
Management Functions		
CDF Manager	v	v
Team Leader	v	v
Disciplines		
Cost	v	v
Communications System	v	v
Environment	v	v
Future Options and Developments	v	
HF/ Habitability	v	
Life Support (ECLSS)	v	
Operation	v	
Power System	v	v
Resource (In-situ)	v	
Radiation	v	
Risk/Safety	v	v
Robotics, Mobility &EVA	v	
Structures and Configuration	v	v
Thermal	v	v
Transportation & Logistics	v	
Outreach, PR and Marketing	v	
Index: x = concurrent design position. Acronyms: HF (Human Factors), IDP (Integrated Design Process), ESA (European Space Agency), SSDW (Space Stations Design Workshop).		

Team Training

The second one of the SSDW phases focuses on training. The acquisition and verification of knowledge was performed using a preparation work package, with an introduction, a suggested bibliography, and specific tasks in the field. The author, who had the duties of an HF tutor, had prepared the HF work package in order to apply the IDP to training, too (*Appendix G*).

The SSDW training of each team member was performed in his/her position with a specific tutor from the respective field. The members also had access to consultation and materials from the other fields, which guaranteed multidisciplinary support. In particular, during the workshop each field was presented with a specific lecture that was attended by all the team members.

At ESA, there is no HF position and as consequence, there are no specific skills requested for this position. At the SSDW, the HF position was asked to learn general HF skills applied to space missions (SSDW, 2010b).

In the IDP, the HF skills needed are:

- General HF knowledge
- Support of habitability factors
- User-centered approach
- Holistic methodology

Table 5.3: Mission goal and HF background (SSDW 2009, ESA, 2007; Bandecchi et al. 2000, Tutor's personal communications 2011)

Goal	SPACE MISSION	MOON BASE	ASTEROIDS MISSION
Design Process	ESA	SSDW-IDP	SSDW
Human Factors Training	The position is divided between the other engineering disciplines. There is only one team.	Habitability factors User-centered approach Holistic methodology	Safety, resilience, ergo-nomics, work conditions in a control room
Human Factors Background Team Blue		Architecture	Aerospace Engineer
Human Factors Background Team Red		Human Factors	Aerospace Engineer

In 2009, the HF positions were assigned to an architect from Paris in one team and to an HF student from Technische Universität Berlin in the other team. The two team members performed the requested task as described in a work package prepared in line with the IDP goals. The result shows a strong impact of the background field. In particular, the member with a background in architecture reported that humanistic disciplines, like philosophy, are related to HF, anticipating the IDP approach. Regarding the needs on long duration missions, the same member explained the relevance of going beyond mere survival: "able to innovate, improvise and develop to go beyond mere survival and predefined mission accomplishments". In contrast, the member with an HF background applied more of an HF engineering and less of a multidisciplinary approach. More bibliography was given to the HF team members to support the weak point that emerged with the task. This and the tutoring of the work resulted in the development of the skills required to support the IDP.

In 2010, the HF position was covered by two aerospace engineers. Classical training was performed focusing on HF as a quantitative domain but also supporting the habitability factors. No specific focus was placed on user-centered design and holistic methodology as during all the previous SSDW sessions (Messerschmid, 2008; SSDW, 2010 and 2010b).

Table 5.4: Skills requested for design with IDP, SSDW and ESA (SSDW 2009, ESA, 2007; Bandecchi et al. 2000)

SKILLS HF POSITION	ESA	IDP	SSDW
HF as Numerical Domain	v	v	v
Habitability Factors		v	v
User-Centered Approach		v	
Holistic Methodology		v	

Design Workshop

The design workshop lasted for one week.

The workshop was structured and planned to cover every skill needed for each position. Each tutor completed the field learning with a detailed presentation, assisted by all the teams, to guarantee the basic multidisciplinary knowledge requested. The HF presentation held in line with the IDP highlighted user experience, presenting different projects that integrate humanities and scientific disciplines to support the user-centered approach and holistic design.

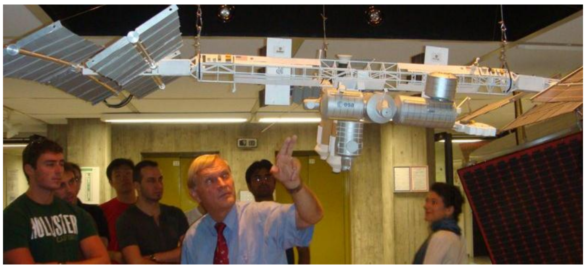


Figure 5.3: Examples of participatory design (right) and experience design (Left): Participatory Design: Prof. Messerschmid, in the picture under an ISS model, supports the workshop by contributing his experience as an astronaut. Experience Design: The designers experience the user condition by simulating a Soyuz-ISS docking (© SSDW2009).

Prof. Messerschmid as the director of the workshop and as an experienced astronaut supported both teams, guaranteeing the contribution of the astronaut perspective to the design, thus also supporting one of the IDP's core parts: the participatory design of the user. The IDP's empathetic design was also supported by letting the team members of the SSDW 2009 experience user conditions. For this, a Soyuz mockup from the IRS was available to perform a docking with a complete interface and environment simulation.

The concurrent design sessions united all team members in one room to apply the design of each field concurrently. Each field was represented by an Excel worksheet. In the room, each team member had access to a computer that shared all the worksheets. Just as in the Concurrent Design Facility at ESA, each modification of a worksheet influenced related fields supporting the relations between HMS elements. To execute the design, each discipline tutor was available to review each member's contribution. Also, a complete recipe (guideline) and requirement were given from each field to all members so that they were aware of the work of the others. After a preliminary phase during which the students worked on the worksheet, the more detailed development of the Moon base was performed by both groups holding discussions and creating posters. The final report was based not only on Excel worksheets, but also on descriptions and illustrations, leading to a more flexible, innovative, and complete project design.

Figure 5.4: Example of concurrent design with computer worksheet (right) and with paper sheet (left) (©SSDW2009)

The IDP was applied in particular to the HF design activity. The recipe and the requirements elaborated by the author for the "HF and Crew Performance" specialist are given (cf. *Appendix G*, *Table 0.20* and *Table 0.21*). The content is aimed to <u>support the astronauts' qualitative experience in the holistic design of the system elements and their relations.</u> The HF recipe and requirements apply the IDP, focusing in particular on the user experience given by the habitat.

Selection, Training and Design

In conclusion, the IDP process was applied in selection, training, and design. The summary in *Table 5.5* lists the issues presented so far.

In this table, we can see that the process was not applied sequentially, but rather covered all the different components of the IDP, unlike the standard SSDW approach and the ESA design process, as shown in *Table 5.6*.

Table 5.5: IDP application at the SSDW 2009

IDP PROCESS PHASES	USER-CENTERED DESIGN			HOLISTIC METHODOLOGY		
	User Experience	Participatory Design	Empathetic Design	Concurrent Design	Multidisciplinary Design	Human-Machine Environment inter.
1.	Selection					
1.1 Multidisciplinary and International Call					x	
1.2 Selection of the Participant Positions					x	
1.3 Composition of Teams					x	
2.	Training					

2.1 Acquisition of Field Knowledge	(only HF)	x	x		x	x
2.2 Multidisciplinary Learning	x	x	x		x	x
3.	Design					
3.1 Space Station Concurrent Design	(only HF)	x		x	x	x
3.2 Support with Guideline	(only HF)			x	x	x
3.3 Cooperation of Tutors	x	x	x	x	x	x

Table 5.6: IDP and ESA (ESA, 2007 & 2011b; SSDW, 2009; Bandecchi et al. 2000)

IDP APPLICATION										
	HF HABITABILITY FACTORS				USER-CENTERED APPROACH			HOLISTIC METHODOLOGY		
	Operational	Physiological	Psychological	Socio-Cultural	User Experience	Participatory Design	Empathetic Design	Concurrent Design	Multidisciplinary Design	Human-Machine-Environment Interaction
IDP	v	v	v	v	v	v	v	v	v	v
ESA		v						v		
SSDW		v	v			v		v	v	

5.1.2 SSDW Design Solutions

The IDP habitat system results were published in the final report (Messerschmid, 2009). This report presents the habitat system summary and the HF contribution. In 2009, the HF contribution was compiled by the author on the basis of the HF team members' work on the habitability factors. The final result shows the concurrent multidisciplinary design of the system part and their relation supporting the HMS and taking into account the user needs.

Habitat System

Team RED: Team RED decided on a lunar surface installation at the near side eastern limb, north of Mare Fecunditatis, due the accessibility and anytime return capability for transportation as well as constant and direct Earth communication and visibility. The proximity to the limb and the far side might also allow for exploration of far side locations once extended mobility capabilities are installed. Dictated by the site selection, a major challenge of the design is the energy management during long and repetitive darkness periods in extended surface operations. The lunar base of team RED provides habitation and utilization for a crew of four astronauts in four pressurized modules. At assembly the complete base concept comprises: one service module as central connecting node, an initial habitat for early crew accommodation, an extendable habitat for long-term habitation, a laboratory element, an extendable storage and supply module. The primary structure is a monologue composite pressure shell, to which a 60 cm regolith cover is applied robotically for radiation and micrometeorite protection. At a later stage of the infrastructure development, the team also outlined the addition of an inflatable pressurized module to increase utilization and habitation volume of the base. Mobility and utilization aspects are enhanced by a set of robotic assets such as a large rover platform with pressurized cabin, small scouting robots as well as cargo carrying EVA assistant platforms (Messerschmid, 2009).

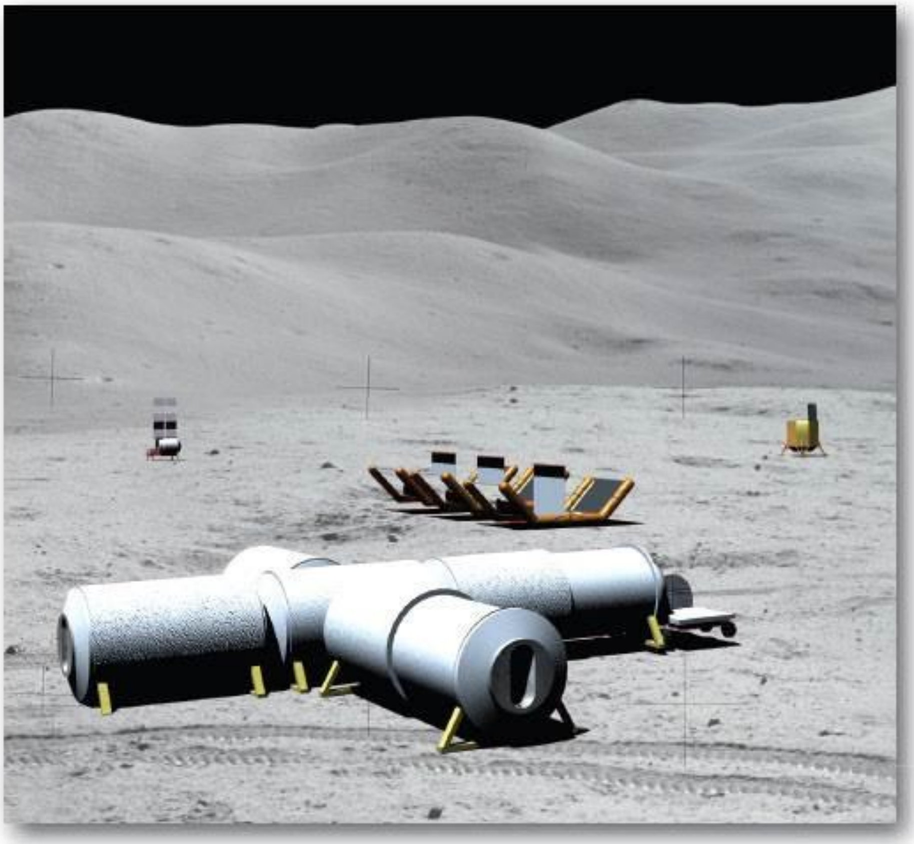


Figure 5.5: SSDW-IDP LunoX, Team Red Moon Base (SSDW, 2009)

Team BLUE conceptualized and assessed a concept in the South Pole area in the vicinity of the Shackleton crater rim. Promising solar illumination for more than 95% of the time, the infrastructure can profit from the benign environmental conditions as well as from the interesting surface features in the proximity of the base, while adequate means for continuous Earth communication are more challenging. The abundance of energy as well as considerations on extensive utilization, human interaction, and Mars forward planning led to the selection of a nominal crew of six astronauts at the polar site. The base core consists of four pressurized modules with associated connecting nodes and airlocks in a racetrack configuration. The initial habitat is a rigid full cylinder module that will be partially buried in the lunar ground and covered by a regolith layer of up to 2 m to ensure long-term radiation and micrometeorite protection. Including an attached airlock/node assembly, this initial module allows for habitation of a crew of two astronauts very early in the program. The other three pressurized elements are half-domed cylindrical modules with a diameter of 7.4 m and a length of 9.5 m. Together with the node elements they complete the full core base configuration and provide further habitation and common areas for four astronauts, a laboratory, and storage space. Assembly and utilization phases of the base are supported by three redundant mobile elements, namely six-legged heavy lift vehicles for unloading and cargo transportation, unpressurized mobile crew platforms, and small robotic rovers for inspection and servicing tasks (Messerschmid, 2009).

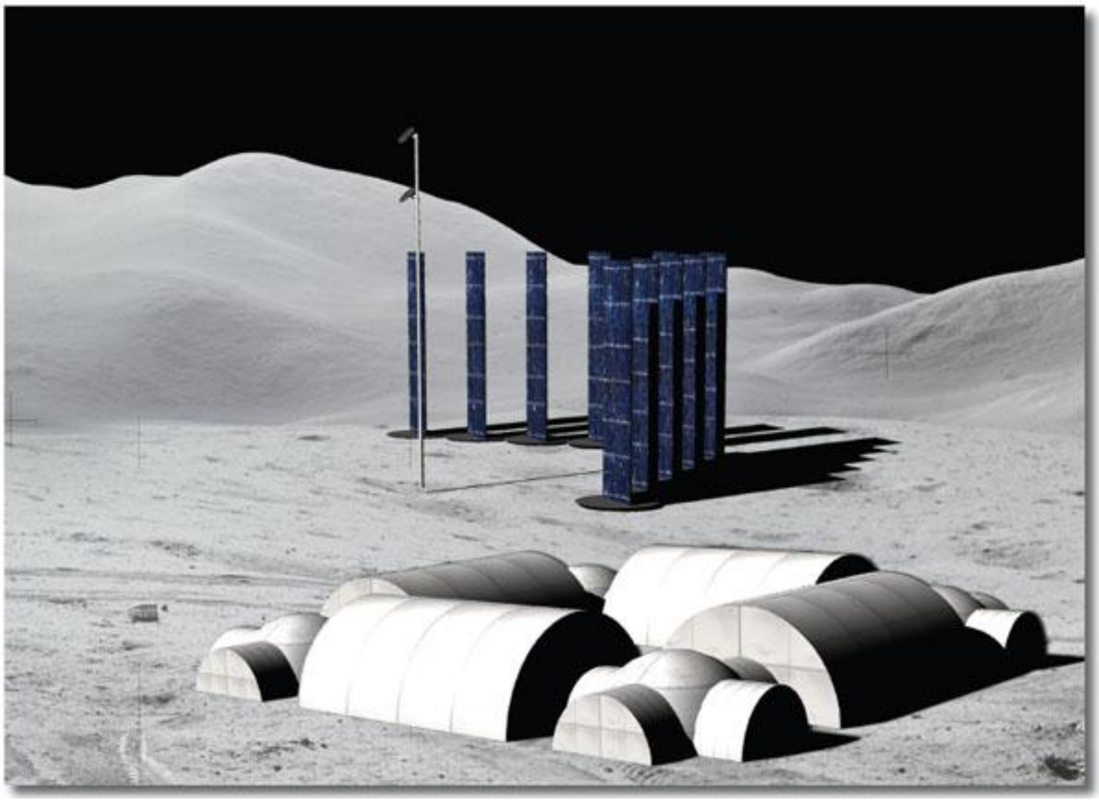


Figure 5.6: SSDW-IDP Loretta, team blue´s Moon Base (SSDW, 2009)

Habitability Solutions

In the HF contribution, aspects related to user experience are approached and solved more in detail, fully applying all of the IDP methodology and approach. User experience, in particular, is supported taking into account the HME relation:

Human Factors team Red: Human Factors Engineering is essential in the design of long duration surface infrastructures, where an ideal habitat system should support human´s experiences allowing the active gain of further knowledge. While the allocation of windows was disregarded for safety and cost reasons, many creative ideas and the use of modern technology has been introduced to avoid the psychological and functional problems of confined space and outward visibility. The walls between crew quarters and walkways are made of "liquid crystal intelligent glass" to simulate windows.

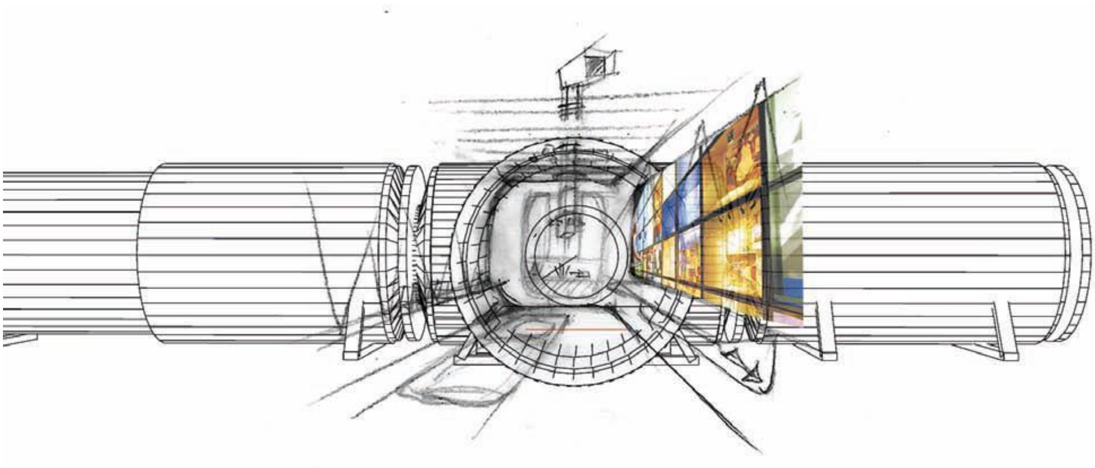


Figure 5.7: SSDW-IDP Liquid glass to simulate windows in Loretta, Team Blue Moon Base (Leonard Boeldieu, SSDW, 2009)

In crew quarters, the use of periscopes supports an individual place of exploration and spiritual and meditative dimension. Light colours and intensity can automatically change for day/night simulation or animation. Floors are flexible to allow for increased comfort of movement and relaxation. The "Camera Obscura" provides a really innovative idea, where little holes in the wall of a dark module sealed with lenses will create the inverted projection of the external environment. The crew quarters are distributed in two highly personalized habitation modules, also featuring personal communication centers based on augmented reality foldable touch screens. The composition of the four crews is assumed to comprise a commander (pilot & management), an engineer (pilot & servicing tasks) and two scientists (research), where gender mix is possible for psychological balance. The crew timeline for working days is distributed as shown below. One free day per crew and week is envisioned in accordance with the activity schedule. Crew operations will be more extensive during lunar day (Messerschmid, 2009).

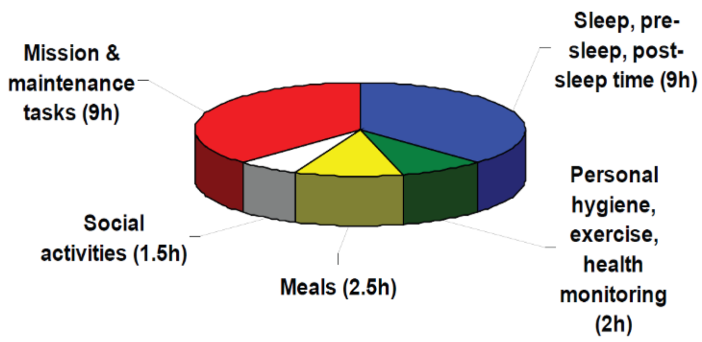


Figure 5.8: Time schedule in Loretta, Team Blue Moon Base (© SSDW, 2009)

Human Factors team Blue: Human Factors become notably important when considering crew surface stays of 180 days and more. Thus, human experience and human-centered design has to be combined with latest technology developments. The racetrack configuration of the lunar base reflects historical human dwellings and creates a feeling of safety against a potential harmful environment, supporting psychological well-being. Local materials are used to protect the base from radiation, with regolith covering reaching up to about 2 m. In the interior, dynamic multi-purpose furniture, ambient lighting and quarter`s walls folding systems, allow each person to be an active creator of his/her own place and space, providing the possibility to arrange the modules in almost countless combinations. This configuration also provides an effective guard against boredom and depression due to monotony. The six crew quarters provide 11 m^2 (27 m^3) each and are distributed in the two habitation elements (Messerschmid, 2009).

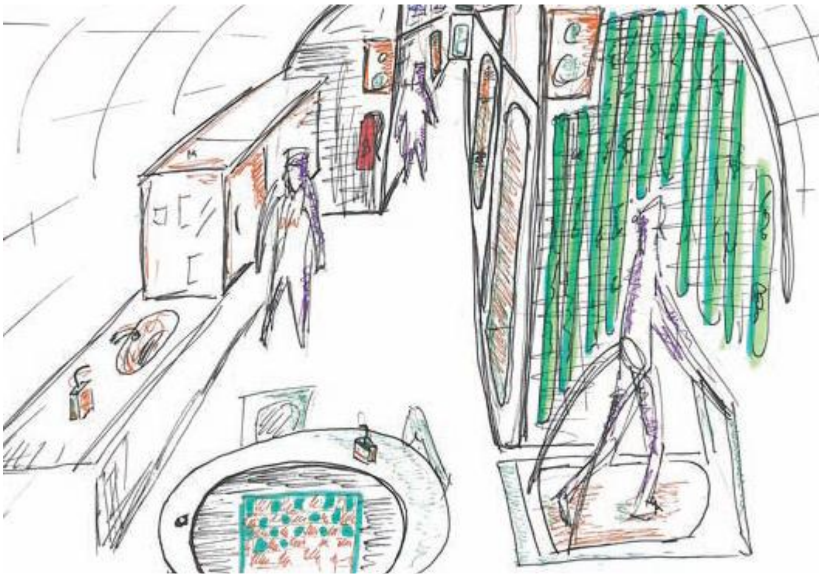


Figure 5.9: SSDW-IDP Habitability aspect of Loretta (Jan Grippenkoven, SSDW, 2009)

Overall System Evaluation

The final phase of the workshop was the evaluation of the two projects in competition. "Throughout the design phase the team members gain considerable insight and experience in their respective fields of expertise and the available technologies, constraints and complexities" (Messerschmid, 2009, p. 20). Considering also that they had the greatest knowledge of their own project, the same team members were subsequently invited to directly evaluate the final design concepts as committee members. The original teams were disbanded and the participants were assigned to one of seven evaluation committees related to their role in the design phase. In the committees, they discussed and evaluated their solutions and approaches taken. The evaluation committees were:

1. Utilization and Programmatic
2. Overall Configuration
3. Mission Design
4. EPS/TCS Subsystem Issues
5. ISRU and Robotics Subsystem Issues
6. Human Aspects
7. Operations and Servicing

The final overall evaluation report showed a positive feedback: "The elaborated lunar base concepts show a sophisticated work in all major aspects of conceptual design and meet the objectives and requirements issued in the Mission Statement. The difference in site selections and system approaches allow an interesting comparison of the solutions" (Messerschmid, p. 20).

The HF design solutions were evaluated in the Human Aspects committee in conjunction with life support and radiation protection design solutions. The following was reported by the students:

> The Human Factors considerations can hardly be captured quantitatively, and different approaches have been implemented in both teams. Aspects such as crew composition, operational timelines, interior design, zoning, and recreational activities were assessed, where Team BLUE received slightly higher score from the participants (Messerschmid, 2009).

Table 5.7: SSDWISP Moon Bases results comparison (Messerschmid, 2009, p. 22)

General Aspects	**Team RED (LunoX)**	**Team BLUE (LOReTTA)**
Location	0.8N, 60E (Equatorial)	89.5S, 135W (South Polar)
Crew size	4	6
Number of pressurized base elements	5 (central service, 2 habitats, laboratory, storage)	8 (2 habitats, laboratory, storage, 4 nodes)
Number of flights	11 for assembly 2 crew, 2 cargo per year for operations	19 cargo, 14 crew flights during 8 year assembly & operations
Estimated program cost	45.6 B€	65.2 B€
Subsystems		
ECLSS	Hybrid (closures: 90% water, 80% air, 20% food)	Hybrid (closures: 95% water, 100% air with ISRU, 21% food)
ECLSS Logistics	1.7 t per crew mission	1.6 t per crew mission
EPS	Nuclear fission: 100 kW Backup systems. PV, RFC, Li-Ion	PV arrays: 74.7 to 149.3 kW RFC: 200 kWh
TCS	Double redundant fluid loops with compressors, heaters, 3 shaded vertical condensing radiators	Redundant pumped fluid loops, heaters, 5 flat condensing radiators
Radiation/micrometeorite protection	0.6 m regolith cover	1.5-2 m regolith cover
Communication System	S-/Ka-band direct to Earth, 50 Mbps	S-/Ka-band, relay antenna on Malapert Mt., up to 200 Mbps

5.1.3 SSDW Result Validation

A more profound evaluation was performed regarding the logic of the IDP application. Taking into account each IDP element, it was verified that the entire methodology and approach had been supported and that innovative ideas for increasing habitability had been obtained.

IDP Verification

Different kinds of foci were applied. Multidisciplinarity and concurrent design of the team turned out to be the most relevant methodology supported by the workshop with the participatory design approach. However, the HF results show innovative solutions for increasing habitability in line with the IDP methodology.

Table 5.8: IDP Application at SSDW 2009

SSDWIDP 2009			
IDP		SSDW 2009	Focus
HF METHODOLOGY		Applied by the whole team	Dark Gray
HME	Holistic approach	Design solution with correlation between the fields	Gray
MD	Multidisciplinarity	Team composition (selection and training)	Dark Gray
CD	Concurrent contributions	Team working concurrently	Dark Gray
UCD APPROACH		Support from the whole team	Gray
PD	User in the design	Astronaut Prof. Messerschmid as workshop director	Gray
UE	Qualitative dimensions	Multidisciplinarity contribution to support user experience within the HF and also in the other disciplines	Dark Gray
ED	Simulate user	Soyuz experience	Gray
Index: Dark Gray= Full focus; Gray = Partial focus, White= Considered			

Result Verification

In order to verify the IDP results, the following question had to be answered: Does IDP increase habitability? To answer this question, the final results were compared with the SSDW 2010, where the IDP was not applied. The comparison was made on the basis of the final report, where only the key elements of the project were reported. It needs to be mentioned that the SSDW is an innovative method that supported the quality of the project from the start. In comparison with the ESA project, the SSDW allocates different specialties such as HF, is more flexible, has multidisciplinary learning, and allocates descriptive variables. In 2009, the project focused on habitability support with the IDP, introducing the dimension of habitability, the user-centered approach, and the holistic methodology.

The differences that emerged are:

- The IDP HF has its own section and is not incorporated into Life Support.
- The IDP sections address usability, livability, and flexibility topics.
- The IDP sections use a multidisciplinary approach to all habitability factors.

Table 5.9: Comparison between SSDW 2009 and 2010

	SSDWIDP 2009		SSDW 2010	
Goal	Moon Base		NEA (Near Earth Asteroids) Mission	
Statement	Flexible, sustainable, and extendable mission architecture for a human mission scenario based on an international exploration concept			
Team	BLUE	RED	BLUE	RED
Mission Duration	More than 180 days	More than 180 days	139/365	180/317
Crew	6	4	3	3

SSDW 2010 Team Blue HF

> The interior design of the mother vehicle provides a very low degree of isolation, but since there are only three crew members, isolation is not a major issue. The compartments are arranged keeping human factors engineering at its core and allocating open compartments for minimal confinement. The daily crew schedule allots 8.5 hours for work, including planning and coordination as well as daily systems operation tasks. Another 8.5 hours are allowed for sleep. The remaining time is used for exercise, meals, and personal hygiene.

SSDW 2010 Team Red HF

> Human factors issues include suitable zoning of the spacecraft interior and proper color and illumination schemes as well as ergonomic work stations. The zoning allocates areas for social, private, and work activities. A crew social structure is proposed, as one astronaut serves as the commander, whereas the other two crewmembers have an equal standing in the hierarchy. From the professional point of view, the crew is made up of a pilot, a scientist, and a robotic controller. Coming from a military background, the pilot also acts as commander of the spacecraft. The crew schedule is arranged in a “round robin” format, a rotating schedule that allows alternating rest and work phases for the individual crewmembers. The crew works ten-hour days during the week and five-hour days on weekends. Eight hours are allocated for sleep and the remaining time is available for exercise, leisure, and social activities. Exercise equipment on board includes the Advanced Resistive Exercise Device (ARED) and a COLBERT treadmill & vibration reducing rack. Both enable µg countermeasures. In total, the human factor equipment accounts for a mass of 1.8 t, comprising hygiene items such as towels and clothing, medical devices, and exercise equipment.

The comparison was based on the Häuplik-Meusburger variables: usability, livability, and flexibility, and on the support of the habitability factors: physiological (Hf_p), operational (Hf_o), psychological (Hf_{ps}), socio-cultural (Hf_{sc}). The results of the two groups were analyzed individually (see *Appendix H*), then grouped according to methodology and compared.

While the IDP applied all the elements of the user-centered approach and the holistic methodology to the process, the validation group was based only on two elements: concurrent and participatory design.

Table 5.10: Results Comparison (SSDW, 2010)

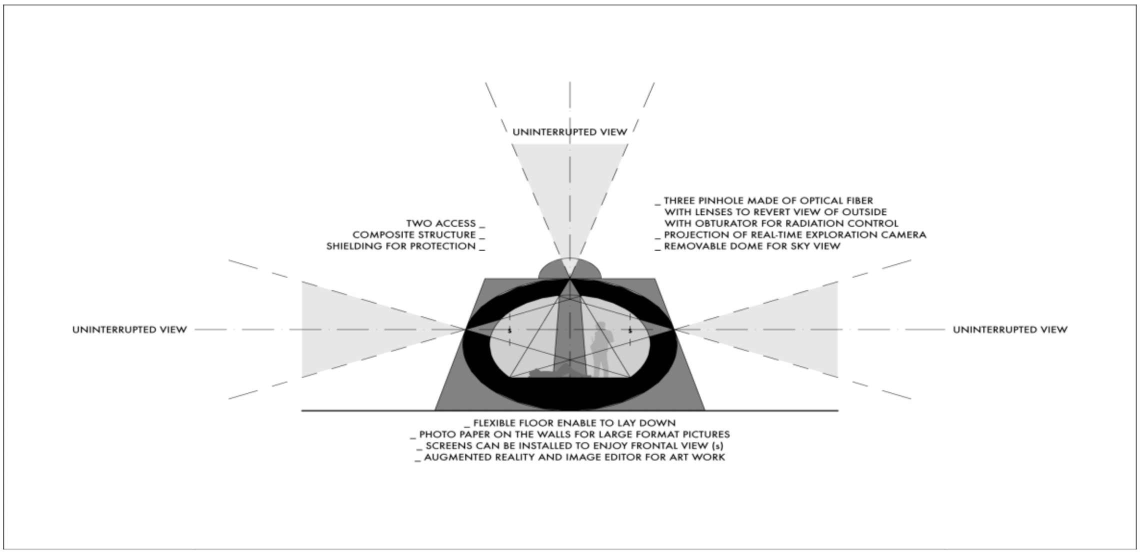
		IDP (SSDWIDP 2009)					VALIDATIONS GROUPS (SSDW 2010)			
	FACTORS	KEY ELEMENTS	Usability	Livability	Flexibility	FACTORS	KEY ELEMENTS	Usability	Livability	Flexibility
		MOON BASE					NEAR EARTH ASTEROIDS MISSION			
Human Factors	All	Human Factors is relevant	v	v	v	Hfp	Quantitative dimension			
Innovation	All	Technology and innovation to support human	v	v	v		Not described			
Configuration	All	Consideration on: Innovative solution Social anthropology, Safety feelings, Variability, Radiation shielding, Comfort, Relation with the external environment	v	v	v	Hfp Hfps	Consideration on: Equipment Social isolation	v		
Interior	All	Consideration on: Innovative solution Personalization, Variability, Psychological support, Habitable volume Privacy	v	v	v	Hfp Hfo Hfps	Consideration on: Dimensional confinement Zoning Equipment Physiological health	v	v	
Crew	All	Consideration on: Hierarchy Skills Psychological balance Gender mix	v	v	v	Hfps	Consideration on: Hierarchy	v		
Schedule	All	Consideration on: Innovative consideration Environmental constraint Flexibility	v	v	v	None	Consideration on: Work quantity	v		
Habitability Factors	All	**New sustainable technologies and solutions for habitability**	6/6	6/6	6/6	Hfp	**Absence of new technologies and solutions for habitability**	4/6	1/6	0
User-Centered Approach		User experience Participatory design Empathetic design					Participatory design			
Holistic Methodology		Multidisciplinary design Concurrent design Human-machine-environment interaction					Multidisciplinary design Concurrent design			

Table 5.11: Habitability Factors Results Validation (SSDW, 2010)

	SSDW-IDP				SSDW				Astronaut Interview			
	Operational	Physical	Psychological	Socio-Cultural	Operational	Physical	Psychological	Socio-Cultural	Operational	Physical	Psychological	Socio-Cultural
Usability	v	v	v	v	v	v			x		x	
Livability	v	v	v	v				-	x			x
Flexibility	v	v	v	v			-				x	
Innovation	v											
Tot	All the factors are supported in each part of the project plus Innovation				Factors considered more than 50% of time in the project				Problems selected in the user analysis (cf. *section 3.1.1*)			

The results show that the human factors contributions, from the IDP and the validation groups, focus on the topics of human factors, innovation, configuration, interior, crew, and schedule. The IDP groups found sustainable technologies and solutions for habitability considering all the factors. The validation groups did not find any innovative solution and supported mainly the physical factors, not considering the socio-cultural ones and the flexibility dimension. This is a relevant gap, considering that flexibility and the socio-cultural dimension are elements already underlined as being a current problem from the user analysis, and also taking into account that these two dimensions are the ones that will become more relevant in the long duration and long range scenarios presented here. Moreover, the validation groups aimed at the maximum utilization of the human as a resource, without scheduling any rest day, while the IDP group aimed at the conceptualization of an ideal habitat system that supports human experiences and allows the active gain of further knowledge.

> Mankind, with the target in mind to settle down on the moon, should not only rely upon the latest technology, but also on the experience of the entire human existence (Jan Grippenkoven and Irene Schlacht communication, September 2009).



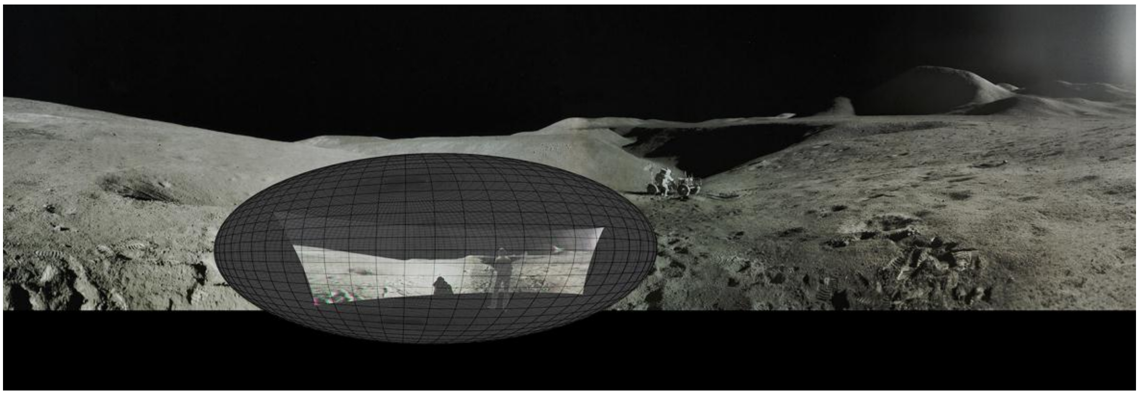


Figure 5.10 & 5.11: SSDW-IDP LunoX Moon Base camera obscura: Little holes in the wall of a dark module sealed with lenses will create the inverted projection of the external environment, with sky and EVA (SSDW 2009, Leonard Boeldieu).

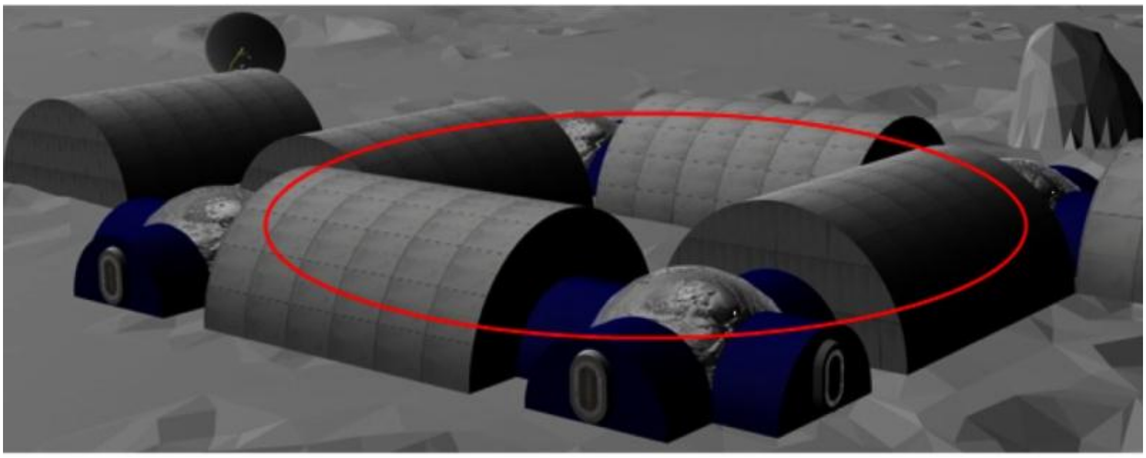


Figure 5.12: Moon Base Team Blue SSDWIDP 2009. This configuration, used also by the ancient Romans and by nomadic populations until today, creates a feeling of safety against a potentially harmful environment, supporting psychological well-being.

5.2 MDRS

The aim of the second IDP study was to perform research on human aspects for future extra-terrestrial planetary exploration during a mission simulation at the Mars Desert Research Station in Utah (USA). The results, when compared to the study from the previous year, revealed that problems related to both the working and living conditions were tackled, that a complete analysis of habitability challenges was supported, and that the opportunities for personal and creative experiences were increased.

Terrestrial analog studies are used to prepare for future planetary Lander missions (Foing et al. 2011b). With the Moon being approximately 380,000 kilometers from Earth, the Mars Desert Research Station (MDRS) in the San Rafael Swell of Utah is the most accessible analog to a Moon-Martian habitat. The MDRS on Earth provides a testing environment for experimentation in extreme and isolated situations (Schlacht, 2010). The MDRS is a facility for testing technologies, methodologies, and protocols, for training instrument and operation teams, and for understanding astronaut mission scenarios (Foing et al., 2011).

This subchapter presents HF research applied to Mars mission simulations in analog environments.

The research was performed using the IDP methodology on Moon-Mars mission simulations in analog environments. It was performed during the EuroMoonMars mission campaign (supported by ILEWG, ESA, SKOR, Mars Society) by crews 92 and 94 in February 2010 and by crews 100a and 100b in 2011, and has been proposed for the campaign of 2012. The research results and the methodology are compared with the HF research performed (without applying the IDP; supported by ILEWG, ESA, NASA Mars Society) during the EuroGeoMars mission campaign by crews 76 and 77 in February 2009. The results from 2010 presented here have been published in Schlacht et al., 2010c and 2010b; the results from 2011 are in the process of being published; and the results from 2009 were published under Thiel et al. 2011.

5.2.1 MDRS Research Process

The project based on the IDP methodology performed at the MDRS in 2010 and 2011 was called the “Moon-Mars Habitability project”; it is identified here by the acronym MDRS-IDP. The project performed without the use of the IDP methodology at MDRS 2009 was called “Human crew-related aspects for astrobiology research”; it is identified here by the acronym MDRS-HC (Schlacht et al., 2010; Thiel et al., 2011).

Research Structure

The MDRS-IDP and MDRS-HC projects have the same goals and constraints:

- Goal: Research “technical and human aspects to prepare for future extra-terrestrial and planetary exploration” (Thiel et al., 2011).
- Constraint: Perform the research during the two-week Mars mission simulation at the MDRS facility in Utah (Schlacht et al., 2010; Thiel et al., 2011).

Both projects are composed of two main parts:

- HF investigation
- Field experiment

However, different methodologies are used.

While the MDRS-IDP research is based on all of the IDP elements, the MDRS-HC was based only on some of these. In both cases, the research was performed by involving the researcher in the simulation as a crew member and asking the crew about problems and possible solutions. This supports both the participatory and the empathetic design. Also, the human-machine-environment interaction is strongly considered in the MDRS environment. Regarding the research, while the MDRS-HC focused more on operational and physical factors, the MDRS-IDP aims at supporting all the factors that affect habitability, including psychological and socio-cultural ones.

Table 5.12: Comparison between the MDRS-IDP and MDRS-HC

	HF HABITABILITY FACTORS				USER-CENTERED APPROACH			HOLISTIC METHODOLOGY		
	Operational	Physical	Psychological	Socio-Cultural	User Experience	Participatory Design	Empathetic Design	Concurrent Design	Multidisciplinary Design	Human-Machine-Environment Interaction
MDRS-IDP	v	v	v	v	v	v	v	v	v	v
Focus	HF investigation				HF investigation Field experiment Research process			Research process		
MDRS-HC	v	v				v	v			v
Focus	HF investigation				HF investigation Field experiment			Project design		

Research Methodology

The IDP on-going project investigates sensory perception and creativity for human planetary exploration missions with the main goals of improving the well-being and productivity of the astronauts, and supporting situational awareness and problem-solving skills during the mission.

In the context of habitability analysis, the crew's daily life, social dynamics, schedule, and daily attitude are also recorded and investigated. The methodologies include instruments, questionnaires, interview techniques, and direct and remote behavioral observation.

The research methodology covers all the elements of the user-centered approach and holistic methodology.

The first step of the research, based on previous research about long duration mission needs, consists of the selection of a multidisciplinary team of experts from the field. The team works together and concurrently from different locations using the Internet, analyzing the problems and proposing solutions, and carefully considering the human-machine-environment scenario. This first part, which is mainly organizational in nature, applies the holistic methodology particularly intensively, while the user-centered approach is applied more intensively in the second part. The second part of the research focuses on the performance of the experiment and the collection of data during the Mars mission simulation. The researchers are part of the team and take part in the simulation as simulating astronauts, supporting in particular the empathetic design principle.

Table 5.13: IDP Research Process apply on MDRS

MDRS-IDP RESEARCH PROCESS	USER-CENTERED APPROACH			HOLISTIC METHODOLOGY		
	User Experience	Participatory Design	Empathetic Design	Concurrent Design	Multidisciplinary Design	Human-Machine Environment Inter.
1. Design of the Project						
1.1 Selection of experts from Extreme-Design Research group based on LDM user-needs analysis. The group is composed of: - Multidisciplinary experts - Internationally located - Experts on the space human-machine-environment scenario					v	v
1.3 Group works concurrently and simultaneously on the project from different locations via: - Skype conferences - Gmail document sharing facility				v		
1.2 Problem analysis based on: - Interviews with astronauts and mission simulation crew* - Discussion of problem solutions by the mission simulation crew - Human-machine-environment simulation scenario		v				v
2. Performance of the Project						
2.1 Focus on supporting the user experience	v					
2.2 Execution of the experiment by the crew of the Mars mission simulation*		v				
2.2 Experimenter participation in the Mars mission simulation			v			
COVERED ASPECTS	v	v	v	v	v	v
(*) To apply IDP for future scenarios, it is fundamental to consider analog missions and mission simulations. Indeed, Mars has not been reached by any human mission; we have no Mars astronauts and Mars station where to test the experiment. LDM= Long Duration Mission						

Research Scenario

The MDRS was selected to verify the IDP user-centered approach with the Moon-Mars Habitability Project. As part of the user-centered approach, empathetic design is based on the idea that in order to design habitability for space missions, you need to personally experience the user condition - you need to know it, test it, try it, feel it, and do it. The mission simulation at the MDRS provides not only an opportunity to experience the user condition regarding the principle of empathetic design, but also constitutes a perfect platform for the investigation of HF and habitability with the overall IDP methodology (Schlacht, 2010).

The MDRS is an analog station that is located in the desert of southern Utah, USA, near Hanksville. “The station’s centerpiece is an 8m-diameter “Habitat”, a two-deck structure mounted on landing struts, peripheral external structures, such as a small greenhouse and a small telescope facility”. The MDRS serves the “analog astronaut” crews of the MDRS-IDP and MDRS-HC projects as research locations. The habitat is a cylinder with a diameter of 8m, 6 m high, and has two floors, the lower and the upper deck. The lower deck includes a laboratory area, two airlocks, hygiene facilities/toilets, EVA-suit storage, and a small workshop. “The upper deck (command deck) comprises sleep bunks, the kitchen area and the stations computers (including the satellite communication equipment, the remote operation computers for the telescope, etc…), a small library and medical supplies. A fictional satellite provided direct communication with “Earth” including a 10min time delay and reduced bandwidth” (Grömer, 2006 p. 36).

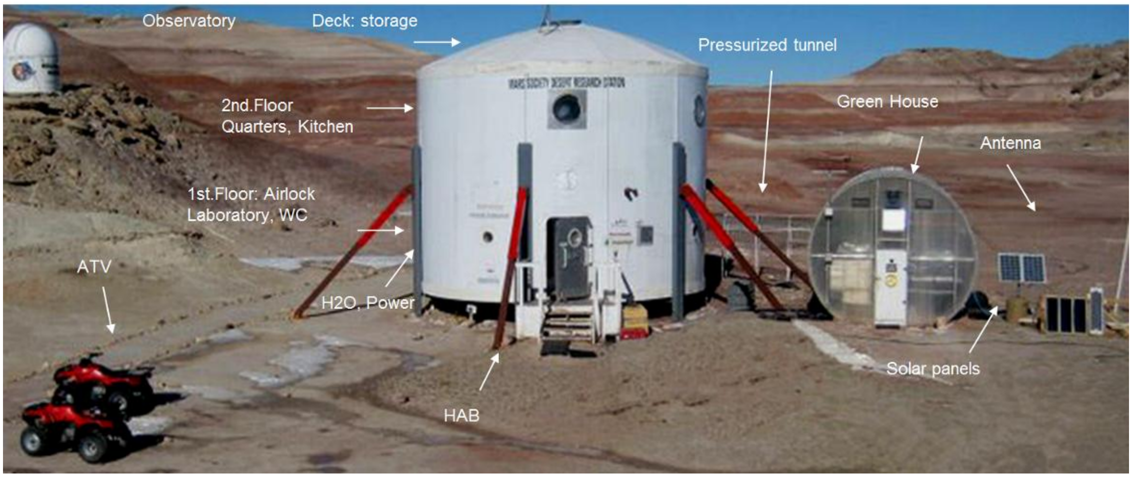


Figure 5.13: MDRS structure (computer manipulated photo based on photo by Mars Society)

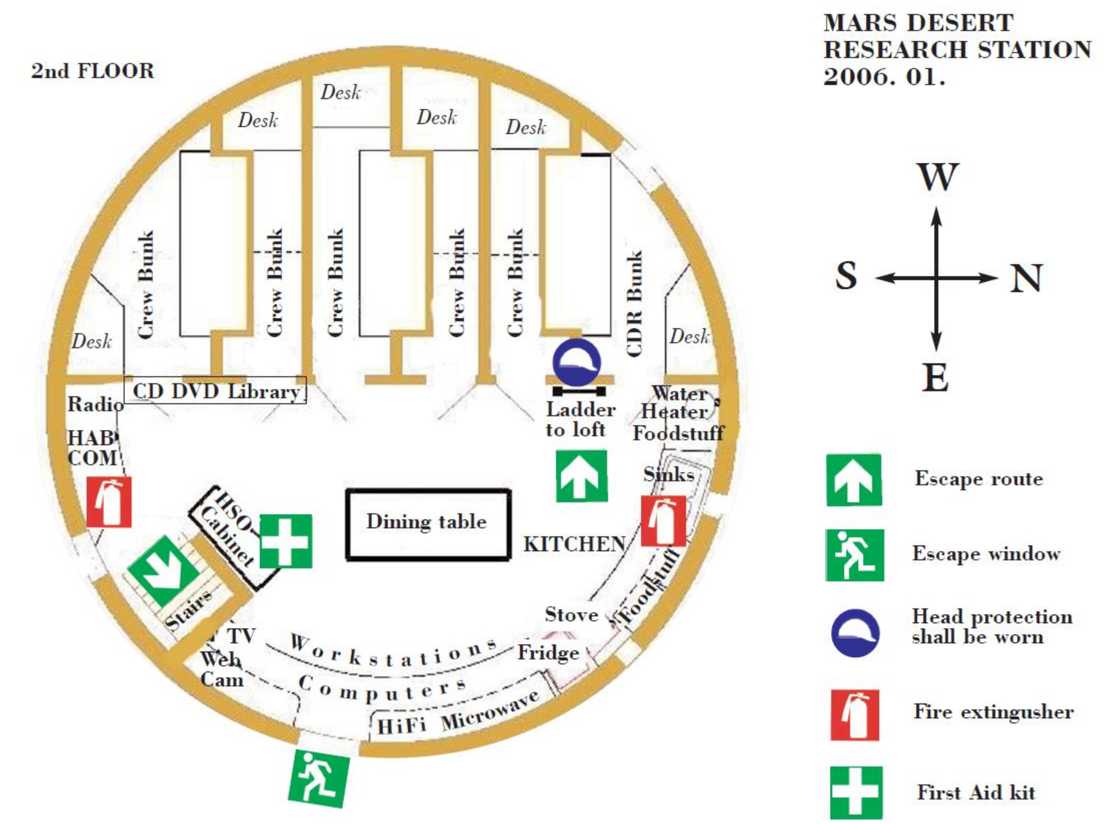


Figure 5.14: Upper deck (design by Henrik Harfitai for Mars Society MDRS Guide, published in Grömer, 2006)

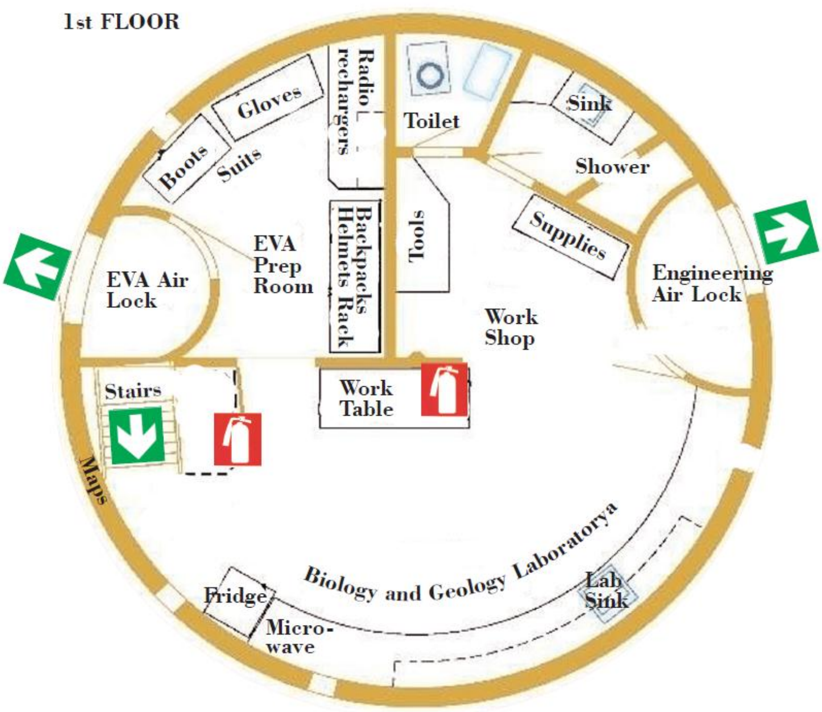


Figure 5.15: Lower deck (design Henrik Harfitai for Mars Society MDRS Guide, published in Grömer, 2006)

The simulation is made to resemble a Mars mission as closely as possible by confining the crew in the habitat without any direct contact with the outside world and by conducting field activities in EVA (Extra Vehicular Activities) or IVA (Intra Vehicular Activities) mode depending on the specific goals of the field activities. The EVA expeditions simulation is conducted wearing unpressurized EVA space suit simulators and following EVA rules and protocols, with a delay in radio communications, self-autonomy at all stages, etc. (Thiel, 2011).




Figure 5.16, 5.17, 5.18 & 5.19: I.L. Schlacht during Extra Vehicular Activity preparation and performance at MDRS (2010).

The IVA are the working and living activities. IVA social activities are done in the group. The crew takes their meals together, during which outings and crew activities are planned, briefed, and debriefed. Other team activities are conducted in the evening, such as seminars, presented by each crew member in turn, watching DVDs, listening to music, or performing physical exercise activities. All chores are shared equally, meaning that each day, one or two different crew members are in charge of preparing meals and taking care of kitchen chores. Other specific tasks needed to maintain the station are shared according to the crew members' skills. Water usage is restricted for personal hygiene (on crew 94, for example, showers were allowed every four days and for 3-4 minutes; the shortage of water caused a shortage of flushing water for the toilet).

5.2.2 MDRS Research Results

This section presents the results of the MDRS-IDP. The habitability research was performed with the main idea of testing the experiment in a short duration mission to improve the procedure and to be able to propose the experiment in a long duration mission simulation. The secondary purpose was to increase the awareness of HF relevance in the field. For this reason, the research process and methodology are part of the results. The methodologies used include the performance of tasks, questionnaires (POMS, AttrakDiff, and others), interviews, AVA-IVA and social behavior analysis, performance tests (NASA TLX), heart rate measurement, and collective debriefing. The Mars Habitability Project is continuing in the EuroMoonMars-2 and 3 missions. In this report, preliminary results are presented; the final results will only be available at the end of the EuroMoonMars campaign. The MDRS-IDP focuses on:

- Habitability experiment: sensory stimulation and creative performance
- Habitability analysis: crew behavior observation, crew collective debriefing on habitability problem analysis, and solution hypothesis.

TOPICS	MAIN INVESTIGATION TECHNIQUE				
	Experiment	Questionnaire	Interview	Observation	Collective Debriefing
Creative performance	v	v		v	
Sensory experience	v			v	
Habitability (IVA-EVA)	v	v	v	v	v
Behavior / Mood	v	v	v	v	

Table 5.14: Mars habitability project topics and investigation techniques.

Habitability Experiment

One of the possible problems in the future scenario of long duration and long range missions is the sensory monotony and autonomy. Sensory experience and creative activities are proposed here as countermeasures to this problem (cf. *section 3.1.3*).

- Experiment Design

The experiment design process has the following structure, concurrently applied by the Extreme-Design multidisciplinary team:

1. Analysis of the scenario and identification of user problem: sensory monotony and user autonomy
2. Solution hypothesis: sensory stimulation and creative performance
3. Selection of sensory stimulation and creative activity based on the literature
4. Experiment design and preparation of sensory stimuli
5. Experiment execution
6. Result verification and publication

- Hypothesis

The experiment on sensory experience and creative performance was based on the following hypotheses:

(1) Sensory experiences are needed in long duration missions to maintain active brain activities to fight mental drowsiness, and to support the active experience of the astronaut dur-

ing the mission (cf. *section 2.2.3*, part *Sensory Monotony and Variety* and *section 2.2.4*, part *Countermeasures*).

(2) Creative activities are needed in long duration missions to increase creative performance applied to problem solving, as a psychological countermeasure, and as a possible cultural activity (cf. s*ection 2.2.1*, part *Creative Performance*; *section 2.2.4*, part *Countermeasure*; s*ection 3.2.3*, part *Gap: Humanities Contribution* and part *Gap: Humanities Application*).

- Experiment Execution Procedures

Sensory stimuli, such as displays and visual interaction with colors, tactile interaction with plants, auditive interaction with sounds, and olfactive interaction with fragrance samples were selected and prepared by specialists to be investigated during the experiment. An additional neutral stimulus was prepared as validation measurement. During the experiment, focused tasks on creative activity and mood analysis were used to measure the effect of sensory stimulation on creative performance and well-being. Separate from the sensory stimulation experiment sessions, a dedicated creative expression activity was performed by the author as art therapy and cultural utilization of the place (details are reported in *Appendix I*). On different days, one of the five experimental sessions lasting 30 minutes each was performed in random order by each member until the completion of the five sessions. Numerical and descriptive variables were collected as quantitative and qualitative data during the mission simulation from crews 91 and 94 as well as 100a and 100b. The experiments with crews 100a and 100b coordinated by Ayako Ono from Tohoku University in Japan are currently undergoing analysis. The results are based on the data of 12 simulated astronauts from crews 91 and 94 coordinated by the author. The crew data are: Crew 91 - international, mixed gender, multidisciplinary, aged between 20 and 35; Crew 94 - Belgian, mixed gender, multidisciplinary, aged between 20 and 35 (details are reported in *Appendix I*).

- Results

The tasks stimulated sensory activity, creativity, and well-being. These factors were evaluated as being relevant for the success of long duration missions where a monotonous, non-stimulating environment may lead to mental drowsiness. The stimuli were felt to be a relevant factor for LDM; fragrance variation, in particular, had the strongest effect and was considered relevant to habitability. This is of interest in light of the current odor neutrality requirement for the ISS.

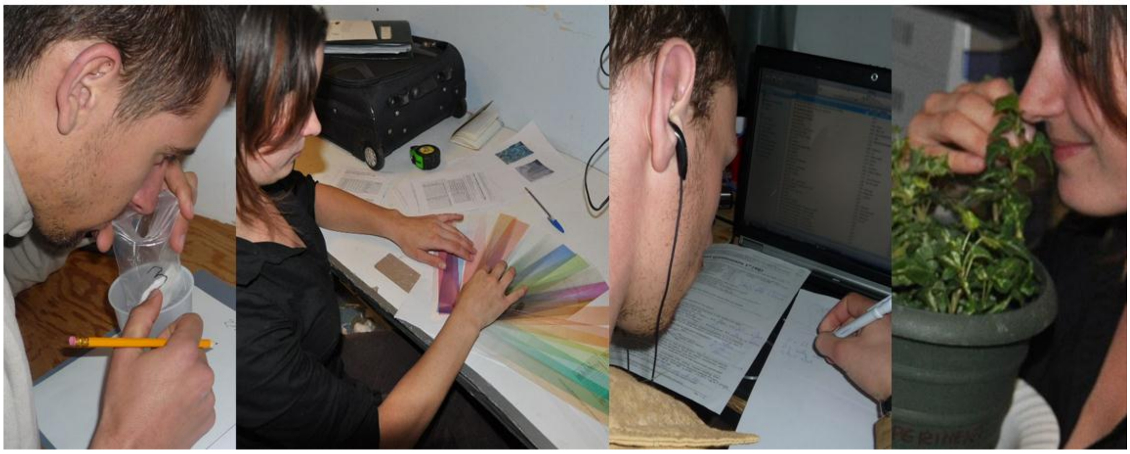


Figure 5.20: MoonMars Habitability sensory experiences at MDRS 2010: fragrances, colors, natural sounds, and plants. MDRS.

The effect performed with numerical data shows no statistical relevance; however, the experiment made with descriptive data led to the following findings:

- Color gradation: evokes visually aesthetic feeling;
- Plants: stimulate a connection with other forms of life;
- Listening to natural sounds: relaxes and stimulates the imagination;
- Smelling fragrances: evokes past experiences and memories;
- Creative performance: relaxes and may be used to remember at home

The “painting” of a “mandala”, an artistic expression using locally available colored sand, was scheduled and performed by I.L. Schlacht outside the habitat. The work was highly beneficial for the author, both in terms of counteracting stress and in acquiring knowledge. With respect to social aspects, no interest was shown in it, and it did not prompt any discussion with the author. In order to demonstrate the possibility of ‘composing’ with colored sand, a portable composition was installed inside the habitat: Interest was raised and each crew member was really happy to take a personal sand composition home as a memento. Only one member showed interest in active interaction regarding this creative activity.

From the questionnaires, interviews, observations, and collective debriefings, it can be seen that sensory experiences and creative performances were initially regarded as an unclear goal, but were expected to become relevant in increasing habitability during long duration missions.

Figure 5.21: Creative expression with in-situ resources at MDRS 2010

Habitability Analysis

One of the goals of a mission simulation is to investigate habitability problems for future planetary missions.

- Hypotheses

The habitability analysis is based on the hypotheses that:

(1) Debriefing procedures must be structured to cover all habitability factors, in particular those relevant for future missions (cf. *chapter 3*).

(2) If the crew is informed about the meaning and goal of habitability, they will be able to better discuss habitability problems and propose solutions.

- Analysis procedures

The analysis was performed using directed observations, interviews, and debriefings. The debriefings were done in the final days of the mission by asking the crew to write down a list of relevant problems at the MDRS regarding socio-cultural, psychological, physiological-environmental, and operational topics. From each crew member's list, the three main problems were selected and copied to a common list divided by topics. Then each highlighted problem was voted on and problems voted to be relevant by the entire crew were then discussed in an attempt to find solutions.

The debriefings included:

1. Project objective and motivation (10 min.)

2. Habitability concept definition and short discussion (5 min.)

3. Crew investigation of habitability problem and solutions (25 min.)

Figure 5.22: Crew 91 Mars Habitability experiment investigation at the Mars Desert Research Station (Schlacht et al., 2010b)

- Results:

All debriefings performed with the direct support of the experiment coordinator were successful, whereas all the experiments performed by remote control had problems, increasing the time needed for the post-mission data analysis. The best performance was achieved when the experiment coordinator was part of the crew (crew 91). If it is not possible to meet with the experiment coordinator, it may be beneficial to provide a short training on the experiment procedure.

From the habitability debriefing at the MDRS, the following points emerged as the problems and solutions of crew 91:

- Work maintenance has a low level of safety and control and needs too much time. Proposed solution: System automation and interfaces for managing the system's work maintenance would improve the system.

- Difficulties in finding objects caused by a bad storage system lead to stress and are time consuming.
Proposed solution: An easy and flexible catalog system based on checklists was introduced to improve this system.

- EVA equipment and instrumentation are a problem that can increase frustration and decrease orientation and confidence, with a negative impact on research results. Proposed solution: Design dedicated field instrumentation based on the particular human-machine-environment interaction in space missions.
- From a social perspective, the crew felt the need for familiarity, friendship, and cohesion between the members.
Proposed solution: Knowing each other before the mission may also be relevant for improving communication and work performance.

Figure 5.23: Problems with geological instrument interaction at MDRS, 2010: The instrument monitor is not visible because of solar light and helmet; the interface is not usable with EVA gloves; the instrument's design should be dedicated to the particular human-machine-environment interaction of space. It is not convenient to adapt earth instruments for use in space exploration.

Observations: Some problems were due to language and culture differences; however, these problems led to a discussion that increased crew familiarity and cohesion. Crew 94 demonstrated that the same language as well as cultural similarities and friendship bring high performance and cohesion to the crew. Crew 91 experienced a positive mood and cohesion with daily sugar consumption and sports activities; in particular, eating Nutella® and performing push-up exercises with background music became a new social ritual with benefits on performance.

The Mars Habitability Project achieved its goal of increasing awareness of and knowledge about habitability factors, more details on the result are reported on *Appendix J*.

5.2.3 MDRS Result Validation

To validate the methodology, the MDRS-IDP results were compared with those of the MDRS-HC project. MDRS-HC results:

- Crew schedule: Time optimization is needed for maintenance activities in order to increase scientific research.
- Traffic analysis: time and location of crew members on each day Optimization of the laboratory layout/interiors may support different types of dedicated research. Examples are an inflatable clean room, partitions, or permanent separations.
- Habitat and equipment functions and interfacesTechnology progress regarding equipment and instruments will lead to time and space savings. Current issues in this respect include lack of storage area, limited Internet bandwidth, and no easy access to the results database.

IDP Verification

In this part, the application of the methodology is analyzed and the results are compared and verified. Different foci were applied with respect to different parts of the research. The user-centered approach emerged as the more relevant methodology, supported by the opportunity to take part in a mission simulation.

Table 5.15: IDP Application at SSDW 2009

IDP		MDRS-IDP	Focus
HOLISTIC METHODOLOGY		Applied by the entire research group	
HME	HME interaction	HME was analyzed by the research group	
MD	Multidisciplinarity	Research group composition	
CD	Concurrent contributions	The research group worked concurrently	
USER-CENTERED APPROACH		Support from the entire crew	
PD	Crew in the design	The crew found solutions to the problems	
UE	Active experience	Sensory experience and creative performance tasks	
ED	Designer as user	The experiment coordinator was part of the crew	
Index: Dark Gray= Full focus; Gray = Partial focus, White= Considered			

Result Verification

In order to verify the IDP results, the following question had to be answered:

Does IDP increase habitability?

In order to answer this question, the final results were compared with the situation at MDRS 2009, where the IDP was not applied. The comparison was done on the basis of the final report, where only the key elements of the project are reported. It is worth noting that the MDRS-HC is a high-quality research project performed with qualified specialists from the field. The comparison is not aimed at establishing the research quality, but rather at verifying the support of HF and habitability in the context of future long duration missions.

The two research projects have really similar scenarios, goals, and constraints.

Table 5.16: Comparison between MDRS-IDP and MDRS-HC (Schlacht et al., 2010; Thiel et al., 2011).

RESEARCH SCENARIO	MDRS-IDP		MDRS-HC	
Goal	Habitability		Human Crew Relations	
Statement	Research technical and human aspects to prepare for future extra-terrestrial and planetary exploration			
Crew	91	94	76	77
Mission Simulation	2 weeks	2 weeks	2 weeks	2 weeks
Crew Members	6	6	5	6

The comparison was based on the Häuplik-Meusburger variables: usability, livability, and flexibility, and on the support of these habitability factors: physiological (Hfp), operational (Hfo), psychological (Hfps), and socio-cultural (Hfsc). The results of the two groups were analyzed individually, then grouped according to methodology and compared.

The differences that emerged between MDRS-IDP and MDRS-HC are:

- The MDRS-IDP introduces concepts related to psychological needs and socio-cultural relations among the crew.
- The MDRS-IDP addresses flexibility.
- The MDRS-IDP supports user experience with a multidisciplinary team (integrating humanities and scientific experts) working concurrently.

The IDP applies the user-centered approach and the holistic methodology to the process; however, the validation group as well as the IDP group was based on participatory design, involving the crew in finding project solutions to the problems that emerged.

Table 5.17: MDRS Results Comparison (Schlacht et al., 2010; Thiel et al., 2011).

		MDRS-IDP					MDRS-HC			
	FACTORS	KEY ELEMENTS	Usability	Livability	Flexibility	FACTORS	KEY ELEMENTS	Usability	Livability	Flexibility
		Habitability					Human Crew-relation			
HF experiment	All	Mood, Sensory experience, Creative activity, Humanities knowledge	v	v	v	Hfo Hfp	Time and traffic records	v	v	
Work time and equipment	All	Bad equipment increases frustration and decreases orientation and confidence, impacting on the research result. A solution is to design dedicated field instrumentation based on the particular human-machine-environment interaction in space missions.	v	v	v	Hfo	Technology progress regarding equipment and instruments will lead to time and space savings.	v		
Maintenance activity	All	Work maintenance has low level of safety, no control, needs too much time and causes frustration. As a solution, system automation and interfaces for managing the system work maintenance will improve the system.	v	v	v	Hfo Hfp	Time optimization is needed for maintenance activities to increase scientific research.	v		
Configuration		Not considered as a focus problem				Hfo Hfp	Optimization of the laboratory layout/interiors may support different types of dedicated research. Examples are an inflatable clean room, partitions, or permanent separations.	v		v

Stowage	Hfo Hfp Hfps	Bad storage system leads to stress and is time consuming. An easy and flexible catalog system was introduced to improve this system.	v	v	v	Hfo	Lack of stowage area			
Crew social relations	Hfo Hfp Hfps	Crew felt the need for familiarity, friendship, and cohesion between the members. Knowing each other before the mission may improve communication and work performance	v	v	v		Not considered as a focus problem			
Free time and cultural activities	All	Positive mood, better performance and cohesion with daily sugar/chocolate consumption and sports activities with background music. These activities became a new social ritual.	v	v	v		Not considered as a focus problem			
Habitability Factors	All	**New sustainable technologies and solutions for habitability**	6/6	6/6	6/6	Hfo Hfp	**New sustainable technologies and solutions for Hfo and Hfp**	4/4	1/4	1/4
User-Centered Approach		User experience Participatory design Empathetic design					Participatory design Empathetic design			
Holistic Methodology		Multidisciplinary design Concurrent design Human-machine-environment interaction					Human-machine-environment interaction			
V= habitability qualities investigated										

Table 5.18: Habitability Factors Results Validation (Schlacht et al., 2010; Thiel et al., 2011).

	MDRS-IDP				MDRS-HC				Astronaut Interview			
	Operational	Physical	Psychological	Socio-Cultural	Operational	Physical	Psychological	Socio-Cultural	Operational	Physical	Psychological	Socio-Cultural
Usability	v	v	v	v	v	v			x		x	
Livability	v	v	v	v					x			x
Flexibility	v	v	v	v							x	
Innovation	v				v							
Total	All factors are supported in each part of the project plus Innovation				Factors considered more than 50% of time in the project				Problems selected in the user analysis (cf. *section 3.1.1*)			

The results show that the human factors contributions, from the IDP and the validation groups, focus on the topics of HF experiment, work time and equipment, maintenance activity configuration, storage, crew social relations, free time, and cultural activities. The IDP group found sustainable technologies and solutions for habitability, taking into account all factors. The validation group found relevant and innovative solutions related to operational and physical factors, but did not consider socio-cultural and psychological factors. In addition, flexibility, as a relevant habitability quality for long duration missions, was considered only once. This is a relevant matter considering the goal of both research groups: “to prepare for future extra-terrestrial and planetary exploration” (Thiel et al., 2011 p. 255). Flexibility and the socio-cultural dimension are elements already identified as a current problem from the user analysis. We must also not forget that these dimensions are the ones that will become more relevant in the long duration and long range scenarios investigated here.

More detail on this analysis is reported on *Appendix K*

5.3 MMS

The aim of the third IDP study was for students attending different university courses to find concept solutions to habitability problems in long duration missions. In order to create a dedicated multidisciplinary team, new disciplines specifically applied to the space context were created. The results revealed that the classes attempted to find innovative design solutions and new equipment dedicated directly to the difficult space scenario. This turned out to effectively support the increase of habitability and fulfill the user needs from a multidisciplinary perspective.

During 2010 and 2011, the author led the MMS seminar class on the topic of habitability of space systems at the Chair of Mensch-Maschine-Systeme at Technische Universität Berlin and tutored the MMS multidisciplinary teamwork on the space storage system project. The students who took the class were from different fields and of international provenience. Applying the IDP methodology, the three classes received guidance regarding how to acquire specific knowledge and how to find design solutions in the context of habitability for long duration missions. The learning process and the design results are presented in this subchapter.

5.3.1 MMS Learning Process

The application of the IDP to the MMS Seminars aimed to find guidelines for a concrete habitability problem for long duration space missions. The first semester students came from the following disciplines: transport systems, human factors, architecture, and aerospace engineering. Of the six students, three were German and three were of different or mixed provenience (Poland, Venezuela, Portugal). The summer semester group worked in parallel with the student group from the multidisciplinary teamwork project. This student group was to find a concrete habitability design solution. There were twelve students in this group, all German and with different engineering backgrounds. During the winter semester, the application of the IDP to the MMS Seminar was aimed at finding project solutions for habitability in long duration space missions. The students came from the following disciplines: architecture, art, geodesy, and design. The seven students were all visiting students with international provenience (India, Australia, Hungary, Israel, USA). All the different classes apply the IDP within the same methodology, satisfying all the IDP principles as reported in the follow Table.

Table 5.19: MDRS-IDP Research Process

MDRS- IDP RESEARCH PROCESS	USER-CENTERED APPROACH			HOLISTIC METHODOLOGY		
	User Experience	Participatory Design	Empathetic Design	Concurrent Design	Multidisciplinary Design	Human-Machine Environment inter.
1. Learning						
1.1 Class building on LDM knowledge: - Multidisciplinary students - International provenience - Lecture on human-machine-environment interaction in space					v	v
1.3 Team works concurrently and simultaneously on the learning project: - Interview of astronauts - Student seminar - Revision and discussion in team - Simulation of the user (Identification process)		v	v	v		
2. Designing						
2.1 Each student learn a specialization in one space field					v	
2.2 Each “specialist” analyze a specific problem and solution related to his field considering the habitability factors	v					
COVERED ASPECTS	v	v	v	v	v	v
LDM= Long Duration Mission						

5.3.2 MMS Design Solutions

Project 1. Space Architecture

Frame: 1 Student, 1 semester, 6 research group members

Project: “Apertura”, the new window to space.

Goal: Minimize visual monotony within the ISS’s interior while increasing the astronauts’ feeling of connection with Earth.

Problem: The astronauts’ preferred activity in space is looking out of the windows. The ISS windows do not always offer a view, decreasing contact with the external environment and increasing isolation.

Solution: Apertura is a personal, portable viewing device that will render the outside view relative to the angle the user is holding the device, allowing for a truly dynamic visualization of the station’s exterior. The device allows the user to dictate which direction they would like to view, and is used for personal reflection and research. It is not a substitute for architectural windows, but rather a personal supplement. The Apertura is an interactive tablet computer with great potential for improving the astronauts’ lives.

Figure 5.24: “Apertura”, the new window to space. Clare Lillian Johnston under the tutoring of I.S. Schlacht MMS Seminar WS 2010. TU-Berlin.

Project 2. Space Physiology

Frame: 2 Students, 1 semester, 6 research group members

Project: Dance Training as a Countermeasure

Goal: Countermeasures to the psychological and psychological effect of microgravity

Problem: ISS long duration missions take a toll on the individual, both physiologically and psychologically (Schneider et al., 2008). The absence of countermeasures aggravates the physical effects of microgravity on the tendons (particularly of the spine) and on strength. Moreover, astronauts need social connections, teamwork, trust, and interdependence.

Solution: Developing countermeasures for space by offering dance training with partnering. The training achieves spine compression through contraction by partnering or using an elastic band. It focuses on alleviating the problem of spinal tendon and nerve elongation as a result of prolonged exposure to microgravity (Gerzer, 2010; NASA, 2010b pp. 48-51), and on resulting team-building benefits. Dance training can give an astronaut a greater understanding of his/her physiology and thereby produce more refined movement, thought, and experience for themselves and their team members.

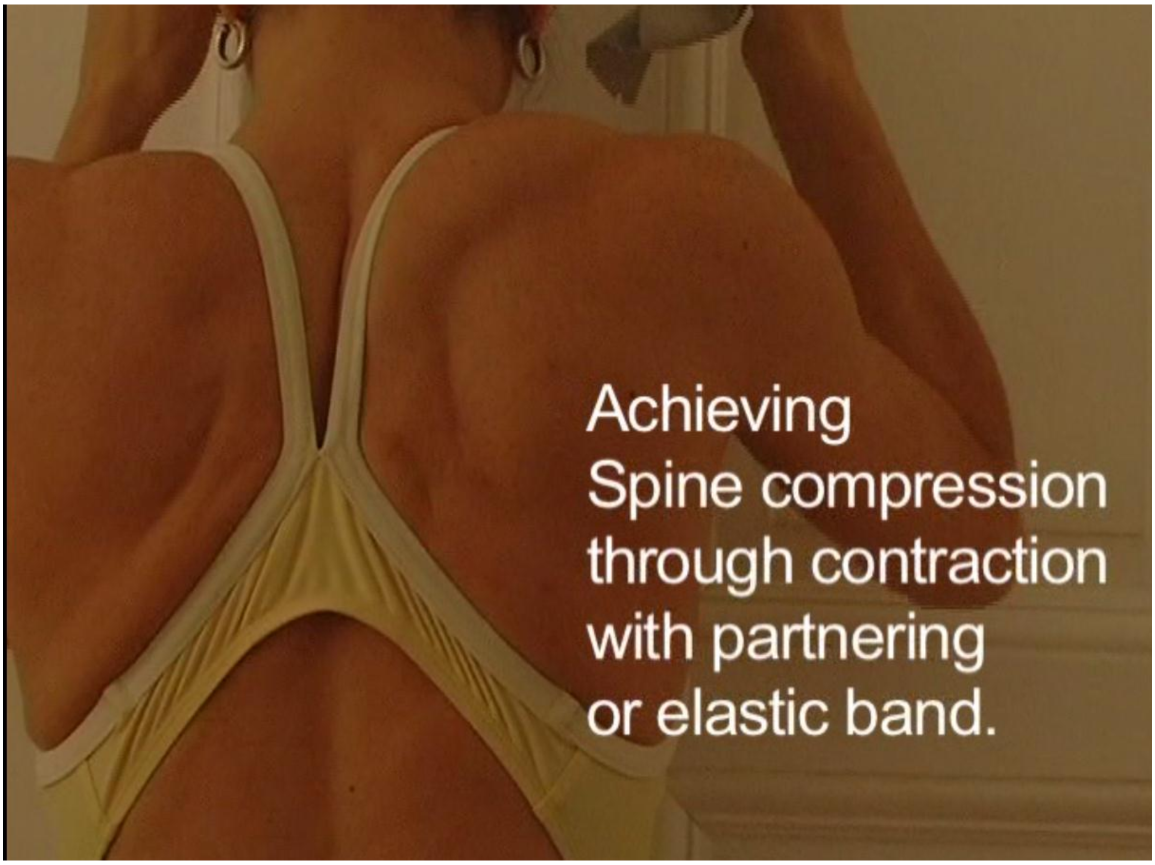


Figure 5.25: Dance training as a countermeasure in space. Video, Catherine Kavanaugh under the tutoring of I.S. Schlacht MMS Seminar WS 2010. TU-Berlin.

Project 3. Space Structure for Exploration

Frame: 2 Students, 1 semester, 6 research group members

Project: Apparatus and assembly method for space stations for human presence and experimentation in space.

Goal: Develop a cost-effective space station to encourage private investors but also accelerate the efforts for the development of space exploration.

Problem: The projected end of operations at the International Space Station (ISS) in around 2020 makes a continuation of space habitat development and space colonization necessary for humans in the future. To foster a deeper understanding of space, the sustainability of human life in space environments must be ensured.

Solution: An expandable spherical structure that can be deployed in space, with a general scheme for minimizing assembly duration and sequences, and a reduction in costs achieved through a minimum number of launches, with the possibility to expand the station with similar structures attached to it. The spherical shape provides specific advantages: The distances from the core to the habitat modules is the same, thus reducing the length of cables and duct to a minimum. The shape of the station also provides a natural orientation towards the solar arrays, so that at least a minimum number of the arrays is always oriented towards the sun. The truss itself will be within reach from any point of the habitat modules for any EVA. Distributing the habitat modules evenly on the truss would provide extra strength to the whole station.

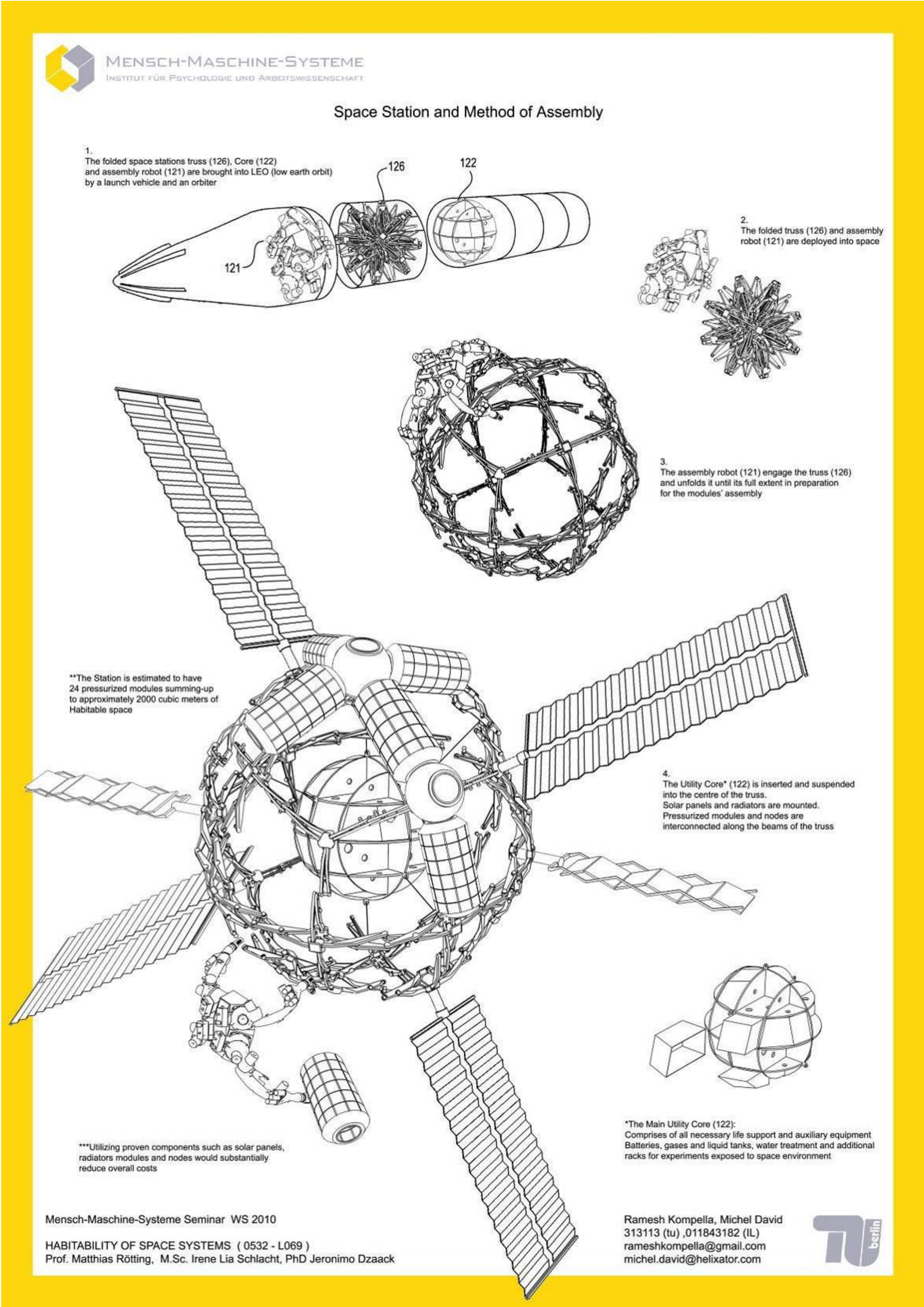


Figure 5.26: Space station and assembly method. Michel David, Ramesh Kompella under the tutoring of I.S. Schlacht MMS Seminar WS 2010 TU-Berlin.

Project 4. Storage System

Context: 12 students, 1 semester, 12 research group members
Project: Storage system for a thousand-day mission to Mars.

Goal: Develop a sustainable storage system to support a long duration mission

Problem: Currently astronauts are living in a chaotic mix of equipment, supplies, and food. Little things are constantly being lost.

Solution: Following a human-centered design, the team first did research on human needs and analyzed the advantages and disadvantages of the current storage system. The group designed a flexible soft bag and marked it with RFID chips to indicate approximate location. Furthermore, the bags were tagged with labels and different colors. The colors help the astronauts with orientation in a room, and the labels identify which things to put into which bags using a pictogram system. The effectiveness of the final configuration was verified when the solution was tested in the context of a simulation process. This work was developed in constant cooperation with the client, the Extreme-Design Group, and an experienced supporter, Arch. Giorgio Musso of Thales Alenia Space.

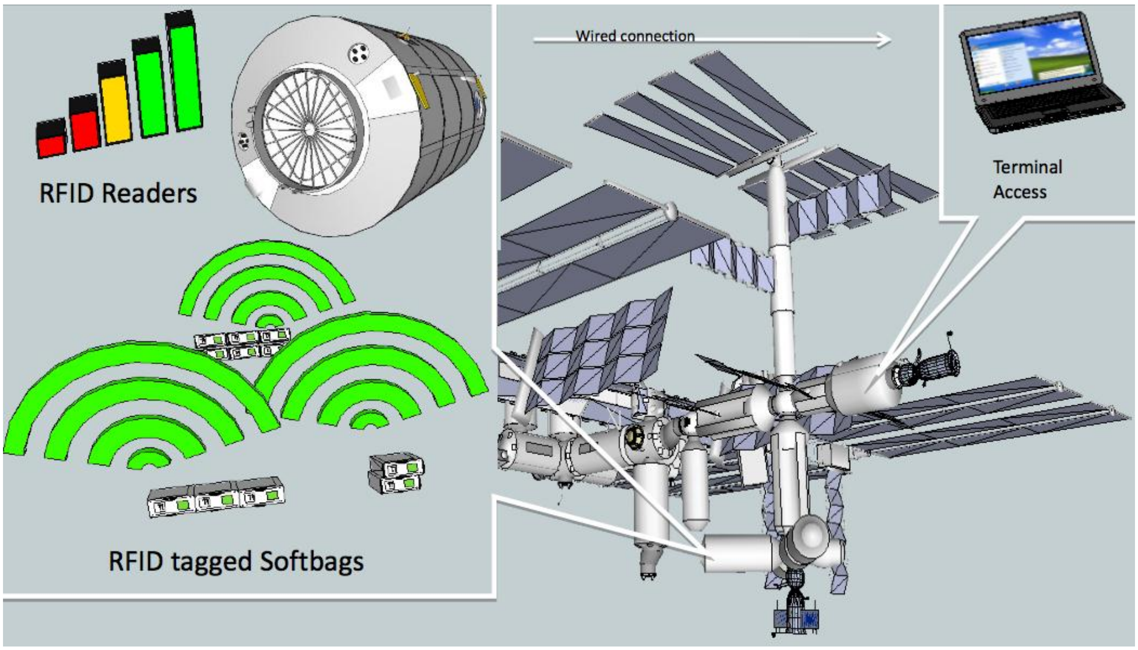


Figure 5.27: Storage System, RFID Integration Scheme (Tutors: Jessica Reissland, Irene Schlacht, MMS Multidisciplinary Team Project, TU-Berlin 2010)

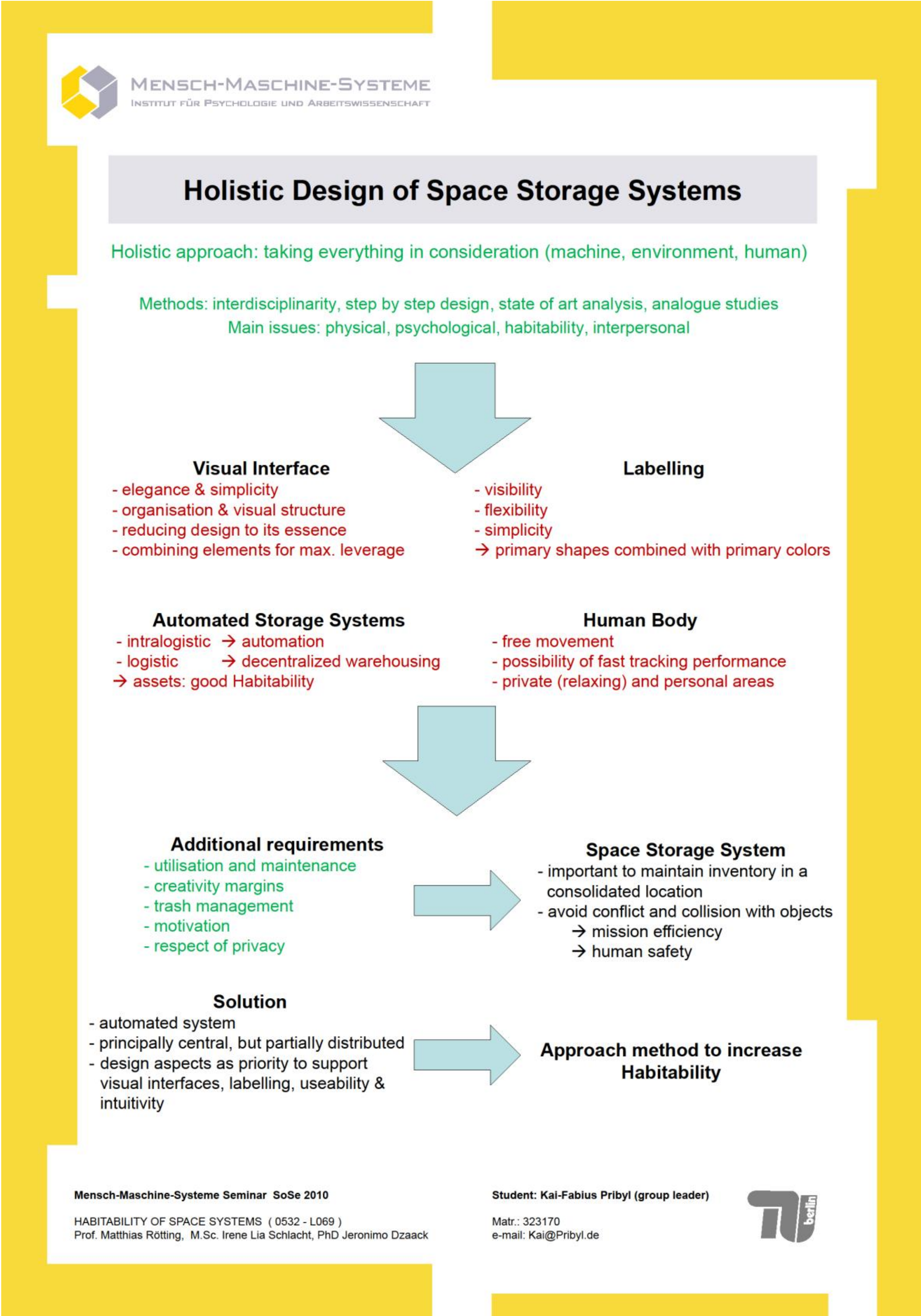


Figure 5.28: Holistic requirements of space storage systems (Kai-Fabius Pribyl, under the tutoring of I.S. Schlacht, MMS Seminar SS 2010 TU-Berlin)

Project 5 Holistic Requirements of Space Storage Systems

Context: 6 students, 1 semester, 6 research group members

Project: Storage system requirement for a thousand-day mission to Mars.

Goal: Develop the requirement for a sustainable storage system to support crew performance and decrease stress.

Problem: Storage systems in space are important for any kind of operation. An inappropriate system on the current ISS and its negative effects demonstrate the need for analysis and improvement.

Solution: Once the autonomy of the crew will increase with the duration and distance of future missions, e.g., on Mars missions, a good storage system that supports usability, flexibility, and creativity with a high security standard will be crucial. It will also have a positive impact on habitability and the crew‘s mood. The crew will have to face the unexpected and will have to find creative solutions for their problems. Providing equipment for arts, leisure activities, or different cultural traditions on long duration missions will be as important as providing basic technical tools. Moreover, the storage system should be flexible itself, so all shelving, racks, and containers should be adjustable and provisions should be made for the installation of additional storage facilities. Multiple gravity environments with changing basic conditions must be considered on future missions as well. The storage system in a Space Habitat Station can be central part of the system itself, or it can be distributed to and integrated into other parts. An item should be stored in an area as close as possible to where it is used, ensuring short ways for transport. The key requirements for enhancing the functionality of any storage system are visibility and accessibility. This also includes plans for orientation and an easy and flexible labeling and coding system. Concerning accessibility, taking an item out of a container or out of the central storage room should not require removing any other items. Room for temporary storage might be useful. An increase in automating storage processes might lead to quicker and easier storing, but an automated system will be a complex facility itself that will require maintenance and energy in a small environment with limited resources.

5.3.3 MMS Result Validation

To validate the methodology, the MMS-IDP application methodology was analyzed using the following table. The result shows the application of the complete IDP methodology, with a particular focus on the application of the user-centered approach for project 4 and the holistic methodology for projects 1, 2, 3, and 5 (cf.

Table 5.20).

Table 5.20: MMS-IDP

IDP		MMS-IDP	Focus
HOLISTIC METHODOLOGY			
HME	HME knowledge	HME is introduced with lecture	
MD	Multidisciplinarity	The students are from different fields, specializing in a specific topics applied to the space field.	
CD	Concurrent working	The class works concurrently as a multidisciplinary team, with field seminars, revision and discussion.	
UCD APPROACH			
PD	Astronaut interview	User interview on habitability problem	
UE	User experience design	User experience is focused on the design	
ED	Identification process	The student identifes himself with the user in order to understand the scenario and acquire new knowledge.	
Index: Dark Gray= Full focus; Gray = Partial focus, White= Considered Acronyms: HME= Human Machine Environment, MD=Multidisciplinary Team, CD=Concurrent Design, PD=Participatory Design; UE=User Experience; ED= Empathetic Design			

The result, when compared to the state of the art, supports innovative project solutions to increase the level of habitability in long duration space missions. Only in one case did the result not fully support livability. This was the case in project 5 Storage System, where the team did not consider psychological and socio-cultural habitability dimensions. Instead, the team focused its research on the user-centered approach; this was demonstrated as not being sufficient to support an increase of habitability in the project. Team number 5 approached the same topic as team number 4, but focused on a holistic methodology. The results show that it was possible to support all the qualities as well as the interdisciplinary habitability factors (cf. following table).

Table 5.21: MMS-IDP

	QUALITIES				INTERDISCIPLINARY HABITABILITY FACTORS				USER-CENTERED APPROACH			HOLISTIC METHODOLOGY		
	Innovation	Usability	Livability	Flexibility	Operational	Physiological	Psychological	Socio-Cultural	User Experience	Participatory Design	Empathetic Design	Concurrent Design	Multidisciplinary Design	Human-Machine-Environment Interaction
State of the art					v	v						v		
MMS Projects														
1	v	v	v	v	v	v	v	v	v	v	v	v	v	v
2	v	v	v	v	v	v	v	v	v	v	v	v	v	v
3	v	v	v	v	v	v	v	v	v	v	v	v	v	v
4	v	v		v	v	v			v	v	v	v	v	v
5	v	v	v	v	v	v	v	v	v	v	v	v	v	v

5.4 CEF

The fourth IDP conceptual study took place in a closed-loop habitat facility for long duration space missions developed by the German Space Agency (DLR). Unlike the previous procedures, which had only been used for robotic missions prior to this study, a more dynamic approach was incorporated with descriptive and visual data, which fully integrated user-centered design and a holistic methodology. The result not only supported the integration of multidisciplinary human factors, but also considered the overall complexity of human needs and project qualities.

The first human project for long duration missions was performed at the Concurrent Engineering Facility (CEF) of the DLR Institute of Space Systems in Bremen with the support of the IDP design model. The idea is that effective and self-sustainable artificial habitat design for humans in the hostile environment of space is essential for human spaceflight and for the expansion of mankind in orbit or to other celestial bodies. To fully experience this objective, the DLR plans to build a ground-based laboratory facility to test new and innovative habitat technologies. The project terrestrial Facility of Laboratories for Sustainable Habitation (FLaSH) was carried out following the IDP methodology (DLR 2011, 2011b).

This chapter presents:

- CEF Workshop Process
- CEF Workshop Result

5.4.1 CEF Workshop Process

The workshop took place at the CEF of DLR from 28 August to 2 September 2011. The facility contains 12 workstations for specialists from several disciplines and additional positions for customers, visitors, and experts, as well as CEF Support. The CE process is based on the Integrated Design Model (IDM) used at ESA ESTEC's Concurrent Design Facility (CDF) and also on an Excel worksheet (Romberg et al., 2008). A total of 25 persons took part in the FLaSH study.

The workshop was about:

- Mission and System Requirements
- Concurrent Engineering Process.

Figure 5.29: FLaSH DLR workshop members at the CEF 2011

Requirements

The requirements were defined prior to the workshop. They consisted of the overall project and workshop goal and the responsibilities of the different study domains.

The overall project aims to create "an effective and self-sustainable artificial habitat design for humans in the hostile environment of space". The primary goal is "to test different technologies that can be used in order to create a nearly closed-loop within a habitat", and to perform "long term psychological investigations of the test crews" (DLR, 2011b pp. 2-3). The project covers space as well as terrestrial applications, allowing "more resource saving and efficient habitation of human populations, not exclusively, but especially for megacity environments. This could reduce pollution, desertification and be a possible solution for issues arising due to human over-population, by e.g. including decentralized farming within an urban environment or a living space " (DLR, 2011b p. 4).

The first workshop aimed at gathering preliminary ideas and getting an understanding of the possibilities and the resources needed. The study domain was constrained to considering the steps related to a pre-A(0) phase. Apart from the management functions and the configuration, all the disciplines were different from the ones usually allocated by ESA, and most importantly, HF had its own distinct position covered by the author as a Human Factors discipline specialist.

Table 5.22: CEF-IDP Disciplines FLaSH Workshop (DLR, 2011b)

Concurrent Design	CDF- IDP	ESA
Management Functions		
CDF Manager	v (Customer)	V
System	V	
Team Leader	V	V
CEF responsible	V	
Disciplines		
Air	V	
Water	V	
Waste	V	
Animal	V	
Greenhouse	V	
Sick Bay	V	
Configuration I	V	V
Configuration II	V	
Workshop	V	
ISRU	V	
Living Unit	V	
Food Processing Facility	V	
Design	V	
Human Factors	V	
KM Officer	V	
Guest	V	
Index: x = concurrent design position. Acronyms: HF (Human Factors), IDP (Integrated Design Process), ESA (European Space Agency), CEF (Concurrent Engineering Facility).		

Each study domain was characterized by distinct requirements called responsibilities. The human factors domain was defined by the author to support all of the IDP habitability factors as follows:

> Responsibilities of the human factors specialist:
>
> Advise the study team about essential factors regarding general needs of humans. Exemplary tasks are:
>
> • Integrate the support of human psychological, physical, socio-cultural, and operational factors (e.g., anthropometric requirements, nutrient requirements, ergonomic requirements, and ethical requirements)
>
> • Supervise the support of human needs (physiological, motivational, etc.) by the other domains (e.g., Living Module, Design…) and the overall system design
>
> • Reveal the different input and output relationships of humans in the space habitat system
>
> • Advise the study team about essential factors regarding general needs of humans in relation to psychological, physical, socio-cultural, and operational factors
>
> • Consider and implement the global study and system requirements for the selected domain (DLR, 2011b)

Process and Implementation

During the workshop, all multidisciplinary experts sitting in the CDF designed a first habitat configuration. As in the common procedures previously used in the design of robotic mission, after the introduction of the system and the mission requirements, the experts started to work on their domain, collaborating either in the main room or in splinter meetings. The first summarized overview with the presentations by each expert identified the deviations from the desired target. Next, the task was either to revise the data or to define a different design level. This depended on the conclusions drawn from the first iteration and its analysis. Repeating these sequences several times led to a sound finalization of the design (Romberg et al., 2008).

Figure 5.30: Projection of sketches at the CDF Bremen (FLaSH study in 2011)

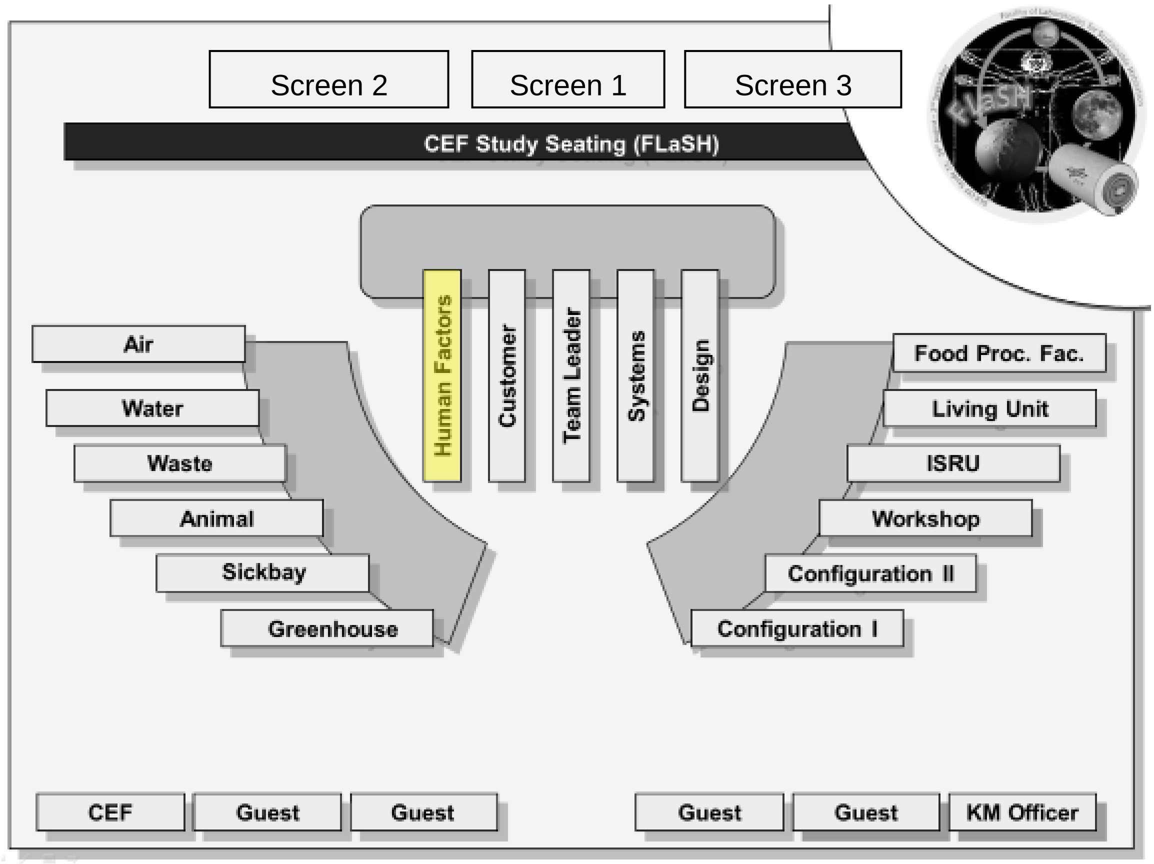


Figure 5.31: Concurrent Engineering Experts Configuration

The study domain of human factors was integrated into the CEF for the first time, and was also present from the preliminary phase of the project. During the first workshop day, the author was invited to give a detailed introduction to the HF discipline, presenting the concept of the role of HF in line with the IDP methodology. In the presentation, the relevance of the following issues was pointed out:

- Support all of the habitability factors
- Apply a user-centered approach
- Use a holistic methodology

Figure 5.32: Integration of Human Factors at the CDF in Bremen (FLaSH study in 2011)

During the pre-A(0) phase, each IDP methodology element was approached and covered.

- User-Centered Approach

The user-centered approach based on the application of user experience, participatory design, and empathetic design was integrated into the CEF for the first time. The user-centered approach was supported by the entire team fully cooperating with the author in the role of the HF specialist, in particular regarding the support of user experience. In the context of experience design, qualitative data was shared using a dedicated Excel sheet that supported descriptive variables, discussion, and projection of sketches. In order to integrate user experience within qualitative data, the presence of architects was fundamental. Participatory design, usually applied with the contribution of the user to the design, was realized with the contribution and the feedback of the author as a user of terrestrial isolation facilities. Indeed, taking into account that the workshop goal was to design a terrestrial facility to simulate long duration missions, the author was able to cover the role of the user, considering her research experience during two weeks of isolation at the Mars Desert Research Station. An experienced long duration mission user was recommended and, as a consequence, planned to be supported during the A(0) phase, with the invitation of an astronaut or researcher from Antarctica with more than six months of experience. In this particular case aimed at building a simulation facility on earth, empathetic design, as one of the elements of the IDP, was also covered by the presence of the author on the team with her experience during the MDRS. However, the optimal circumstance of "learning by doing" will be the application of empathetic design from the whole team or parts of it, with the full experience of the user condition in earthly closed-loop and isolated facilities. With less impact, this process may also be applied in a process of identification, where the workshop members mimic experiencing the user condition for a short period of time. The presence of a member who experiences the user condition or applies the process of identification should be considered during the A(0) project.

- Holistic Methodology

The holistic methodology was fully applied to the following three elements: (1) Concurrent design was realized by utilizing the concurrent engineering facility. (2) Multidisciplinary design was realized by having expertise in engineering (aerospace, system, and industrial), science (physics, biology, and horticulture), architecture, and design present in the team. In this pre-A(0) phase, many people had to cover different disciplines; for example, the human factors specialist also needed to cover the expertise on physiology, psychology, sociology, cultural utilization, and public relations. Also, cost and energy were a shared task. The consideration of multiple domains by each expert is normal and should occur in order to guarantee the multidisciplinary approach; however, the number of dedicated domains in the team should be increased during the A(0) phase. (3) Human-machine-environment interaction was supported in the concurrent process, as was the interaction of expertise regarding humans, machines, and the environment. However, the focus was on the interaction with the simulated environment (e.g., Moon and Mars), and a focus on the interaction with the real environment (Earth environmental issues related to the construction location) was supported only by the human factors study.

- Habitability Factors

Habitability factors were supported by the contribution of all the disciplines that worked concurrently on the basis of human-machine-environment interaction. The major focus were physiological parameters and, with the human factors contribution, also the operational factors. With the application of human factors to the design and to the living quarters, the human factors specialist was able to also integrate socio-cultural, environmental, and psychological issues.

As a conclusion, an interesting point was the great team work with all of the discipline specialists. In fact, the approach and the predisposition of the team members to collaborate are fundamental factors that were necessary to support the overall requirements and workshop process.

Table 5.23: MDRS-IDP

IDP		MDRS-IDP	Focus
HOLISTIC METHODOLOGY			
HME	Team workshop	PreA(0) phase: HME is supported by the interaction of Human, Machine and Environment experts in the team.	
MD	Multidisciplinary experts	PreA(0) phase: The team members were from engineering, science, architecture and design. A(0) phase: Integration of more expertise is needed.	
CD	Concurrent Engineering Facility	PreA(0) phase: The team workshop was carried out at the Concurrent Engineering Facility at DLR.	
UCD APPROACH			
PD	Experienced user on the team	PreA(0) phase: The author was considered as the user with experience regarding isolation in terrestrial habitat. A(0) phase: Proposition and plan for user experienced in long duration missions in Antartica or space.	
UE	User experience support	PreA(0) phase: The user experience was supported by all the disciplines, in particular human factors, design, living module, animals, and workshop.	
ED	Designer experience user condition: “learning by doing”	PreA(0) phase: The author was considered as the designer with experience on the user condition. A(0) phase: suggestion for simulation of the user as “one-self” (identification process).	
Index: Dark Gray= Full focus; Gray = Partial focus, White= Considered Acronyms: HME= Human Machine Environment			

5.4.2 CEF Workshop Result

The result of the one-week workshop on the pre-A(0) phase was the structuring of the A(0) objectives, the calculation of the physical input and output quantities needed to complete a closed loop (e.g., O_2 and CO_2, water and urine, etc.), and the integration of the human into the system. The main achievements are reported here (DLR, 2011c):

Goals

- Test the concept of a fully self-reliant artificial human habitat for a lifetime of 20 years
- Test the technology for a system and modules for space and terrestrial application
- Plan input and output relationships on the module level with respect to, e.g., power, biomass, CO_2, O_2, water, food, inorganic waste, etc.
- Involve public outreach for exploration and urban application (e.g., megacities)

Facility

- Accommodate 6-8 permanent residents for a period of 1 year
- Accommodate up to 4 residents for a period of 2 weeks (4 times a year)
- Closed loop of up to 95% in all habitat loops, with 5% to be covered by ISRU (In-Situ Resource Utilization)
- Autonomous production of consumer products (up to 90%) and machinery components (up to 30%)

Design

- Efficient accessibility from inside and outside (the module should be connected with the central part through a walkway with four air locks)
- Dedicated area for public engagement shall be implemented for education and public outreach
- Module dimensions are 6x6x10m in an area of 50x90m to 70x70m
- Module modularity to support easy exchange of a functional module’s system and/or subsystem

Feasibility

- Test run will allow exchange of system and subsystems
-

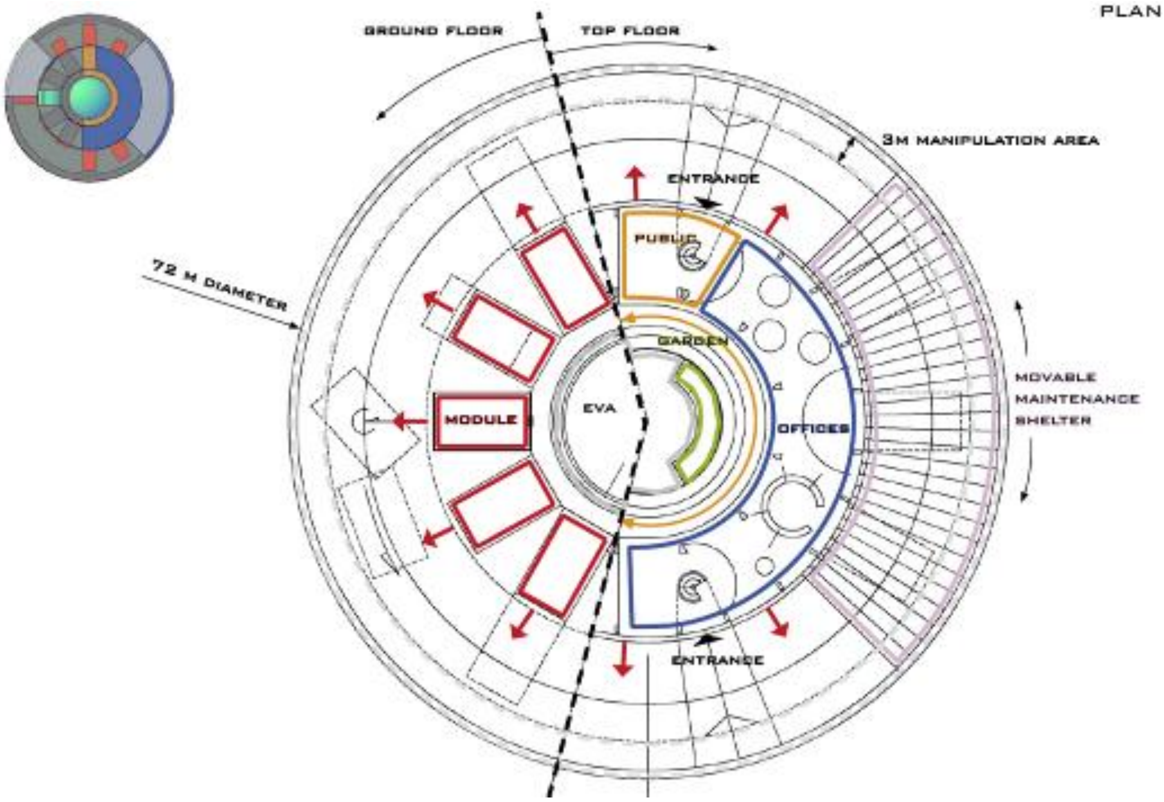


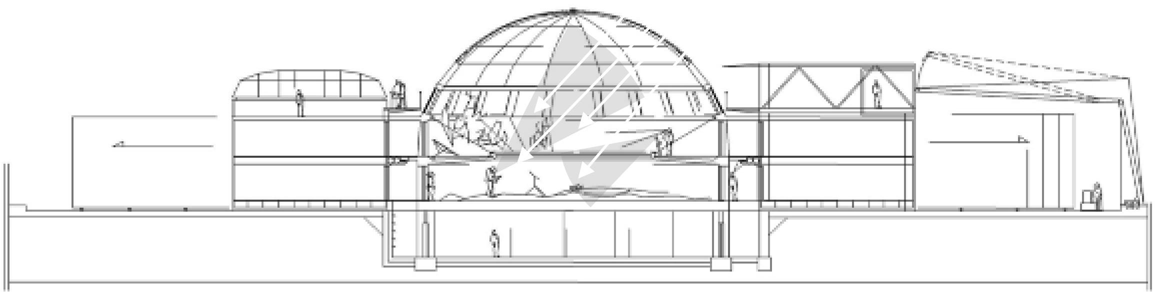
Figure 5.33: FLaSH habitat plan, drawn by Ondrej Doule (DLR FLaSH study in 2011)

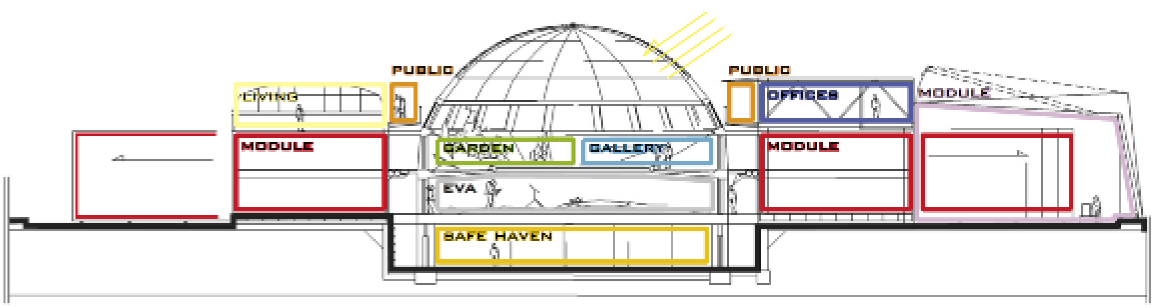
Human Factors

The HF specialist, with the cooperation of the other specialists, applied usability, flexibility, and livability as main requirements to guide the design of the configuration, the living facility, and human interaction within the other facilities.

- Configuration Design

The configuration selected is similar to the shape of a daisy flower, where each petal can be pulled out, modified and put back in, in accordance with different necessities. Each petal is a module of 6x6x10m in size, with a specific purpose within the closed loop. On the top of the module, room is allocated for ground control, office, and public area. On the roof of the module, a pathway may be used to support guided visits of the facility from outside. The modules are: (1) Air, (1) Water, (1) Waste, (1) Animal, (2) Greenhouses, (1) Sick Bay, (1) Workshop, (1) ISRU, (1) Living Unit, and (1) Food Processing Facility. Each module is divided into two floors and connected with the central part through a walkway with four air locks. The central part, the pistil, is a big dome with an arboretum and a transparent cupola, which provides visibility to the outside and a view of the distance in order to avoid myopia caused by isolation in a closed-view environment. This set-up also provides a variation of stimuli and supports the circadian bio-rhythm. The dome is divided into two floors: The first floor is dedicated to verifying EVA and geological sampling procedures, while the second floor covers only the circumference perimeter creating a kind of perimetral balcony facing the sky and the first floor. This configuration supports the monitoring of activities from the second perimetral floor without disturbing the person working on the first floor, but also supports the connection to the outside from both floors with the transparent dome to counteract claustrophobia. On the second floor, ornamental plants (e.g., agave or other plants that do not need much water) are intended to serve as psychological support by enabling contact with another form of life. The shape of the floor supports running, which is an optimal activity from both a physiological and a psychological perspective, to reduce tension and maintain the body. Inside the dome, a central safe bay can ensure crew survival for several days. This may also be used for testing procedures.





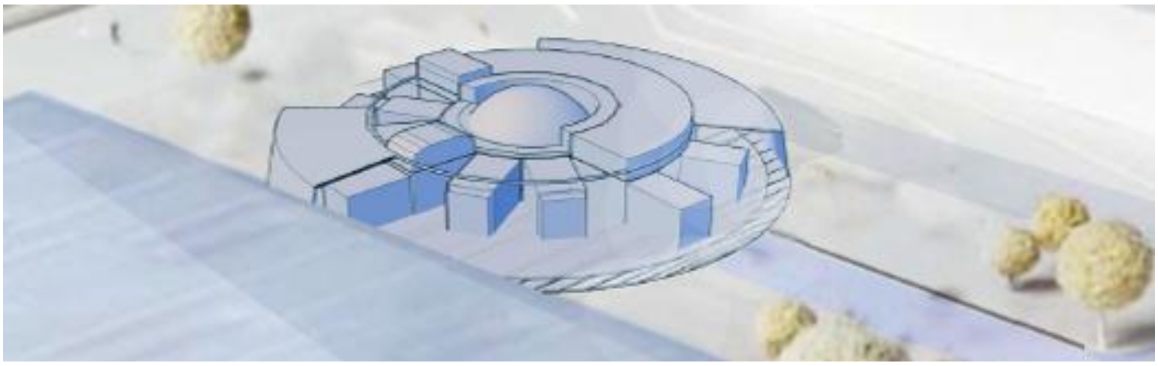


Figure 5.34: FLaSH habitat section, drawn by Ondrej Doule and elaborated by Irene Schlacht (DLR FLaSH study in 2011 draw An)

- Living Module

Unlike the other modules, the living module is composed of three floors to support eight crew members for a one-year stay. On each floor of each module, there is an emergency exit, but only this module also contains windows on each floor.

The first floor comprises one bathroom and the crew quarters, which is an area with low luminosity and with fewer walkways. Each crew member has private quarters with one small window each.

The second floor houses the sports and exercise facility, to be used by two to three crew members at a time. A special isolation mattress is used to reduce possible vibration of the equipment when it is in use. On this floor, there are also two multi-purpose rooms, able to house a visiting crew of four members for two weeks, as well as the commander's quarter and two toilets.

On the top floor, a big cupola supports the connection with the outside as in the central dome. The light from the dome is distributed like a waterfall; with a transparent floor around the central stairs on the second and first floors.

The command crew is separated from the other crew members to guarantee more privacy, and, if possible, the use of a private toilet. The closeness of the commander to natural illumination is also a symbol of hierarchy, since the commander is one level above the rest of the crew. The main purpose of this floor is that of a social area, where the crew can have meetings, presentations, meals, social activities, but where they can also relax and perform private activities. A detailed breakdown has been studied based on private and public needs, from research activities to entertainment and communication within social and cultural activities.

The break-down study has been used to design a consistent configuration of space and areas that respects the user needs; this is called zoning. The equipment consists not only of common furniture such as tables, beds, and lamps, which need to be fully adjustable to fulfill personal needs, but also of portable and stationary communication systems, audio-video equipment, computers, a library, art/modeling equipment, and analog or virtual games.

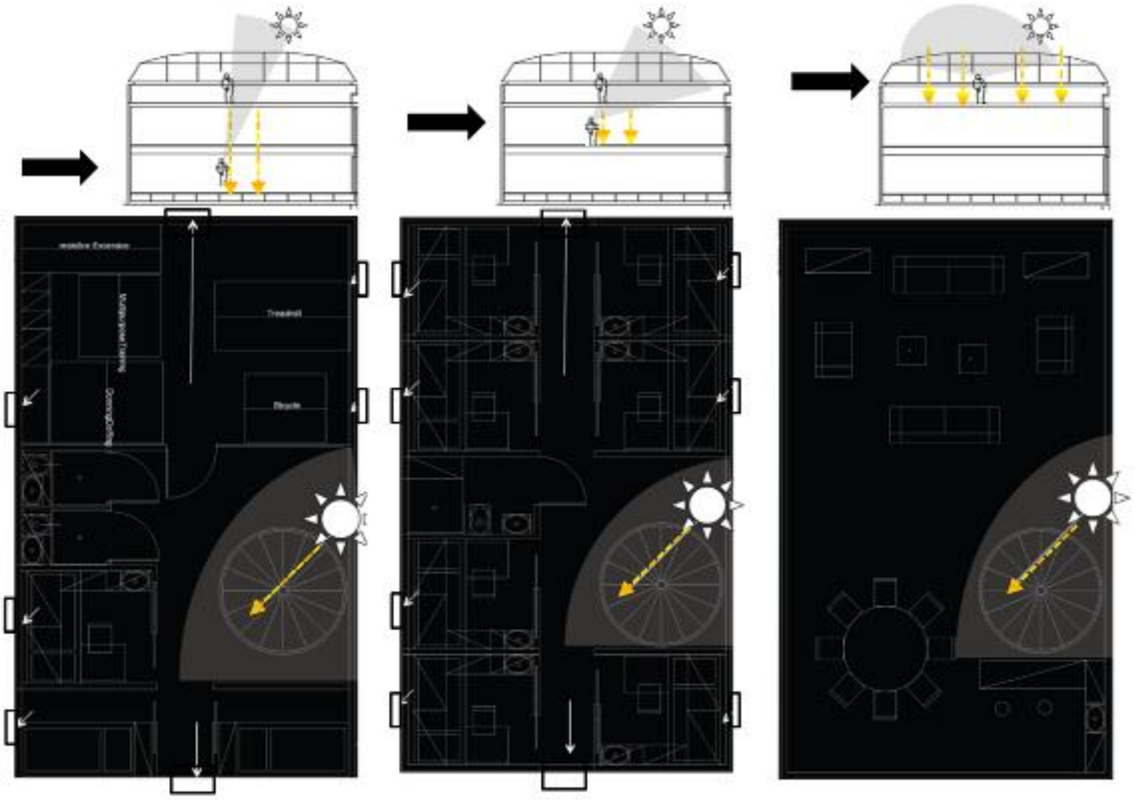


Figure 5.35: FLaSH living module, first, second and third floors, drawings by Irene Lia Schlacht, Kijell Hermann, and Ondrej Doule (DLR FLaSH study in 2011)

- Working Modules

In the modules, high-tech automatic interfaces and a centralized alarm system connected with ground control, emergency exits, and fire extinguishers support the safety of the crew and minimize human maintenance work. The allocation of maintenance work is thus reduced to a minimum of four hours per shift for each of the eight crew members. This gives the opportunity to perform four hours of research, for a total of eight hours of work per day. In case of an overall system emergency, it has been calculated that only six hours are needed by all crew members to restore the system autonomously. Also, one day off per week has been allocated, with a minimum amount of 30 minutes of maintenance work per person, which only comprises the safety checklist. Shifts can be assigned in advance in order to give more flexibility regarding organizational issues. Night shifts are not recommended; the crew should maintain the same day-night cycle for different reasons:

- With a crew of eight, night work is not needed.
- Night work does not support social relations and communication among the crew and increases stress (e.g., disturbance of the circadian rhythm)
- Night work requires more energy for all systems (e.g., lights)

Each module without windows that has a high working time rate has been equipped with Sivra biodynamical lights (Daniele Bedini, © I-Guzzini, Italy). The system mimics the circadian cycle of a day, supporting the circadian biorhythm of people and plants, as well as that of the fish in the animal module. As an optimal condition and new proposal, the light should be manipulated to also mimic the variation in color temperature throughout the year. It should be noted that unlike humans, plants and fish may also be selected without attention to this kind of needs: this is primarily necessary for areas where human beings work continuously. Another technology related to the installation of natural light is the utilization of polymer optical fibers. These fibers collect solar light from outside and guide it inside the module. For example, when applying such a “sollektor” (Stefanie Gabel, © Pofac, Germany) “the radiated light, when coupled to a light guide (plastic tube with reflection coating inside), corresponds to about 50 halogen bulbs 100 W each, but blocks the inherent heat usually generated with it” (Gabel, 2005).

- Habitability

In the whole habitat: Bathrooms, air condition system, lighting system, temperature control, humidity, and pressure are set up to support human needs and flexibility. In particular, a dedicated worksheet was used for the calculation of the input and output regarding physiological aspects. The environmental requirements mostly focused on the protection and the maintenance of the structure in relation to environmental factors such as snow, rain, and wind. The environmental effects of the external environment have to be adequately considered after the location has been determined. In Germany, for example, the fact that temperatures may drop to -20 degrees Celsius in the winter may affect the internal temperature of the structure if not considered in advance. Socio-cultural factors supporting personal development were considered by providing dedicated equipment such as a library, and a social area such as the cupola of the living module. Also, training and crew selection were presented as fundamental factors affecting the crew from the physiological and operational perspectives, and also with regard to psycho-social stability. The crew should be of mixed gender to represent the human parameters of the population in closed-loop research.

- Ethics

Finally, from the ethical perspective, the crew members were taking part in the experiment as volunteers. They also had the possibility to interrupt and leave the experiment at any time.

Public involvement can also be planned, provided ethical issues are considered and the voluntary involvement of the crew is obtained. For example, a webcam showing the crew’s activities is already in use at the MDRS facility (with real-time refresh every 3-4 minutes) and published online at http://www.freemars.org/mdrscam/. However, no audio is transmitted and private areas are not filmed. The possibility of making a documentary one day per week can be supported by a structured time schedule, but takes away the crew members’ day off. For this reason, it is suggested that only one of the eight crew members at a time should perform this activity. If possible, this should be integrated into the weekly working hours. However, if this is not possible, this may result at worse in taking out the weekly day off of each person once every eight weeks, which is acceptable.

The day off is necessary for the crew members not only for ethical reasons, but also for psycho-physiological reasons. It is absolutely fundamental to have a day to relax, where one can perform any activity, completely independent of the daily schedule. This also increases creative performance.

- Public Relations

The purpose of the facility will not only be scientific research and technology testing, but also education and sensibilization regarding the topics involved. On this level, the place also has a high potential of reaching sponsors. There are many possibilities to achieve this: dissemination via television programs and newspaper interviews, and publication of scientific results and progress. The use of the facility for public relations can be both for entertainment and education, to reach an audience ranging from the young to the old, and also for scientific progress, reaching a scientific audience. For example, cameras can be installed inside the facility to show daily life in a closed-loop environment. A series of documentaries can also be recorded on a weekly basis, which would take one day off per crew member per week. Detailed ethical considerations need to be implemented in order to seriously deal with the ethical aspects of public relations, such as privacy or workload (cf. part *Human Factors*, paragraph *Ethics*).

It is suggested that the construction and the corporate image should be designed to support this kind of activities. The building may be appealing and modern: For example, the structure of the model may be covered with highly impact-resistant panels, which could also serve to offer protection against environmental factors.



Figure 5.36, 5.37, 5.38: Frank Ghery architectures in Bilbao and Berlin.

5.4.3 CEF Result Validation

The FLaSH study was the first and only study performed until now on a human habitat at the DLR facility. For this reason, the results are here compared with the standard CED procedures used at DLR and the standard CDF procedure used at ESA.

From the workshop process it emerges that all elements of the IDP were supported, even including a new element: innovation. Indeed, taking into account that the workshop was not only aimed at finding results, but also at preparing the design procedure for the A(0) phase, the IDP approach has been able to also support innovation both in the process and in the design results. Sound and justified suggestions and propositions have been presented in the process, which are based on:

- Habitability factors
- User-centered approach
- Holistic methodology
- Innovation

The workshop results illustrate that all the process elements have been applied to a design based on:

- Usability
- Livability
- Flexibility
- Innovation

In particular, the final configuration is based on the testing of innovative technology, which supports flexibility thanks to the possibility of pulling modules out, modifying them, and putting them back. Livability was supported within each individual habitability factor (for details, see the table in *0*), and usability was supported both by the holistic methodology and the user-centered design, which were mainly applied to support the user needs regarding all of the disciplines.

The contribution of the IDP added a new qualitative dimension indispensable to human well-being and overall system performance. In contrast, the classical methodology used at DLR and ESA aims at supporting the set-up of robotic missions and does not need those qualities. It is evident that the application of the robotic mission process to human missions cannot support the quality of life needed during long duration missions and, as a consequence, will have a negative impact on mission success.

Table 5.24: CEF-IDP Disciplines at FLaSH Workshop (Bandecchi et al. 2000, DLR, 2011b, ESA, 2007 & 2011b; Romberg et al., 2008).

	QUALITIES ON THE RESULT				HF HABITABILITY FACTORS				USER-CENTERED APPROACH			HOLISTIC METHODOLOGY		
	Innovation	Usability	Livability	Flexibility	Operational	Physiological	Psychological	Socio-Cultural	User Experience	Participatory Design	Empathetic Design	Concurrent Design	Multidisciplinary Design	Human-Machine-Environment Interaction
CEF-IDP	v	v	v	v	v	v	v	v	v	v	v	v	v	v
CEF	v				v							v	v	
ESA	v					v						v	v	

5.5 CONCLUSION

The IDP concept model has been applied in four stidies. Within a specific process of verification to the results, it has been demonstrated that it fully meets the objective of increasing the sustainability of habitability solutions for human space missions.

To verify the validity of this methodology, the IDP has been applied to the conceptual phase of studies related to long duration space missions. The case studies varied from the design of an individual element of the system, such as debriefing procedures, sensory stimulation, entertainment, and fitness equipment, to overall habitat design, such as the design of a Moon Base.

- The aim of the first study was to design a Moon Base habitat. The study was conducted by two teams of students in the context of a Space Station Design Workshop, which is performed every year at the University of Stuttgart. The results were compared with the results of the teams that applied the usual methodology. The comparison revealed that the IDP teams focused more on the human factors in the project and found highly innovative solutions by applying new technologies to increase habitability in long duration missions.
- The aim of the second study was to perform research on human aspects in preparation for future extra-terrestrial planetary exploration. The study was conducted during ESA-ILEWG mission campaigns at the Mars Desert Research Station. Habitability debriefing procedures, creative activities, and innovative sensory equipment to counteract sensory monotony were prepared and tested. The results were compared with the previous year one. The comparison revealed that both studies dealt with problems related to the working conditions; however, the IDP study tackled problems related also to the working conditions, supporting personal expressions and creative approaches, which are needed for acquiring and communicating new knowledge, finding problem solutions in unknown scenarios, but also for psychological stability.
- The aim of the third study was to find solutions to habitability problems in long duration missions. The study was conducted with three classes of students of the Human-Machine System Chair at TU-Berlin. During the study, new disciplines specifically applied to the space context were created. New technology and equipment were developed that considered the challenges related to space habitability right from the start. The result revealed that the class attempted to find innovative design solutions and equipment dedicated to the difficult space scenario. This turned out to effectively support user needs from a multidisciplinary perspective.
- The fourth study concerned the conceptual design of the first habitat design realized by the German Space Agency DLR for a closed-loop habitat facility for long duration space missions. In comparison to the standard procedures used for robotic missions, a more dynamic procedure was incorporated, which fully integrated user-centered design and a holistic methodology. This resulted not only in support for problems related to physical and operational factors, but also led to a new project solution related to psychological and socio-cultural human needs.

The results verify that in all research phases and when considered as a whole, the IDP sustains not only functional but also sensory, cultural, and emotional needs in the habitat system. Before, space projects were based only on operational and physical needs. The IDP methodology also supports psychological and socio-cultural factors. In comparison to the classical quantitative design process used by space agencies, this process also supports the qualitative dimension of habitability and the social and “cultural significance of human space exploration” (Arts Catalyst, 2005). Finally, in comparison with projects carried out without the IDP methodology, the results show high value scores, following an evaluation system based on usability, livability, flexibility (Häuplik-Meusburger, 2011), and innovation values.

"I often hear that our space program
is all about doing science.
It is about much more than that.
It is about opening up a new frontier"
Astronaut Ed Lu (2003).

6. CONCLUSION

In the conclusion, verification is performed by comparing the initial goal and the meta-objectives to the overall achievements of this thesis and checking their fulfillment. In the discussion section, a critical review of the achievements is presented. Finally, possible future applications are also sketched.

Space missions are performed to make the human dream of getting to know the universe at large come true. This research aims to realize the optimum level of habitability and performance for astronauts in order to allow them to reach and communicate new heights and reveal the unknown so as to benefit all of humankind. The currrent design process for human space missions does not properly integrate the basic principle of quality of life into the astronauts' environment. However, this is necessary to achieve not only new knowledge, but also to ensure the safety of the astronauts. Considering the need to integrate this principle from the start of the mission design, the Integrated Design Process is the concept of a design model that aims to fulfill this need. This concept model has been used in different projects and experiments, in particular considering the context of long duration and long range missions. The results increase the sustainability and quality of habitability solutions for human space missions in order to support astronaut performance and safety.

6.1 Achievements Verification

To verify the fulfillment of the main goal and the meta-objectives of this thesis (cf. *subchapter 1.2*), the achievements presented in this dissertation are evaluated here.

1. To identify possible field challenges and their roots.

Challenges have been found, after a deep analysis of the state of the art and the user needs (cf. *subchapter 3.1, chapter 2,* in particular *subchapter 2.5*), in the low habitability caused by the lack of HF and an interdisciplinary design methodology from the start of the mission design process (cf. *section 3.1.4, subchapter 3.2*; in particular *subchapter 3.3*).

2. To find solutions for the challenges

A solution to the challenges has been identified with the creation of a concept of a new design model named Integrated Design Methodology (IDP). The IDP aims to provide interdisciplinary integration of sound HF design from the preliminary conceptual phase into all phases of human space mission design (cf. *chapter 4,* in particular *subchapter 4.3*).

3. To create the context for the application solution

The low sensitivity among space field experts regarding HF was identified as a possible problem that may hinder the application of the solution. The overall research was developed, presented, and discussed with field experts both in university and industry contexts (cf. personal communications quoted throughout this thesis). This strategy led to an increase in sensitivity regarding the relevance of HF design applied to human space missions, and opened up opportunities for applying the solution within university and industry contexts (cf. *chapter 5*).

4. To apply the solution

The IDP was applied in the conceptual stage of four case studies aimed at implementing habitability in long duration missions. As a part of the IDP concept, a user-centered approach and holistic methodology were integrated into the projects in order to support the interdisciplinary design of HF solutions (cf. *chapter 5* and, in particular, *subchapter 5.5*).

5. Verify the resolution of the challenges

The verification of the increase in habitability due to the application of the IDP were evaluated by comparing the result with the methodology currently applied as the state of the art. The solutions found in the application of the IDP enhance the projects´ usability, livability, and flexibility, as well as the design of innovative project solutions, which in turn increases habitability (cf. *section 5.1.3*, *section 5.2.3*, *section 5.3.2*, *section 5.4.3* and *subchapter 5.5*).

6. To achieve the main goal

The main goal of increasing habitability by enhancing the capability for designing human space missions through the application of the IDP was verified by checking the fulfillment of the meta-objectives 1 to 5 (cf. *subchapter 6.1*).

The conclusion drawn from the verification is that the goal and all meta-objectives have been fullfilled.

6.2 Discussion

On November 2, 2000, humans established a permanent presence in space on board the ISS. From the inception of the ISS through the conclusion of expedition 28 in September 2011, 551 humans have logged in space flight, accumulating knowledge and skills that will be critical to allow human beings to move beyond low earth orbit and explore Earth’s neighborhood (Harwood & Navias, 2010; NASA 2011f, 2011g). Long duration space flight on board the ISS as well as in previous missions such as Skylab and Mir has introduced new challenges in the field of habitability and human factors. One of the biggest challenges is building and maintaining a habitable environment in space (AIAA, 2006). Considering the extreme conditions of space (with differences in gravity, radiation, micro-meteorites, dust, no pressure, isolation), a complex system needs to be built in order to enable human life in space. For a system to be habitable, it must provide an adequate living environment for humans where there is ample space and protection from hazards, and measures have to be taken to ensure their quality of life and overall system performance.

Challenges

To ensure quality of life and overall system performance, the first step that is needed is a user analysis. Data collected from astronauts of the ISS, the Space Shuttle, Mir and Spacelab have been used. Various avenues have been explored to collect this data, including: analysis of astronauts' debriefings, interviews with astronauts, questionnaires completed by astronauts, mission simulation analyses, and an analysis of the publications on these topics. The interviews and questionnaires as well as the mission simulation analyses were performed from 2004 to 2011, with the courtesy voluntary cooperation of a total of 14 astronauts. Crew debriefings had been performed previously by NASA, and 56 publications (on habitability problems ranging from the Apollo missions to the ISS) published between 1965 and 2011 were also analyzed (cf. *chapter 3*).

From the user analysis, it emerged that as the state of the art, only physical and functional elements are currently supported during space missions, without consideration for psychological and socio-cultural factors, which are necessary to support performance and safety. Considering the history of human space flight and its military background, the goal was more the success of a country than the acquisition of new knowledge. This led to a gap in the support of the users' quality of life (cf. *section 3.2.1*, part *Machine-Centered Design*). The root of this gap has been identified as being the mission design process, which allocates only engineering factors from the start of the design process, and HF only at the end, when the resource budget is depleted (cf. *section 3.2.1*, part *Need for Architect and Designer*). The goal of HF, as a discipline, is to design to accommodate the user and not force the user to fit into the design. Training and selection are used to fit the human into a poorly designed environment; however, these should be used to optimize human performance, in an environment designed with the aim of supporting quality of life and usability. Through HF and habitability design, humans have a major influence on the design, development, and verification of the space habitat system. Habitability research aims to ensure that the needs of crew members are fulfilled in order to allow them to live and work productively, particularly under the difficult conditions of long duration/range space missions.

Since long duration space flight is still in its infancy, and due to the limited experience available in this area, the implementation of the human factors principle of design has not always been optimal. It is critical to capture knowledge gained during long duration space missions not only quantitatively, but also qualitatively, in order to improve the capability to accommodate the crew in future space programs (AIAA, 2006). Full integration of the qualitative dimension, with descriptive and not only numerical variables, is essential for charting our future path in human space exploration.

Need for a Solution

This work documents and investigates a new methodology for implementing astronauts' quality of life and system performance during the design process, from the user debriefing to the design requirements and specification. The focus of this work is on the HF and habitability design process. The knowledge gained in space HF and habitability through in-orbit crew experiences has provided significant information sources. This information has resulted in the identification of four critical habitability factors that need to be applied together with the full integration of HF into the remainder of current space station design and future space exploration endeavors.

These four interdisciplinary factors are:

- Operational factors
- Physical (environmental, physiological) factors
- Psychological factors
- Socio-cultural factors

Compared to the state of the art, there are two main factors that have not been considered to date: psychological and socio-cultural factors. However, the lack of qualitative dimensions has been proven for all the factors that have been addressed only quantitatively until now.

The analysis of the problem of habitability revealed that the biggest challenges are posed by excessive in-orbit storage (operational) and the interior design of the habitat (physical), but also by an absence of flexibility and privacy, which are qualitative psychological and socio-cultural factors. Unlike the astronauts, space employees related the lack of habitability to the constrained space, seeing it mainly as a quantitative physical and operational factor.

Considering long duration as well as long range missions, variability is also becoming ever more important, and autonomy has emerged from the investigation as a possible new problem related to future missions.

To face these circumstances, a project needs to be oriented towards three main qualitative variables (Häuplik-Meusburger, 2011):

- Usability
- Livability
- Flexibility

Based on automated interfaces that require low maintenance with:

- Innovation

And supported by these design principles:

- Human-centered approach
- Holistic methodology

The human-centered approach attempts to accomplish these qualitative variables by designing to accommodate the user within the design. The holistic methodology accommodates human-centered design while considering the influence of the overall system. Both of these processes have been missing to date as far as space station design is concerned. The application of human-centered design and a holistic methodology needs to be supported by the integration of the HF discipline from the preliminary stage of the mission.Experience has shown that incorporation of human factors and habitability requirements and design principles early in the development process positively affects the design of a piece of hardware/software and limits the operational/re-engineering cost to the program associated with a poor design (Aguzzi, 2005; AIAA, 2006; ECSS, 2008; Messerschmid, 1999).

Work Contribution

The current situation of the space industry does not support the human factors discipline from the preliminary stage of a project, causing low usability, habitability, and flexibility.

The resulting low habitability affects the productivity of the astronauts. Considering that in long duration missions, habitability as well as system autonomy become fundamentally important, the need emerges for a better sustainable environment able to support human quality of life and system performance.

The hypothesis of this work was that when considering the scenario of long duration missions, integrating the HF discipline as part of habitability requirements and design principles from the preliminary stage of the design process would increase the user's quality of life as well as overall system performance.

The contribution of this work is the creation of a new design process called "Integrated Design Process" (IDP), which integrates HF from the preliminary design stage on in order to support:

- Habitability factors (operational, physical, psychological, socio-cultural)
- Project qualities (usability, livability, flexibility, innovation)
- Design principles (user-centered approach, holistic design)

The IDP methodology has been applied in four case studies:

- SSDW design project
- MDRS habitability investigation
- MMS TU-Berlin university course
- CDF workshop project

During the studies, the qualities and habitability factors were identified as user needs for long duration space missions, and the user-centered approach together with the holistic methodology was identified as a methodology for supporting the identified needs. In each case study that applied the IDP methodology, these qualities and habitability factors as well as the user-centered approach and the holistic methodology received complete and comprehensive support. Finally (as presented in *Table 6.1*) the result from the application of the new IDP project methodology was compared with the methodology previously used, showing that the latter only partly integrates the elements considered within the IDP.

As a conclusion the results show that the IDP creates projects for long duration missions that are able to increase habitability, support the quality of life, and find innovative solutions. As a consequence, user autonomy, performance, and safety are supported in the context of quality of life.

Table 6.1: IDP Research process and current process in comparison

	USER NEEDS IN LONG DURATION MISSIONS								METHODOLOGY APPLIED TO SUPPORT THE NEEDS					
	RESULTING QUALITIES				HF HABITABILITY FACTORS				USER-CENTERED APPROACH			HOLISTIC METHODOLOGY		
	Innovation	Usability	Livability	Flexibility	Operational	Physiological	Psychological	Socio-Cultural	User Experience	Participatory Design	Empathetic Design	Concurrent Design	Multidisciplinary Design	Human-Machine-Environment Interaction
USERNEED	v	v	v	v	v	v	v	v						
METHODS									v	v	v	v	v	v
Study 1														
SSDW-IDP	v	v	v	v	v	v	v	v	v	v	v	v	v	v
SSDW		v			v	v				v		v	v	
Study 2														
MDRS-IDP	v	v	v	v	v	v	v	v	v	v	v	v	v	v
MDRS-HC	v	v			v	v				v	v			v
Study 3														
MMS-IDP	v	v	v	v	v	v	v	v	v	v	v	v	v	v
ESA	v					v						v	v	
Study 4														
CEF-IDP	v	v	v	v	v	v	v	v	v	v	v	v	v	v
CEF	v				v							v	v	
IDP														
ACTUAL														

Index.

IDP (Integrate Design Process)
SSDW (Space Station Design Workshop)
MMS (Chair of Human-Machine Systems)
ESA (European Space Agency)
CEF (Concurrent Engineer Facility from German Space Agency DLR)
v=meet the definition;
Colors: Light grey=satisfy on 1 study; middle grey= satisfy on 2 studies; dark grey=satisfy on 3 studies; very dark grey=satisfy on 4 study.

6.3 Final Considerations

Living and working in extra-terrestrial habitats means being potentially vulnerable to very harsh environmental, social, and psychological conditions. Different from machines, “human requirements are not secured constants; instead they are a product of our society and the experience made in it by individuals within a certain time and specific environment”. For this reason the human needs are the result of the unpredictability of the constant interaction between humans and the space environment. “So far this mutable constant was neglected in manned mission strategies” (Häuplik-Meusburger, 2005 p. 1). However, experience shows that the factor time, and thus unpredictability, must be taken into account in the first draft and onwards from there. For this reason it is essential to apply in the project all the dynamics that are currently part of the design and architecture process. Only mutual cooperation between people with a technical or engineering background and people with expertise in the design of human factors will allow achieving a sustainable and competitive system to support human life in space.

If one of the main goals of human space exploration is the furthering of knowledge, creating the best and safest habitability conditions to facilitate such a quest for knowledge must be at the forefront of space research. As demonstrated in this research, this can be supported by integrating the discipline of human factors into the design of long duration space missions through the application of the Integrated Design Process. This methodology increases habitability in the most extreme, life-threatening conditions in which humans are able to live.

Further development of the model from the conceptual stage to actual application has been considered as a post-doctoral proposition for the Concurrent Design Facility at the European Space Agency, as part of a cooperation request regarding the further development of the first DLR CDF project for human long duration missions.

Moreover, further applications of the IDP methodology may also include different contexts, such as improving habitability in retirement homes, prisons, research facilities in extreme environments such as Antarctica or underwater facilities, as well as other contexts much closer related to the acquisition of experience in extreme environments, such as in the newly emerging field of space tourism. The rapid growth of the world’s population and the proliferation of megacities also increase the need for sustainable human-machine-environment systems, making the IDP not only applicable in extreme environments but also in our daily lives.

Man knows at last that he is alone
in the universe's unfeeling immensity
out of which he emerged only by chance.
His destiny is no where spelled out,
nor is his duty.
(Jacques Monod, 1971 p. 143)

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STS 127, 2011, http://spacegizmo.livingdazed.com/wp-content/uploads/2009/07/Crowded-ISS.jpg

Appendix

Appendix A refers to
2.1.3 Interdisciplinary Habitability Design

The overview of space life is based on comments and explanations from people directly involved in space flight and might help provide a better understanding of what these activities entail. Interviews with NASA experts and astronauts like Dr. Voss (veteran of five space shuttle flights, 1997 to 2000) and Dr. Lu (veteran of two space shuttle flights in 1997 and 2000, and one 6-month ISS mission in 2003) are also reported (NASA, 2011b).

Movements and Proxemics

In microgravity, you are floating. In order to move, at first you need to reach something fixed on the station. Handrails are provided for that, and after you grab one of those, you can push yourself in an amazing fly. Movement influences the distance with other crew members, contributing to proxemics relations and involving socio-cultural factors (Masali et al., 2010).

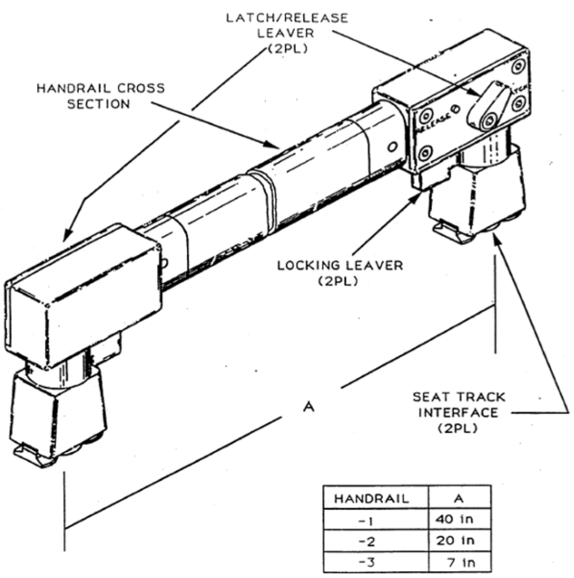


Figure 0.1: Removable ISS handrail (NASA, 2010b, Figure 9.7-1 p. 680; NASA, 1999 pp. 5-27)

In the author's personal experience gained during parabolic flight, she learned that being small can leave you in the middle of the flight without the possibility to move if you are not able to grab something fixed. In this situation, the body reacts instinctively. The funny reaction you may have is to try and swim in the air even though you are conscious that there is no water around you that causes the friction to let you move.

Coordinating yourself in microgravity is not easy and it is even more difficult if you think of the crowded ISS environment where everything is covered with expensive instruments.

Expedition 7 NASA ISS Science Officer Ed Lu described how he flew in the ISS: “[we] almost never run into anything now, and I can zip from one end of the station to the other in no time. My technique for flying is a little different. Instead of flying headfirst like Superman, which requires that you first rotate your body so that it is pointing where you want to go, I find that it is easiest to simply launch yourself in whatever direction your body is aligned. Then I use a hand to absorb the energy and rebound off the wall or ceiling while changing my direction as well as rotating my body, then again rebound off the next surface with my feet. Each time I rebound I slowly correct my direction and rotation until I am going where I want. Usually it only takes 2 bounces. If you've ever seen the cartoon "The Tick" - I move around something like the Tick when he bounds around the city, except I don't crush anything. I like to do flips and spins when I fly around now” (Lu, 2003).

Neutral Posture

In space, there is no difference between standing up and lying down.

When astronauts stand still, e.g., when they are working at the computer, relaxing, or even sleeping, they assume the neutral posture. This is really similar to the fetal posture and is defined as the position “in which there is the least tension or pressure on nerves, tendons, muscles and bones” (University of Connecticut, 2011).

The neutral posture in microgravity is automatically assumed when the muscles relax, and in comparison with the normal sitting or upright earthly posture, it “generates a distorted relationship among the bodily geometry, such as between the expected position of the hands and sight line as in the case of the use of a laptop computer” (Masali et al., 2010 p. 3). For example, in comparison with the standstill posture, “the sight line drops 25-30 degrees down with respect to the Ohr-Augen-Ebene (OAE) or Frankfurt horizontal Plane” (Masali, 2010b p. 168). On earth, “we look about five meters away on the ground to see way ahead and, maybe, obstacles and perils” (Masali, 2010b p. 168). The sight drops in microgravity and “in an evolutionary frame this means an extraordinary conflict with the rotation of the basicranium and the increasing of the occipital surface” (Masali, 2010b p. 168). Moreover, shortening the range of vision increases the possibility of myopia (Schlacht and Birke, 2010).

“The neutral posture adopted by humans in space offers a range of new body movements, gestures as well as repositioning of the body in unexpected manners defining a different workspace envelope. It is therefore necessary to identify the new postural parameters, postural coordinates and their relationship within the man–object interface (ergonomic approach) as well as the interpersonal relationship of those working together in zero gravity field (proxemic approach)” (Masali et al., 2010 p. 4).

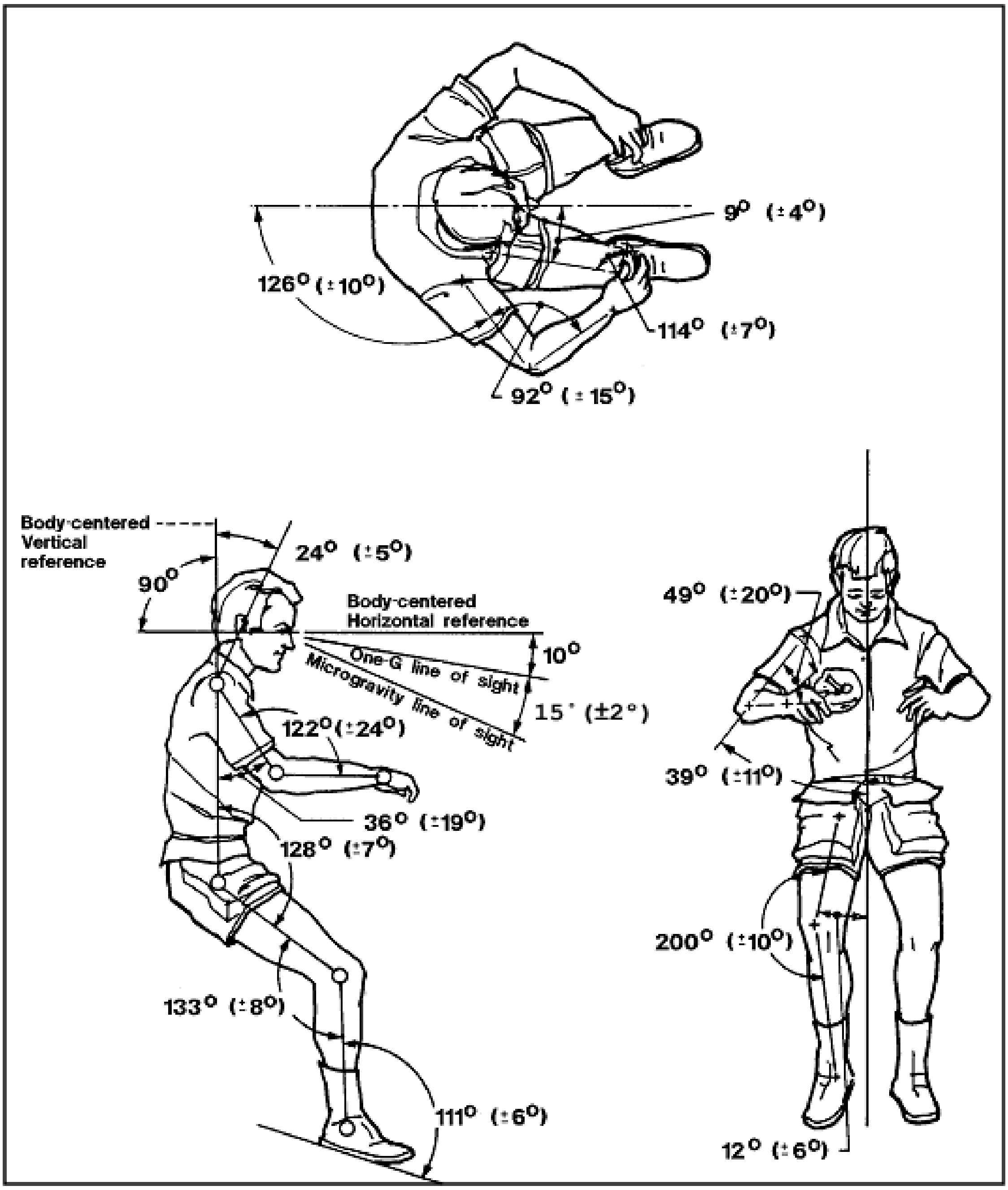


Figure 0.2: Neutral body posture (Griffin, 1978, cited after NASA, 1995 STD 3000, Figure 3.3.4.3-1). The neutral posture changes the angles of joints and the line of sight.

As explained above in part *Movements and Proxemics*, moving is particularly easy in weightlessness. In contrast, not moving – i.e., standing still – is not an easy task. It involves a completely different effort and logic than on Earth.

Astronauts grab handrails to move. But sometimes they use handrails also “to hold themselves with their feet which usually are barefoot” (Ferraris, 2004 p. 74).

“Handrails are simple to install and reposition” (Ferraris, 2004 p. 73), but they are not made to help astronauts stand still. To stand still, other specific restraints are available on the ISS. However, they are reported to be neither simple to install nor comfortable to use (Ferraris, 2004).

The ISS restraints for standing still are the following (NASA, 1999; Ferraris, 2004):

- Long Duration Foot Restraint: holds both feet; it may cause pain after a long time.
- Short Duration Foot Restraint: it holds only one foot; it does not support body rotation.
- Fixed or Adjustable Length Tether: This is a fixed or adjustable length of Kevlar strap with karabiner hooks at the ends; they support the tension force but not the compression force.
- Torso Restraint Assembly: This is an adjustable belt assembly; it takes long to be installed.

These facilities are not frequently used. The main problems are that they do not support the neutral posture; they do not follow the natural body shape and movement; they need more time to be placed, displaced and wear; and they are made of material that is uncomfortable to touch (Ferraris, 2004). In particular, the neutral posture changes the angles of the joint, e.g., the foot angle has 20 degrees of difference (Messerschmid, 2008).

Eating

Food and drink have been developed so as not to generate hygienic problems. They should be easy to swallow and digest and also easy to prepare and consume (NASA, 2000). The Food Systems Engineering Facility (FSEF) at the NASA Johnson Space Center (Houston, Texas) takes care of nutritional values, sensory impression, preservation, and stocking. Other relevant challenges relating to food and drink are temperature, flight acceleration and vibration, and the small storage place available.

In the ISS, “the Russian Zvezda service module is used to prepare meals” (NASA, 2002). “During a typical meal in space, a meal tray is used to hold the food containers. The tray can be attached to an astronaut's lap by a strap or attached to a wall” (NASA, 1996). In microgravity, as astronaut Janice Voss explains, to hydrate and also to prevent that the food flies away, water is added and the food becomes more moist and sticky. The ready-made food is eaten with classical western cutlery in metal and plastic during one of the three meals lasting one hour each (Voss, 2003).

“Astronauts will choose 28-day flight menus approximately six months prelaunch” (NASA, 1996). However, astronauts report different taste perception in microgravity and it is not uncommon that they dislike the meals they selected. With longer mission duration, it becomes more relevant that the food must be “satisfying and delicious as well as nutritionally balanced” as explained by Vikie Klories, subsystem manager for Shuttle and ISS food, FSEF, JSC (Ferraris, 2004).

The water is recycled from the liquid of the urine to the vapor of the breath and then warmed if necessary. As Ed Lu explains: “We humans exhale water vapor (breathe on a cold window to see that), and this water is condensed out of the air using something similar to an air conditioner. The water is then purified and we use it for drinking water” (Lu, 2003).

Sleeping

Most of the astronauts sleep in sleeping bags, which “they just attach to a wall or floor or ceiling to sleep” (Dennis Dillman communication 1997, in NASA, 2011). Inside the ISS, they can sleep in the two-person crew quarters with a window in the Zvezda Service Module (Dismukes, 2003) or in the sleep station, which is “only used on flights where the crew is working around the clock in two shifts”. In addition, “there are some astronauts who just like to sleep floating around” (Karina Shook communication 1999, in NASA, 2011).

Sleeping in space is not so simple and most of the astronauts are reported to sleep only for six of the eight planned hours. Sean Kelley explains: “Sleep pattern changes have been subjectively reported by astronauts and cosmonauts since the beginnings of space travel, and the use of pharmacological agents to initiate sleep are also fairly common” (Sean Kelley communication 1999, in NASA, 2011).

“You need to get used to the lack of touch on your back or on your side, because you are really floating in your bag, only lightly touched by the ties holding you down. Thus, the feeling of tired heaviness which makes you “hit the sack” and feel sleepy in bed, is absent, and some astronauts cannot really get used to that. …Every time that I got into it and closed my eyes I feel like falling. Now I have learned that I string out my sleeping bags like a hammock and make it as tight as I can and then I get in it and zip it up and use those Velcro® straps and make it as tight as I can. I need to feel like I am tied down to something touching something, or I feel like I am falling and it will wake me up” (NASA, 2001).

However, there are astronauts that think differently. The veteran astronaut Dr. Voss reminisces: “It's just lovely sleeping in space, because you just instantly relax. There's no pressure in your shoulders and hips and it's just lovely” (Voss, 2003).

Also, noise from the fans that circulate the air is responsible for aggravating sleeplessness; however, also in this circumstance, astronauts react differently: “[It] makes it easy to go to sleep, just like your fan at home” (Joe Tanner communication 1997, in NASA, 2011).

Besides, “the excitement of being in space and motion sickness can disrupt an astronaut's sleep pattern” (Dismukes, 2003). When it is time to wake up, a shuttle crew receives wake-up music, which is selected each time by a different astronaut, whereas a space station crew uses an alarm clock (Dismukes, 2003).

In conclusion, the majority of the astronauts sleep for six hours. Studies on sleep and circadian cycle have reported that after seven days of six hours of sleep, a person’s performance is equal to that of a person who has not slept for 24 to 36 consecutive hours. Lack of sleep slows the mental processes and compromises reasoning ability and memory, with worrying consequences upon the crewmembers’ return and upon the efficiency and therefore the safety of the mission (Monk, 1996).

Personal Hygiene

Microgravity “makes going to the bathroom rather difficult” (Dennis Dillman communication 1997, in NASA, 2011). On the ISS, the toilet is composed of a small cabin with the Waste Collect System (WCS), a multifunctional system used to collect, recycle, or process biological wastes (Thomas and Oliveaux, 1999).

Expedition 7 NASA ISS Science Officer Ed Lu wrote about the Progress spacecraft: “The toilet is operated by air pressure. A fan does the work that gravity does on the ground. Urine is sucked inside the toilet and is collected in a 20-liter container. When these are full they are discarded in the *Progress*. For collecting solid waste the toilet has plastic bags you place inside, and air is sucked through tiny holes in the bag. Everything gets collected in the bag (hopefully) and the bags self-close with an elastic string around the opening. You then push the closed bag through a hole into an aluminum container, and put a new bag in place for the next person.” (Lu, 2003).

Technically, the WCS consists of two foot restraints and two body restraints to position and hold yourself on the seat for solid biological wastes. For urine, the astronaut uses a personal funnel attached to a hose, and the funnel is differently shaped for women and men (Thomas and Oliveaux, 1999).

The toilet is also used by the astronauts to wash, shave, cut their hair, and maybe change. When they wash or shave, they need to take care not to disperse water drops or hair in the air. To suck up all the hair, they use a vacuum cleaner hose. Astronauts wash themselves with wet pipes soaked in body cleaning solution mixed with warm water and a dry shampoo. Taking into account that the solution and dry shampoo do not need rinsing, the astronauts use four liters of water instead of 50 used to wash on earth (Thomas and Oliveaux, 1999). “We don't have a shower up here (the water wouldn't go down through the drain anyhow), so we wash using no-rinse soap and shampoo and a towel. It is the same stuff they use in hospitals for bedridden patients, and it works really well. That being said I am looking forward to a long hot shower when I get home” (Lu, 2003).

Working

The main work on board is related to

- experiments, observation and reports,
- education and media activities,
- personal physical maintenance,
- instruments and station maintenance and operation,

and, as explained by Astronaut Ed Lu, most of all, to work on getting the base ready for further space exploration.

“We work about 10 hours a day, with a half-day off on Saturday and a full day off on Sunday. …Our day-to-day operations, including repairs and maintenance, are giving us experience that will hopefully help us design and operate long-duration missions to asteroids and to Mars. Sometimes the lessons we learn are how to do things, sometimes the lessons are how not to do things. But we, as well as the engineers, managers, and scientists, are learning things that can help us leave low Earth orbit and explore” (Lu, 2003).

Performance and Workload

As explained in "Living Aloft: Human Requirements for Extended Spaceflight", one of the master guides for space flight, "Maintaining skilled performance during extended spaceflight is of critical importance to the health and safety of crewmembers and to the overall success of the mission" (Connors et al., 2004).

Astronauts are trained to reach maximum performance in extremely difficult conditions. During the mission, they are confronted with the highest expectations; "they are therefore under constant performance stress to which must be also added the psychological discomfort (mainly due to the adaptation in microgravity) and the psychological discomforts (confinement, solitude, melancholy, lack of privacy, etc.)" (Ferraris, 2004).

Performance is a topic strictly connected with habitability, and performance assessment during preflight has been a useful tool for understanding habitability constraints, ultimately leading to guidelines in the layout and structural composition of spacecraft living and working quarters (Fraser, 1968; Barnes, 1969).

Everything is planned and tested on earth to ensure maximum habitability and performance, but the reality is quite different. The space environment is unique and even the best preflight assessment cannot completely avoid problems. This is why to guarantee the best performance, astronauts should commit themselves to optimize and increase the efficiency of the mission day by day. The ground system cannot plan the work schedule effectively, and the risk of the workload being too low or too high may deeply affect the astronaut's psychological balance.

Astronaut Lu explains: "Our job is to get all the tasks done. We often make suggestions for optimizing things, and we work together to make operations more efficient the next time. This is a very good system - think of how it would work if you had somebody several thousand miles away try to organize your day at the office down to the minute. It wouldn't work very well, since they are not there to make real-time decisions on what is best to do at any particular moment. You have certain things you need to get done each day, and you may juggle things around depending on how things are going. We do the same up here. Think of this as one big experimental vehicle - which it really is because it is the first of its type and one-of-a-kind" (Lu, 2003).

From Earth, sometimes the difficulties of working in space are not adequately taken into account. In reality, many problems and unplanned inconvenience always occur and flexibility is the first key word for assuring the best performance: "Although when you live in your office it is a little hard to draw the line between on duty and off duty - we are often called by the ground to perform some task when something goes wrong and they need our help on some procedure. By the way, the ground doesn't micromanage our time, and in fact most things on our schedule are very flexible".

As a conclusion, increasing habitability is of primary importance for increasing performance and mission success. Indeed, it is generally agreed that when the best comfort is offered to crewmembers during their task performance, the less stress they have, the better the result they achieve (Ferraris, 2004).

Habitat Maintenance

“We also have general housekeeping-type activities scheduled. These are things like cleaning filters, doing periodic inspections of our emergency equipment, sampling our water supply for contaminants, vacuuming out the air ducts, etc. These regularly scheduled tasks are something like household chores back home. We each usually have a couple of these a day. Today for instance, I'm scheduled for cleaning air ducts, rebooting the computers, and making some changes in our checklists” (Lu, 2003).

“Many pieces of equipment have fans to circulate air for cooling, and this equipment will have screens that need to be cleaned regularly (usually with tape or a portable vacuum cleaner we fly.) If you don't clean them on schedule, they could overheat and shut down” (Paul Ronney communication 1997, in NASA, 2011).

Physical Exercise

To move, astronauts grab restraints with their hands; legs are not used as the force of gravity does not need opposition anymore. Therefore, astronauts are expected to lose muscle mass, strength, power, weight, bony density, and cardiopulmonary reconditioning. In long duration missions, this is a serious threat to health. As a countermeasure, the daily schedule includes three hours of physical exercise (Wichman & Donaldson, 1996).

In an interview, D. F. Ongaro, former executive manager of the ESA Health Care Network, explains that “to carry out efficient countermeasure …[He] suggest[s] common aerobic/anaerobic exercises.., exercises against endurance for the force and power, and exercise for the bony problem…” (Ferraris, 2004 p. 69).

The main instruments available are a treadmill and a bicycle ergometer.

To counteract microgravity, the “Chibis” pants create decompression to favor blood rushing into the lower limbs and the “Penguin” suits weigh down on the spinal column and muscles (Ferraris, 2004).

Free Time

During free time, the time for cultural activities is really restricted, and as soon as the astronauts finish work, they go to the windows to watch the Earth. Indeed, this is the astronauts’ favorite activity during their free time. Astronauts can also watch the stars. They are really very similar to the view from dark places on Earth. But “they don't twinkle” according to Astronaut Voss. They look unreal: “It's like somebody took a picture of the sky because they're completely static” (Voss, 2003). As an additional pastime, some musical instruments are also available. Here is what the astronaut Ed Lu writes about his free time: “Following that is dinner (always a fun time!), and then we have a few hours of free time before bedtime to do what we choose. I spend this time working on some science experiments of my own…, sending and reading e-mails from home, and taking photographs out the window. There is also a small electronic piano up here that I like to tinker around on” (Lu, 2003).

"The strangest thing about playing music in Space," says the astronaut and musician Carl Walz, "is that it's not strange. In most homes, there's a musical instrument or two. And I think it's fitting that in a home in Space you have musical instruments as well. It's natural.” “Music makes it seem less like a Space ship, and more like a home" (Miller, 2003). Before he went up in 2001, the astronaut Carl Walz recalls that the psychological support people asked him what kind of things he'd be interested in taking along. He said: "Well, a keyboard would be nice." And they said: "We'll look into that" (Miller, 2003). This is why he could experience playing music as a recreational activity.

"When I played the flute in Space," says the astronaut Ochoa, "I had my feet in foot loops." In microgravity, even the small force of the air blowing out of the flute would be enough to move her around the shuttle cabin. In fact, even with her feet hooked into the loops, she could feel that force pushing her back and forth, "just a little bit", as she played (Miller, 2003).

Figure 0.3: Ed Lu, nicknamed Piano Man, follows a music score while Pedro Duque (right) turns the pages (NASA, 2009).

Motivation

Motivation is one of the core elements of living in an extremely dangerous and difficult environment. A positive approach to the space experience is not rare: "It's fun being with people who are having fun; people who are excited about space. Being part of that and knowing that what you're doing is making things better for everybody on this planet, it just puts a whole veil of fun over everything. The people that you meet are proud of what they do, they're excited about what they do, … and it's so special and so much fun to be part of that. Every day is a joy" (Voss, 2003). This interview makes it easy to understand how "the crewmembers are people trained to face difficult space conditions but they are also driven by high ideals, enthusiasm and passion for their job. This helps them to deal with in-orbit difficulties concerning the habitat but also the tasks they must perform and more generally speaking the danger of the space missions. Besides they are aware of the effort the community puts into the realization of space missions and have a sort of respect and sense of gratitude. This is why, if asked how bad the Space Station is, they would not complain. However if invited to advance possibilities of improvement they are willing to give their comments" (Ferraris, 2004).

Appendix B refers to 2.3.2 Machine (Space Habitat System)

Habitation and Pressurized Volume

"The habitable elements of the International Space Station are mainly a series of cylindrical modules. Many of the primary accommodations, including the waste management compartment and toilet, the galley, individual crew sleep compartments, and some of the exercise facilities, are in the Service Module (SM). A third sleep compartment is located in the U.S. Lab, and additional exercise equipment is in the U.S. Lab and the Node" (NASA, 2010 p. 81).

The habitable space is part of the pressurized volume. On the ISS, there are 837 m^3 of pressurized volume for a standard mission duration of 180 days and six crew members.

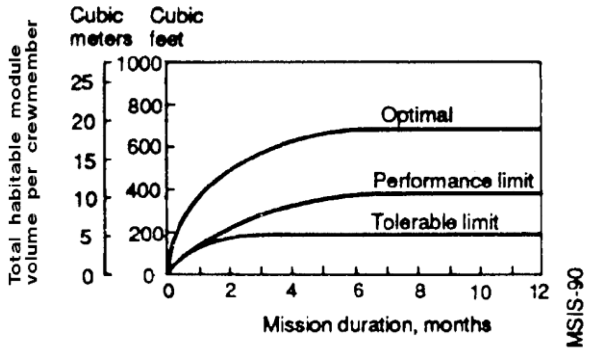


Figure 0.4: Guideline for Determination of Total Habitable Volume per Person in the Space Module (NASA-STD-3000 90 from AA.VV., 1999b, SSP 50008, Figure 8.6.2.1-1)

The pressurized volume is not equivalent to the habitable volume. The habitable volume and the Net Habitable Volume (NAV) depend on" constraints on spacecraft shape, equipment, and layout of areas" (NASA, 2010b p. 554, 562-3 part 8.2.4). Habitable volume, mission duration, and crew members give numbers that provide a starting point for determining the overall habitable size needed in a spacecraft. Even today, there are no recent and/or updated studies on the habitable size needed for long duration missions. To calculate the habitable volume, NASA applies an old logarithm used for military submarines in the 1960s.

The calculation of the habitable volume is based on the following underwater habitat logarithm: Habitable volume per crewmember = 6.67 x (days) -7.79.

This gives: 26.85 m^3 = 180 days

5.19 m^3 = 7 days (NASA, 2010b p. 562).

Following this calculation, the habitable volume for six months is 26.85 m^3 for each crew member, which means 161.1 m^3 for six crewmembers (NASA, 2010b p. 562).

The application of the NASA calculation of habitable volume may be compared to areas of apartments with a ceiling height of 3m.

- 161.1 m^3 = an area of 53.7 m^2 with the ceiling at 3m for six persons for 180 days.
- 5.19 m^3 = an area of 1.73 m^2 with the ceiling at 3m for one person for seven days.

The dimension for one person for one week of 1.73 m^2 is less than the space of 6 m^2 given to an isolation cell in an Italian prison (ex-prisoner interview, 2011).

It is interesting to note that for missions beyond low orbit, NASA states in a less recent publication: “There are not currently methods to determine …the amount of habitable space needed” but a minimum of 16.99 m^2 should be allocated as usable space for crewmembers (NASA, 2003 p. 47).

The ISS habitable volume data is not available; this is why only a hypothesis is possible using the known data. For example, it is possible to consider Node 2 inside the ISS, which has a pressurized volume of 79.4 m^3 and a habitable volume of 25.8 m^3. This corresponds to 32.5% of the pressurized volume. If one considers this data as applicable to the entire ISS, the habitable volume will correspond to around 1/3 of the pressurized volume, i.e., 1/3 of 837 m^3 is 279 m^3.

Compared to the 150 m^3 habitable volume calculated from the actual NASA standard that still applies in military volume constraints, fortunately on the ISS the six astronauts live for six months in more than four times the above NASA standard volume. Indeed, more current data on the needed habitable volume is missing.

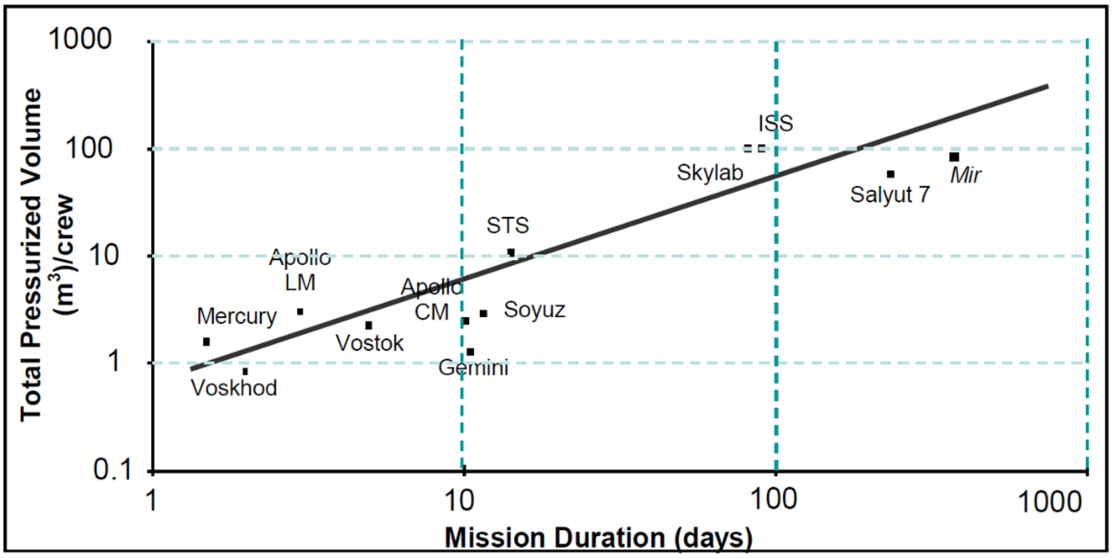


Figure 0.5: Spacecraft pressurized volume (NASA, 2010b p. 562, Figure 8.2-2)

Health and Safety

The Crew Health Care System (CHeCS) “is a suite of hardware on the ISS that provides the medical and environmental capabilities necessary to ensure the health and safety of crewmembers during long-duration missions” (NASA, 2010 p. 83). CHeCS is divided into three subsystems: the Countermeasures System (CMS) provides facilities for physical performance fitness; the environmental Health System (eHS) controls atmosphere, water, and microbial contamination as well as acoustic and radiation levels; the Health Maintenance System (HMS) provides medical and health care (NASA, 2010).

Life Support

The Environmental Control and Life Support System (ECLSS) provides and controls air, water, pressure, temperature, and humidity, but also detects and suppresses fire. This system is supposed to be as regenerative as possible to simulate the closed system on Earth. Recycled wastewater, including water from air humidity condensation and urine, is converted into “drinking water, oxygen for breathing and hydrogen” (NASA, 2010 p. 82).

Odor

Because of the small dimension of the system in comparison to earthly ones, problems such as noise and bad odor can occur. “Materials used in spaceflight are subjected to testing for odour as well as for flammability and toxicity” (Connors et al., 2004 p. 69). However, while materials are supposed to be odorless, humans are not. Usually the air inside the “spacecraft tends to be malodourous” due to the large amount of exhalations produced by the human body’s metabolism and the completely inefficient ventilation and air recycling (Ferraris, 2004 p. 79).

Odor can contribute to general annoyance: “Because particulate matter does not settle out in a weightless environment, odor problems in a space habitat may be more severe than under similar Earth conditions” (Connors et al., 2004 p. 69).

Noise and Music

“Noise has proven to be a problem in several confinement studies” (Farrell and Smith, 1964; Page et al., 1964; Grumman Aerospace Corporation, 1970; cited after Connors et al., 2004 p. 70). It impacts negatively on performance, behavior, physiological functions, motivation, and morale (Connors et al., 2004). Generally, it is considered that a sound level of “45 dB indoors is a desirable and safe maximum” tolerable level. This level supports primary communication, but also creates challenges such as sleep disturbances (Connors et al., 2004 p. 72). “During the launch and reentry phases, propulsion and aerodynamic noise levels can reach 120-130 dB in the cabin” (Connors et al., 2004 p. 73). “Levels of 65-70 dB have been reported for the Apollo” extended space flight (Von Gierke et al., 1975). In Skylab, “sound was considerably dampened, and astronauts separated by only a few meters had to shout at each other to be heard” (Johnson, 1974). And today on the ISS, the noise “can vary from 40 to 60 dB” (Ferraris, 2004 p. 79).

But the unappealing noise notwithstanding, music “can aid efficiency when one is required to perform a repetitious task” (Fox, 1971, after Connors et al., 2004 p. 74). An issue that gains importance in isolation is sound preference. “Even in the dampened acoustical environment of Skylab, the violin selections which enlivened one astronaut's day proved a source of irritation to his two crewmates” (Cunningham & Herskowitz, 1977, after Connors et al., 2004 p. 74). The design focus for the next long duration mission will have “to control unwanted sound (noise) while using wanted sound as a means of enhancing the total habitability of the space environment” (Connors et al., 2004 p. 74).

Temperature

The Thermal Control System (TCS) controls the heat and temperature of the entire ISS, supporting both life and equipment functions. For example, outside the habitat in the solar panel, , heat is transported away through the circulation of anhydrous ammonia, thereby cooling the equipment. In the pressurized compartment, when the insulation is not sufficient, “the air passes heat to the water-based cooling system in the air conditioner, which also collects water from the humidity in the air for use by the life support system” (NASA, 2010 p. 92).

"Temperature on the ISS is between 18° and 27° and the humidity between 30 and 65%. The air must be constantly cleared in order to avoid the carbon dioxide to stall around astronaut's face because of the microgravity that does not create natural convective current" (Ferraris, 2004 p. 78).

Temperature and humidity are considered to have an unpleasant effect on performance and sleep as seen in the Apollo spacecraft, "which was reported to be too cold for sleeping" (Connors et al., 2004 p. 67). "It may be that as space travel expands, and travelers come to expect more amenities, temperature and humidity preferences will need to be taken into account, along with other compatibility considerations" (Connors et al., 2004 p. 67).

Power

On the ISS, the power is provided by a complex system called Electrical Power System (EPS) through the 2500 m^2 of solar arrays and storage in nickel-hydrogen rechargeable batteries (to be replaced in the future by lithium ion batteries) to provide constant power during the orbiting phase in the Earth's shadow (NASA, 2010 p. 90). The following explanation is provided by NASA: "The ISS operates in Low Earth Orbit, ... Consequently, it is in the sun (insolation) gathering and storing energy for approximately 55 minutes of every 90-minute orbit. During the other 35 minutes of each orbit, the ISS is in Earth's shadow (eclipse). …Efficient energy storage is vital since the ISS must use stored solar energy to power the spacecraft during its eclipse mode" (Owens, 2010).

Light and Colors

The artificial light inside the sleeping stations is provided by the EPS, and consists of a fluorescent fixture with a brightness control knob. It produces a flux from 960 to 1174 lumen and 5100 K color temperature with a range of ±100K (Connors et al., 2004). The natural light "in space is different than on Earth" (Sean Kelley communication 1999, in NASA, 2011). It has different physical qualities, as the NASA specialist Sean Kelley explains: "The light is actually brighter" (Sean Kelley communication 1999, in NASA, 2011). "Since there is no atmospheric absorption in space, the visual environment is marked by higher brightness levels than experienced on Earth and, more importantly, by abrupt contrast effects" (Connors et al., 2004 p. 68 c.3). "Brighter illuminated areas and darker shadows lead to very high luminance contrasts" (NASA, 2010b p. 143, part 5.4.12.2).

Also, the day time duration is quite different, as previously discussed in *section Power*, "55 minutes of every 90-minute orbit" (Owens, 2010). This sunrise/sunset frequency is really relevant to habitability because it has an "influence on the sleeping pattern and the individuals' circadian daytime" (Sean Kelley communication 1999, in NASA, 2011). "A related concern is how to simulate day/night cycles. It will be important to determine how the use of lighting might impact this area" (Connors et al., 2004 p. 69 c. 3).

Interior Décor

Décor and color can increase habitability's capacity to support psycho-physiological well-being, orientation, safety, and productivity (Schlacht, 2007).

"The ISS was designed mainly according to the logic of short space missions" (Schacht and Birke, 2010 p. 2) where quality of life and the degree of habitability are not considered a priority. As a matter of fact, there was originally a plan for a dedicated place for living activities, but ultimately the project was not realized, since not enough money was allocated in the final budget to interior configuration and living activities.

The interior décor on the ISS is present mostly in the Russian module as wall coloration, whose function is orientation. Indeed, "although astronauts are provided with a 360° world, they continue to operate as if they lived in a modified two dimensional world" (Connors et al., 2004 p. 97) and to support operation, they need to have references for up and down. For this reason, in the Russian module the feeling of up and down is provided by the different colorations of the walls. In the American module, orientation is provided by the shape of the module entrance (Schlacht and Birke, 2010 p. 2). One can understand that there is no such thing as an international standard or common décor plan; however, mission designers are aware that décor is "increasingly important as spaceflights lengthen particularly with mixed crew" (Connors et al., 2004 p. 67, c. 3).

The impact of bad interior décor on habitability has been reported before: "Skylab astronauts reported that the sameness of colors within their vehicle was disturbing" (Berry, 1973, after Connors et al., 2004 p. 67). The décor should be flexible to change and support visual variety. Indeed, today, one can find in the space agency standard the importance of avoiding boredom with color variety and flexibility:

- "Variety: Extreme simplicity can be carried too far. Drab, singular color or completely neutral (e.g., all gray) color schemes and smooth, untextured surfaces are monotonous and lead to boredom and eventual irritation with the bland quality of the visual environment. The best interior design schemes are a balance of variety and simplicity" (AA.VV., 1999b, SSP50008, Cap. 8.12.2.2.1).
- "Flexibility - Ease of changing decor should be considered. Decor might be changed during long missions, as crews are replaced during normal rotation, or when the space module needs to be refurbished. Plans for such change or rehabilitation should be included in the initial design so that changes can be accomplished with minimum effort, time, cost, and interference with ongoing operations. As an example, techniques for quick removal and replacement of wall and ceiling structural coverings should be considered to vary color schemes as well as replace worn or damaged coverings" (AA.VV., 1999b, SSP50008, Cap. 8.12.2.2.d).

However, despite the promising guideline from the agency, in the current ISS there is a real color plan only in the Russian sector, but there is no flexibility in terms of decoration, not eveno for long duration missions.

"Russian investigators have looked at the visual environment of a spacecraft and have proposed ways that changes in decor could be employed not only to relieve visual monotony but to maintain the space traveler's link to the home planet" (Petrov, 1975; cited after Connors et al., 2004, pp. 67-68).

Natural plants have been proposed before as interior décor for the space station for their beneficial psychological effects (Bates and Marquit, 2010).

However, the current situation in the ISS is far from offering any perceivable wall décor, as the walls are covered with instruments that contribute to the visual chaos. According to a recent survey to gauge the astronauts' opinion on this matter (Schlacht et al., 2008), visual confusion is "the consequence of objects chaotically arranged in the interiors and with different orientations" (Schlacht & Birke, 2010b p. 1).

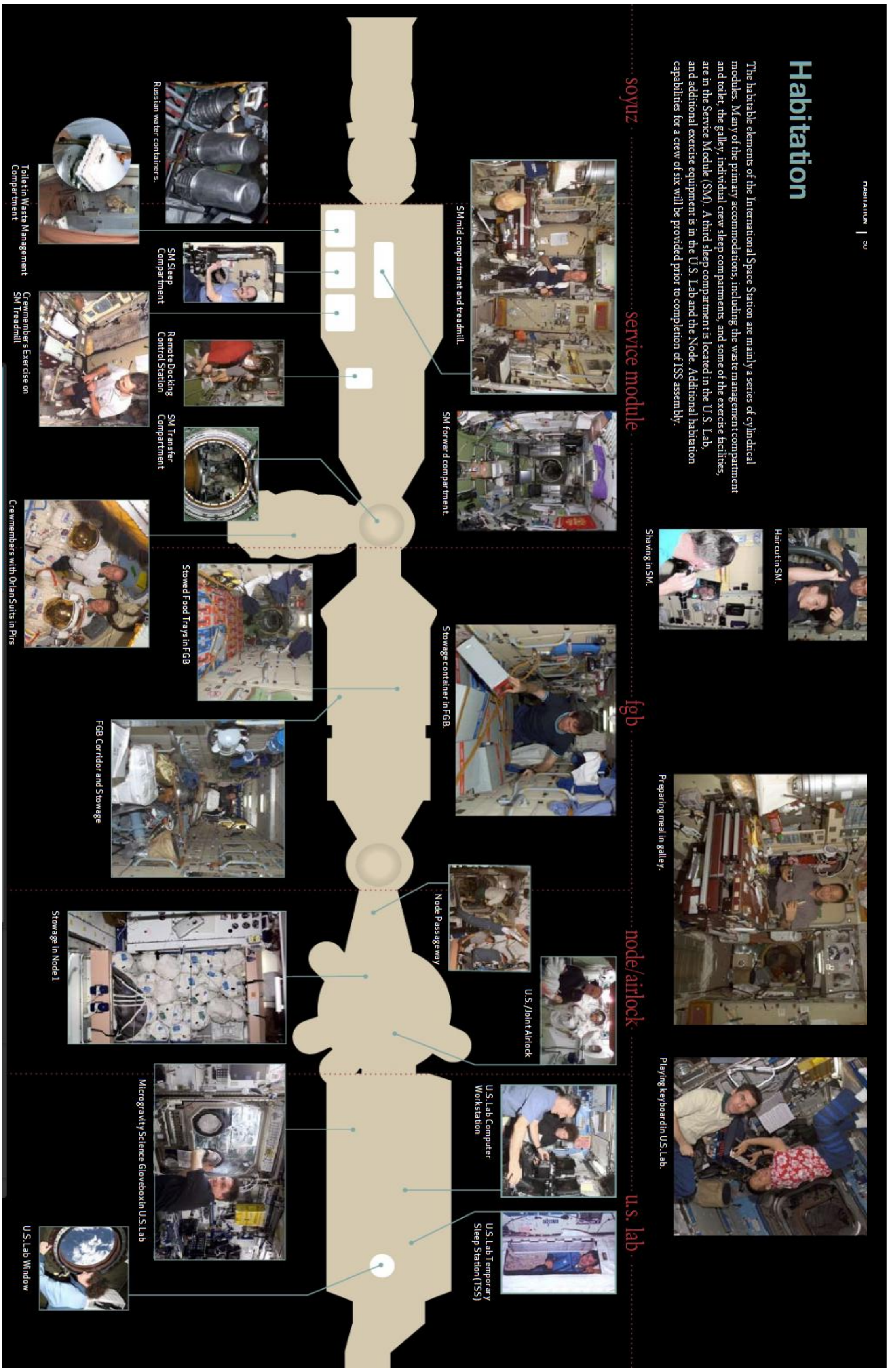


Figure 0.6: ISS Habitation (NASA, 2010 p. 24 pdf, p. 50 print)

Appendix C refers to 2.3.3 Environment (Outer Space)

Extreme Temperatures

Space is a radiation-dominated environment. At 400 km from the Earth´s surface, i.e., in low Earth orbit where the ISS is operating, there is no air. In this vacuum, a sharp change in temperature is coupled with very sharp changes between light and dark. Objects heat up by absorbing sunlight and cool off by emitting infrared energy. The temperature of the orbiting space station's Sun-facing side soar to 250 °C, while thermometers on the dark side plunge to minus 250 °C. The ISS is equipped with an Active Thermal Control System that keeps the astronauts in their orbiting home cool and comfortable. The station's insulation is a highly-reflective blanket called Multi-Layer Insulation (MLI) made of aluminized Mylar and Dacron (Price et al., 2011).

On the Earth's surface, the temperatures change with the conduction or convection of air. In deserts, the temperature is between 0 and 45° C; in the cold desert of Antarctica, the average temperature is between -60 and +15° C (NERC-BAS, 2007). The coldest natural temperature ever recorded on Earth was −89.2° C at the Russian Vostok Station in Antarctica in 1983 (Hudson, 2008). The warmest temperature can be found during volcano eruptions, where the lava temperature is around 1000° C (Pinkerton and Norton, 1995).

Radiation

There are two main kinds of radiation present during space missions, Galactic Cosmic Radiation (GCR) and Solar Particle Events (SPE). Even today, no satisfactory technology exists yet to completely shield spacecraft or space stations from these. For this reason, radiation is considered one of the biggest obstacles for missions beyond low Earth orbit (Shiga, 2009). In the SSP 50005 standard, each mission is required to monitor the individual radiation exposure (AA VV, 1999 p. 5.7.2.2.3).

The radiation dose for long duration missions "will be compared to the career dose limits with the assumption that the astronauts will not participate in another space mission later in their life" (Johansson, 2010 p. 31). The only solution that has been found is to retire the astronauts from the mission upon exposure to the maximum allowed limits of radiation.

> The U.S. Occupational Safety and Health Administration treats astronauts as radiation workers. Therefore, the level of radiation that an astronaut can be exposed to over his or her career falls under the guidance of the National Council on Radiation Protection and Measurements, a not-for-profit corporation created by Congress in 1964 to collect information and develop guidelines about radiation exposure for workers of all kinds. Today, the law limits the amount of radiation that nuclear workers, including astronauts, receive to 5,000 millirem over the course of their careers. The limits have already had effects on astronauts, who are required to wear radiation-monitoring badges on missions—silicon dosimeters on aluminum. In 2002, astronaut Don Thomas, who had flown on four prior missions, for a total of 1,040 hours, was pulled off the ISS Expedition Six crew because NASA decided that the long-duration mission would put him over the lifetime radiation exposure limit. NASA's Frank Cucinotta monitors astronauts and their badges, and often has to compare the badges of all the astronauts on a shuttle

mission to see if anyone’s badge is registering particularly low levels. ‘They sometimes hide their badges’ in a shielded area of the shuttle, he says, ‘because they don’t want to go over their limit’ (Ross, 2006 p. 4).

Microgravity

In space, one of the key environmental conditions to consider is weightlessness or the absence of gravity. In low Earth orbit where the ISS is located, gravity becomes microgravity. This condition is responsible for fascinating effects, such as enabling humans to float instead of moving, but it is also responsible for many physiological disorders. These effects are described in detail in *section 2.1.2*.

In the Oxford Dictionary (2011), microgravity (μg: 1×10^{-6} g) is defined as “very weak gravity, as in an orbiting spacecraft”. μg refers to the lack of acceleration that causes weightlessness inside the spacecraft, while the gravity of the Earth is pulling the trajectory of that spacecraft into an orbit (AA.VV., 2007). The floating condition is caused by the falling; spacecraft crew and equipment are all falling into Earth’s gravity at the same rate (28,000 km per hour); the crew inside the station appears to float (Zona, 2011). The floating condition determines a totally different way of interacting with the environment and between the crew members who are able to react with the environment in 3D, interacting with the surface and the ceiling. Microgravity particularly affects the human body’s functions and shape, creating a series of effects that influence well-being and performance and need countermeasures so as to maintain the capacity to perform in microgravity and to be able to live in normal earthly gravity at the end of the mission.

Meteorites, Micrometeorites, Space Debris

Even today, there really is no effective shield against meteorites, the only one being the Earth’s atmosphere. In space exploration, meteorites are particularly dangerous especially for the less protected parts of the spacecraft such as the solar panels, but also for the astronauts during EVA. “If the spacesuit is hit by a small meteorite, it could possible kill the astronaut because his suit will be depressurized” (Bruins communication 1999, in NASA, 2011).

Lack of Oxygen and Difference in Pressure

Although this can occur during flights, on high mountains, underground and underwater, it is only in space that a completely natural vacuum can be found. One of the “major problems with working in space is "decompression sickness" or the "bends." This is where nitrogen gets in the bloodstream because the astronaut did not purge his body of nitrogen before breathing at a lower pressure while in space. The solution to this is that the astronaut breathes pure oxygen before he goes into space to perform a task” (Bruins communication 1999, in NASA, 2011).

Altered Dark-Light Cycle

Coupled with microgravity, the altered dark-light cycle has a profound physiological and psychological effect that creates “complex adaptive processes” (Kanas & Manzey, 2008 p. 15).

"In an orbiting spacecraft traveling at about 28,000 km/h around our planet, the time between sunrises is reduced to about 90 min. This marks an important difference to the 24-h day-night cycle that we are accustomed to on Earth and can conflict with the circadian system of humans" (Kanas & Manzey, 2008 p. 15). "It has become recognized that sleep disturbances and fatigue, as well as alterations of circadian rhythms in astronauts, are among the most important factors contributing to impaired wellbeing, alertness, and performance during space missions" (Kanas & Manzey, 2008 p. 27).

Appendix D refers to 3.1.1 User Analysis

A questionnaire for space habitats in long duration missions was developed under the Head of the Physical Architecture & Ergonomics unit of Thales Alenia Space in 2005 (Schlacht et al., 2005). The results reported here were collected until 2008 and published on the basis of six astronauts (Schlacht et al., 2008); further investigations were performed and reported as interviews.

Table 0.1: Habitability problems: 14 astronaut interviews (Irene Lia Schlacht from 2005 to 2010)

ASTRONAUT	TOPIC RELEVANCE	NEEDS IMPROVEMENT	OPINIONS
A	*V*	*V*	PROBLEM SELECTED ISS interior interface: relevant, monotonous, indifferent; Function: Orientation. Needs: Privacy, Personalization; PROBLEM DISCUSSED Unpleasant interior color: "In the space habitat unpleasant colors should be avoided. ISS colors are moderately important, they should not be strong (the subject preferences are for luminous and not saturated color). I think colors are important to help orientation, anyway now the majority of the people don't like the colors of the station".
B	*V*	*V*	PROBLEM SELECTED ISS interior interface: relevant, not monotonous, effective; Functions: Storage recognition, orientation, well-being, productivity, visual order, psychological support Needs: Variability, Personalization, Privacy, Open Space, Quiet;
C	*V*	*V*	PROBLEM SELECTED ISS interior interface: relevant, effective; Functions: Storage recognition, orientation, well-being, productivity, visual order, psychological support Needs: Personalization, Privacy, Input to Avoid Isolation, Open Space;

			PROBLEM DISCUSSED Visual Monotony: "Images as aesthetic complement should be variable". Visual surroundings in outer space habitats are relevant. Variation in visual inputs may avoid isolation and monotony.
D	*V*	*V*	PROBLEM SELECTED ISS interior interface: chaotic, boring, too many colors Functions: Storage recognition, orientation, well-being, productivity, visual order, psychological support Needs: Privacy, Feeling of Freshness, Familiarity
E	-	*V*	PROBLEM SELECTED ISS interior interface: monotonous, boring, not interesting Functions: Storage recognition, orientation, psychological support Needs: Input to Avoid Monotony, Variability, Personalization
F	*V*	*V*	PROBLEM SELECTED ISS interior interface: monotonous, boring, effective Functions: Storage recognition, orientation, well-being, productivity, psychological support Needs: Privacy, Input to Avoid Monotony, Quiet, Feeling of Freshness, Order, Variability, Personalization PROBLEM DISCUSSED Low habitability, visual chaos: ISS colors are unpleasant. Is important to improve outer space habitability conditions. The actual ISS visual surrounding, which is chaotic.
G	-	*V*	PROBLEM SELECTED ISS interior interface: chaotic Functions: Storage recognition, orientation, productivity, visual order Needs: Variability
H	*V*	*V*	PROBLEM DISCUSSED Physiological effects (coordination, visual focus, sensorial perception): "Colors are used for warning and safety information, but it should be taken into account that environmental colors may affect mood." "In the passage to zero gravity there was difficulty managing sheets of paper and to focus on the script. There was the sensation of difference in color perception. Also the sense of taste is deeply changed." While aboard the ISS, he had altered levels of visual perception, but he felt that his impressions should be empirically tested. He would feel sad in a pale, pastel-colored environment. (Masali M., informal report from the Astronaut Nespoli conference talk, 20.1.2008, Turin, in Schlacht et al. 2008b)
I	***X***	*V*	PROBLEM DISCUSSED Storage, visual chaos, system maintenance: Is relevant to work on the visual confusion on the interface caused by cables and storage problems. Astronauts, after 3 days, quickly adapted to 3D space perception of the "isotropic world" and oriented themselves using the internal (visual) configuration. The interior shape of Spacelab is efficient. "Space stations are noisy systems but astronauts have also been trained to work in long- duration missions in these conditions, so habitability is not considered a priority". "The problem is

			having to spend time with system's maintenance and equipment storage instead of on experiments, as happened to Thomas Reiter, who was employed to restructure the spacecraft". Space habitat visual chaos is mostly created by the high quantity of labels and electrical caves and also from storage problems. An interior color scheme that intuitively guides the user's orientation is the best solution, but not practicable in the ISS, in all reality.
L	*V*	*V*	PROBLEM DISCUSSED LDM Habitability: Habitability and visual design acquired importance in relation to mission duration "In short missions the color design is not important, however red makes me always nervous, personally I will like to have green and yellow as interior color for long-duration mission and in general the presence of soft colors. Considering long duration space missions, the use of color has to be taken into account to improve orientation and well-being".
M	*V*	*V*	PROBLEM DISCUSSED Visual Chaos: During the mission, everything (e.g. documents, food, personal racks) associated with him was labeled with a colored spot (in the first mission violet and in the second brown) Compared to the other astronauts he was more sensitive to feeling the ISS's internal color. He experienced visual confusion and felt that improved visual configuration is necessary.
N	*V*	*V*	PROBLEM DISCUSSED LDM Habitability: Interface and visual design are relevant, in particular for better habitability in long duration space missions.
O	*V*	*V*	PROBLEM DISCUSSED LDM Habitability, Orientation , Storage System (improvement in particular to find small objects that are constantly lost). "Regarding Human Factors is important to notice that "some astronauts don't feel well in the first days in space. Even with the training they have bad orientation until they get used to everything." Human Factors is fundamental in LDM. Storage System improvement and solution on finding little object is a relevant matter that needs to be approached by Human Factors." (Ernst Messerschmid: Berlin, ILA 2010, DLR official and public astronauts communications)
P	*V*	*V*	PROBLEM DISCUSSED LDM Habitability, Orientation, Storage System (improvement in particular to find small objects that are constantly lost): "Regarding storage system in "mission you are always looking for little things". To improve it "first thing would be to have more space. Like this we could group things together and find them more easily." (Frank De Winne: Berlin, ILA 2010, DLR official and public astronauts communications)
Index: *V*= Yes; X= No; - = Not Specified ; LDM= Long Duration Mission			

User Preferences

As explained above (cf. s*ection 2.2.2,* part *Perception*), visual inputs are the main stimuli for interchange with the environment, before all other sensory data. The visual interface of spacecraft is a key factor for well-being in a confined environment.

For this reason, the focus of the habitability questionnaire was on the interface of the spacecraft, as well as on the preference and sensitivity of the astronauts regarding colors and other visual stimuli.

The questionnaire was structured into four sections:

1. PERSONAL INFORMATION: to learn about the astronaut's level of experience and cultural background.
2. PERSONAL PREFERENCE: to discover taste, personality, and the relevance of colors and texture in the user's daily life.
3. PREFERENCE IN SPACE HABITATS: to identify user preferences, problems, and visual perception in space.
4. AESTHETIC COMPLEMENTS OF THE SPACE HABITAT: to identify user sensitivity and needs related to visual input for aesthetic complements.

The questionnaire was completed by six astronauts as well as by 13 space industry employees directly involved with space habitats (they had to guess the astronauts' replies according to their idea about astronauts' needs). This allows comparing the target needs with hypothetical needs resulting from the employees' answers (Schlacht, 2007; Schlacht et al., 2005).

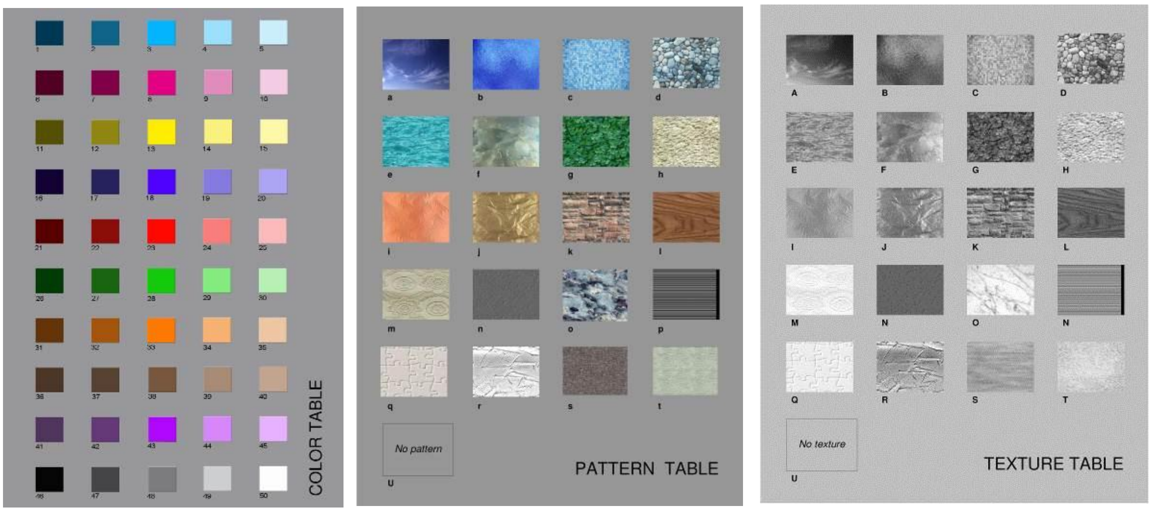


Figure 0.7: Palette tables of 50 colors, 21 textures, and 21 patterns (Schlacht et al., 2008)

- Personal preference

Visual preferences were investigated utilizing a palette of 50 colors, 21 textures, and 21 patterns. The colors personally preferred by all astronauts were cyan and blue. Blue was also the main color selected by the 13 employees. Indeed, blue is also the global favorite color, as shown by international research such as Hans Eysenck's in the 1940s, when he established a universal order of color preference: Blue, Red, Green, Violet and Yellow, Orange (Eysenck, H.J.; 1941).

Regarding pattern and texture preferences, there were inhomogeneous tastes.

Table 0.2: Astronauts' personally most and least favorite colors (Schlacht et al., 2008)

A1. Astronauts favorites colors : Cyan 3					
A	B	C	D	E	F
Cyan 3	Cyan 3	Cyan 3	Cyan 3	Blue 17	Cyan 3
A2. Astronauts not liked colors: Black 46					
A	B	C	D	E	F
Black 46	Orange 34	Yellow 11	-	Black 46	Red 25

- Home, work and ISS preferences

Personal comfort with interior colors at home, at work, and inside the ISS was compared.

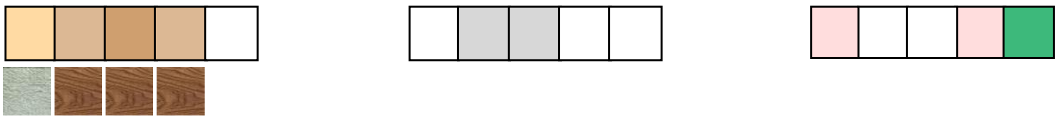
To measure comfort, a 6-point scale was used: "a lot, enough, more or less, not much, not at all, no specific preference".

Interiors at home were mostly wood textures and warm wood colors, slightly preferred (mean values: comfortable enough) in respect to the white and cold gray of the work place (mean values: more or less comfortable) and the one on the space station. The latter were less consistent with each other; they had higher variance of perceived color and preference with respect to the home and the work place (mean values: more or less comfortable).

Table 0.3: Astronauts' Color Preference (Schlacht et al., 2008)

Colors and textures perceived by the astronauts as dominant inside:

Private home	Work	ISS
Sufficiently comfortable	More or less comfortable	More or less comfortable



C2. **Comfort with interior color** of space habitat: "more or less"					
A lot	Enough	more or less	not much	not at all	no preference
	B C G	D E	F		A
C3. **Conflict with color coding** of space habitat: "more or less"					
a lot	enough	more or less	not much	not at all	no preference
	A C F	D	B E G		

To understand interior color preferences, the questionnaire's next question shows virtual images of the ISS module with different color combinations.

The images presented were:

- Image 1, the entire interior is brown (feeling of security, earth, weight);

- Image 2, the entire interior is light blue (feeling of spaciousness, fresh air);

- Image 3, light blue interior and brown floor (eco-mimicry orientation with sky up and earth down);

- Image 4, blue ceiling, green walls, brown floor (strong biological reference).

The astronauts' favorite image was image 3. It showed a balance of color without hyper-stimulus.

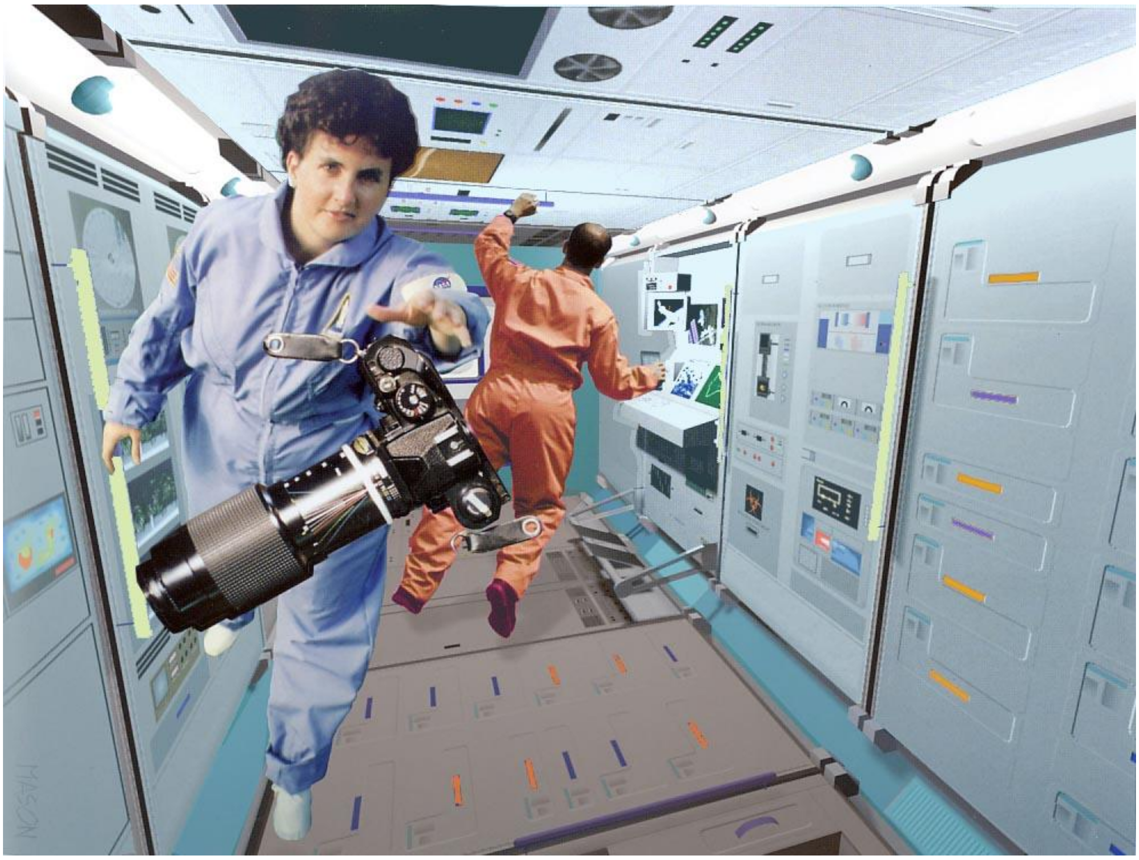


Figure 0.8: Favorite interior color configuration of the astronauts interviewed (Schlacht et al., 2008)

- Feeling and emotions inside the ISS

To describe the space habitat's interior interface, the astronauts used mainly negative adjectives that underline the need for visual environment improvement, such as "chaotic, relevant, monotonous and boring".

Most of the space employees also used negative adjectives, in particular half of the subjects selected monotonous; at a minor rate, relevant, boring, and sad were also selected.

This shows a big gap regarding the design. Indeed, most of the space industry employees found the colors monotonous and no one thought that the interior colors could be chaotic for the astronaut. Vice versa, they thought that the interior could be sad, but none of the astronauts refers to a sad color palette inside the ISS.

As a matter of fact, visual chaos inside the ISS was reported both during the questionnaire (astronauts I, D, G) and as a specific problem during the interviews (astronauts F, I, and M) for a total of five astronauts out of a total of 16 interviewed.

Table 0.4: Judgments of ISS interior interface

Evaluations of ISS visual interface								
D. Visual interface:								
D.1	Negative adjective							
	chaotic	relevant	monotonous	sad	boring	not effective	too many colors	Others: not interesting…
Astronauts	(I, D, G) 3	(A,B,C) 3	(A, E, F) 3		(D, E, F) 3		(D) 1	(E) 1
Space Employees	-	3	7	3	3		1	
D.2	Positive adjective							
	discreet	superfluous	not monotonous	cheerful	interesting	effective	too few	indifferent
Astronauts			(B) 1			(B, C, F) 3		(A) 1
Space Employees	2			1				

- Feelings and emotions needed

As reported in NASA's standard and by Living Aloft, interior décors and color complements may be used to create a better feeling, for example by visually dividing or enlarging the space (Connors et al., 2004; AA.VV.1999b, SSP50008, Cap. 8.6.2.2-1). In 1400, color was already used by Leonardo da Vinci to increase the feeling of distance in his paintings (Schlacht, 2007 p. 106).

Sensations and feelings that a place may evoke can be designed and planned on the basis of the user's needs, which in this research is considered as a fundamental part of habitability.

"Privacy" was selected as a feeling requested by the majority of the astronauts who replied to this question (4 out of 5). It is interesting to note that the answer by the majority of the space employees (8 out of 13) was "open space"; this result did not coincide with the astronauts', which was "open space" (6 out of 13).

Table 0.5: Sensations and feelings needed in long duration missions

Astronauts							G. SENSATION FOR LDM	Employees
A	B	C	D		F	**5/6**	**1. Privacy**	5/13
		C		E	F	3/6	2. Input to avoid monotony of isolation	5/13
	B	C				2/6	**3. Open space**	**8/13**
	B				F	2/6	4. Quiet	5/13
			D		F	2/6	5. Feeling of freshness	1/13
			D			1/6	6. Familiarity	6/13
					F	1/6	7. Order	1/13
							8. Warm feeling	2/13
							9. Well-being	1/13

This result clearly shows how to deal with the problem of isolation: The employees are oriented towards implementing physical space as a quantity, and the astronauts are looking to get psychological privacy, a much more qualitative need.

User Sensitivity to the Topics

The final part of the questionnaire was focused on understanding the astronauts' and employees' sensitivity to habitability and interior interfaces in long duration missions.

Table 0.6: Habitability and visual design needs and functions in space missions. Storage Recognition and Orientation are the most frequently selected functions and Variability and Personalization are both voted as needs.

HABITABILITY & VISUAL INTERFACE (7= tot. astronauts; 13= tot. space employees)							
Relevance		a lot	enough	more or less	not much	not at all	no preference
HABITABILITY & VISUAL INTERFACE NEEDS							
K.1 Variability	Astronauts		4/7: B E F G	2/7: C D		1/7: A	
	Employees	2/13	9/13				2/13
K.2 Personalization	Astronauts		3/7: A E F	2/7: B C	2/7: D G		
	Employees	2/13	10/13				1/13
HABITABILITY & VISUAL INTERFACE FUNCTIONS							
1.1 Storage Recogni-	Astronauts	4/7: B F G E	2/7: C D	1/7: A			

tion	Employees	4/13	6/13		1/13	2/13	
1.2 Orientation	Astronauts	4/7: A C F G	3/7: B D E				
	Employees	11/13	2/13				
I.3 Well-Being	Astronauts		3/7: B D F	3/7: C E F		1/7: A	
	Employees	5/13	8/13				
I.4 Productivity	Astronauts		**4/7: B D F G**	3/7: F C E	A		
	Employees	2/13	2/13		**7/13**	2/13	
I.5 Visual Order	Astronauts		4/7: B C D G		1/7: E		1/7: A
	Employees	Not filled					
I.6 Psychological Support	Astronauts	1/7: F	4/7: B C D E		1/7: A		
	Employees	8/13	5/13				
Index: gray background = majority of the replies							

The astronauts' and employees' evaluation found that when considering habitability and visual design for space missions, "variability" and "personalization" must be taken into account to ensure mission success. With regard to habitability and visual design, the astronauts were asked what function may be improved with the interior décor in long duration space missions. Several options were offered for selection: storage recognition, sense of direction, well-being, productivity, visual order, emotional well-being (psychological mood), other to be specified. For astronauts, color design is a crucial factor for improving storage recognition and orientation in the outer space habitat. It can also be considered sufficiently relevant for improving well-being, the astronauts' productivity, visual order, and psychological state. In the employees' minds, it is particularly crucial for orientation and psychological reliability; however, it does not have much influence on productivity.

In conclusion, the mean values of both the astronauts and the employees showed the questionnaire to be moderately difficult and to have moderate importance.

Participatory Design Involving Astronauts

Following the principle of participatory design, during the user interviews, the astronauts were asked to choose the design configuration for Space Haven, the inflatable habitat design by Alenia for ESA.

Letting the astronauts determine the décor of the place where they will live and work in space is not a new idea. Mainly it is mentioned as the opportunity to personalize the crew quarters. "The ability of a crewmember to personalize certain portions of her or his environment is often a morale booster; this option should be limited to an individual's personal quarters" (SSP50008, AA.VV.1999b, Cap.8.12.2.1c).

In order to understand the needs in accordance with the user-centered design approach, the astronauts were asked directly to select the design of interiors for long duration missions in Space Haven.

Space Haven is an inflatable habitat commissioned by ESA to Thales Alenia Space.

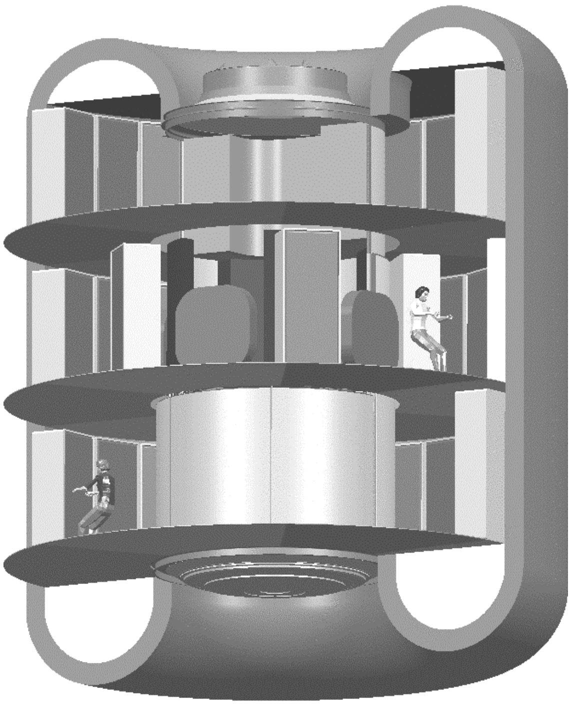


Figure 0.9: Space Haven (Thales Alenia Italy 2006)

- Colors, textures and patterns

From the color, texture, and pattern (achromatic texture) palettes, they selected the configuration for the inflatable interior. The focus was on: upper and lower part (the relative ceiling and floors), private, social and work areas.

- For the ceiling and floors, the majority of the color configurations selected by the astronauts were achromatic: mostly white for the upper part of the module (achromatic 5/6 subjects, white 50: 3/6 subjects) and light gray for the lower part of the module (achromatic 3/6 subjects, light gray 49: 2/6 subjects). Chromatic colors were also selected, such as light cyan for up and dark green and brown for down parts. Regarding the employees, they had similar results but with less homogeneous data. In general, the suggested colors were lighter for the ceiling and darker for the floor (with the exception of one subject out of 13). A variety of colors was proposed for the racks. One subject suggested a color configuration that varies over time for the private and work areas.

One possible interpretation of this result may be that both astronauts and employees select lightness and hues that refer to sky and earth for the up and down interior parts using a kind of “biomimicry” logic.

- For the private areas, both the astronauts and the employees selected mostly cyan; for the social areas, they both selected vivid colors: the astronauts selected cold colors and the employees selected warm ones. For the work areas, the selections were not homogeneous and remained incomplete.

Regarding texture and pattern preferences, the result was mostly that these should be avoided. When there was a preference, it was not homogeneous between the subjects.

Table 0.7: Space Haven interior colors, patterns and textures selected by astronauts and employees (Schlacht et al., 2008)

F. COLOUR – TEXTURE – PATTERN CODE SELECTED FOR SPACE HAVEN					
F.1 Employee UP (ceiling): White (4/13 subjects) Cyan (3/13 subjects)					
F.1 Astronaut UP (ceiling): 50 white (3/6 subjects), U u no texture/pattern (4/6 subjects)					
astronaut A	astronaut B	astronaut C	astronaut D	astronaut E	astronaut F
49 light gray	50 white, U no texture, u no pattern	4 light cyan, U no texture, u no pattern	49 light gray, T wall paper color water), t wall paper	50 white, U no texture, u no pattern	50 white, U no texture, u no pattern
F.2 Employee DOWN (floor): not homogeneous, gray (2/13 subjects)					
F.2 Astronaut DOWN(floor): 49 light gray, U no texture & u no pattern (2/6 subjects)					
40 light-light brown	28 green, U no texture, u: no pattern	49 light grey, U no texture, h carpet	49 light gray, T wall paper color water, t wall paper	50 white, U no texture, u no pattern	26 dark-dark green, D cobble-stone blue, d cobblestone
F.3 Employee Private Area: green or cyan 3 (5/13 subjects)					
F.3 Astronaut Private Area: cyan 3 (2/6 subjects) *neutral texture*					
Wall: 50 white Area: H cream carpet, h carpet, I wall paper pink, i wall paper; Q puzzle light viola, q puzzle	3 cyan, U no texture, u no pattern		49 light gray, T wall paper color water),t wall paper	"Neutral simple"	3 cyan, E cyan water, a sky
F.4 Employee Social Area: different orange and yellow (6/13 subjects)					
F.4 Astronaut Social Area: not homogeneous					
Wall: 50 white Area: H cream carpet, h carpet, I wall paper pink, i wall paper; Q puzzle light viola, q puzzle	4 light cyan		49 light gray, T wall paper color water), t wall paper	18 blue, 23 red. "Stimulating color"	26 dark-dark green, G green leaves, g leaves
F.5 Employee Work Area: not homogeneous, white (2/13 subjects)					
F.5 Astronaut Work Area: not homogeneous					

35 light light orange	D cobblestone blue		49 light gray, T wall paper color water, t wall paper	38 light brown, l wood	20 dark blue, S fabric brown, b glass

It is interesting to compare the results of the selection defined by the astronauts with the color schema proposed by the agencies, which is based on 42 colors (SSP50008, AA.VV.1999b, Fig. 8.12.2.2-2). Indeed, the astronauts selected only a few different kinds of colors, such as:

- light gray 49: 7 times
- white 50: 6 times
- blue variations: 5 times (3 cyan: 2 times, 4 light cyan: 2 times, 18 blue, 20 dark blue)
- green variations: 2 times (28 green, 26 dark-dark green)
- brown variations: 2 times (40 light-light brown, 38 light brown)
- and 2 other colors (23 red, 35 light orange).

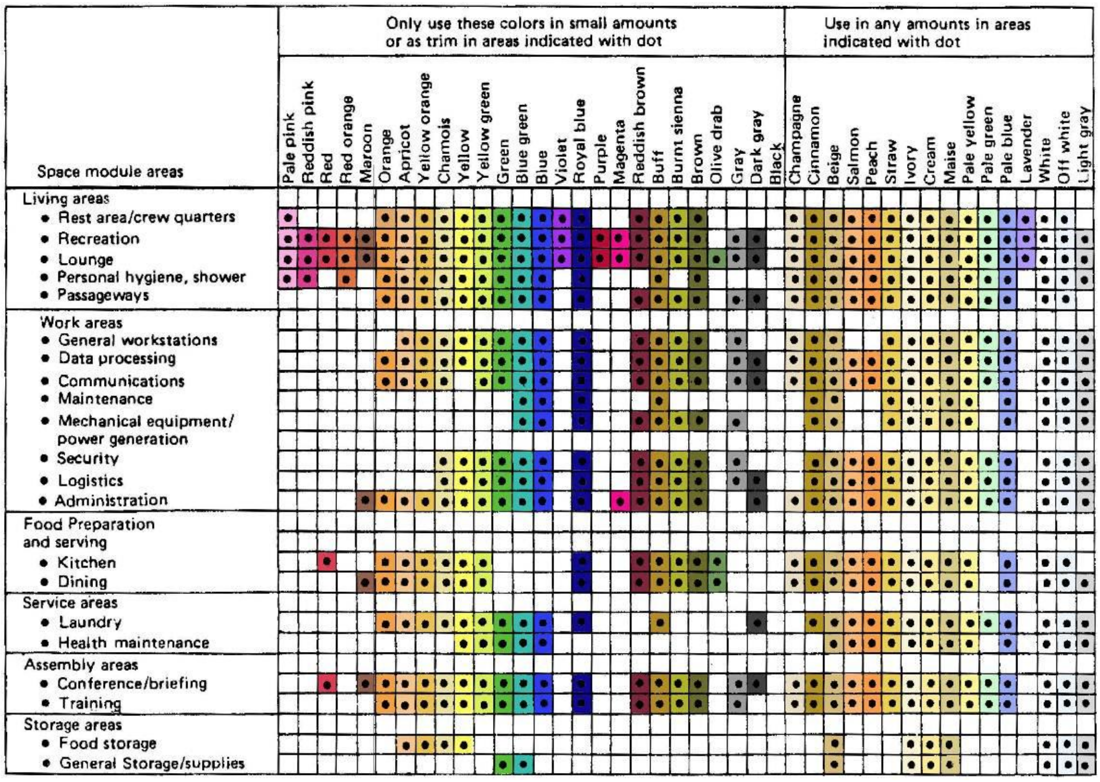


Figure 0.10: Color recommendations for space habitat interiors following the space agencies' standards. (AA.VV.1999b, SSP50008, Fig.8.12.2.2-2)

- Interior complements

The kind of interior complements for long duration missions were described by the astronauts by selecting one or more of the following typologies: picture, paint, abstract, real, nature, city, people, familiar people, familiar place, hot color, cold colors, pastel colors, bright colors, black and white, overview, close view, frontal view (as, up and down orientation reference), view from above (readable in all the up and down positions).

Higher scores were given to these typologies: picture (4 out of 6 astronauts), nature (3 out of 6 astronauts), familiar place (3 out of 6 astronauts), and frontal view (3 out of 6 astronauts),.

These typologies were also confirmed in the selection of an image from a panel of nine as possible decoration for long duration missions.

Figure 0.11: Image selected by the astronauts as interior complement (Schlacht, 2009)

Considering images of people, animals, and nature, from frontal view to overview, the favorite for LDM interiors was an autumnal picture of a forest for 5 out of 6 astronauts.

The image can be described as a picture of nature, showing a familiar place and with a frontal view- It is interesting to note that this image provided a strong reference for up and down orientation.

Appendix E refers to 3.1.2 Debriefing Analysis

Operational Problems

Table 0.8: Operational problems in space missions (Behar, 2006; Häuplik-Meusburger, 2011; Lucid, 1996; Mars 500, 2011; Messerschmid, 2008; Musser Shiner, 2006; Thagard, 1995)

Operational (Task and Instruments)					
	Hazard	Example	Usability	Livability	Flexibility
SCHEDULE		ISS: We refuse to do exercise on the rest day (Lebedev, 1990 p. 237)		x	x
		ISS: We will not rest next weekend (Chamitoff, 2008)		x	
INTERFACE	x	Solyuz: Switches with same name and location, you can risk your life if you press the wrong one (Lucid, 1996)	x		
		Mir: Windows were unusable because of moisture ac-			

		cumulation inside and because of condensation, and the nadir looking don't get enough warning of what's upcoming (Thagard, 1995).			
ZONING		Mir: They slept in the too warm crew quarters in the base block because if anything went wrong, they could be there immediately to take care of it (Lucid, 1996).	x	x	x
		Mir: Windows are allocated without logic (Lucid, 1996).		x	
		Mir: When you were exercising, you were in some-body's way.			
STORAGE	x	Mir: Accumulation of stuff, you can scratch yourself passing through (Thagard, 1995)		x	
		ISS: Small things get lost (Jones, 2010, p. 1) Shuttle; (Astronaut personal courtesy communication, ILA, Ber-lin, 2008)	x		x
		ISS: Difficult to find objects (Jones, 2010, p.1)	x		
		ISS: Visual Chaos (Astronaut personal courtesy com-munication, ILA, Berlin, 2008)		x	
	x	Mir: There is no place to put anything, …The hardest thing is to find stuff. And if I moved too fast through stuff, I would end up bruised or I would scrape myself or something. …a problem - you would get stuff in your eye once in a while." (Lucid, 1996)	x	x	x
		Mir: Personal effects are personal hygiene kits which were stored with little elastic straps on the walls if you did not have a crew quarter (Thagard, 1995)			
HUMAN-MACHINE INTERACTION	x	Mir: Automatic can overheat heaters (Thagard, 1995)			x
AUTONOMY	x	ISS: Unplanned emergency, all the computers and backup systems failed. Consequently, the huge solar arrays were no longer pointing to the sun. And without a steady supply of solar-derived electricity, the controllers knew things would get dark and cold pretty fast. Me-chanical solution was having the crew look out the window, find the sun and then manually rotate the ar-rays toward the light. Lunney says. "It had never been done before." Because radio communications on the drifting station were also intermittent, mission control would have less than five minutes to read the instruc-tions up to the astronauts. Lunney remembers: "I was nervous and the adrenalin was certainly flowing." (Behar, 2006, p. 3)	x		x
PEFORMANCE	x	Mir: High CO_2 after gymnastics, makes you tired (Thagard, 1995)		x	
		Mir: Crew rashly blamed for collision by ground control, disabling of computer (and station) by operator error (Messerschmid, 2008)			
TASK MANAGEMENT		Mir: Bad procedures layout (Lucid, 1996)	x		
MAINTENANCE HOUSEKEEPING		ISS: Thomas Reiter spent one entire mission just order-ing equipment (Astronaut personal courtesy communi-cation, ILA, Berlin, 2008)	x	x	x

		Mir: Enormous amount of time spent just on keeping the station running (Lucid, 1996)	x		
		Mir: Accumulation of trash (Thagard, 1995)			
	x	Mir: Ground control inefficiency (Jones, 2010, p. 2) ISS, (Lucid, 1996)	x		
STANDARDIZATION	x	Mir: American food package incompatible with Russian food heaters (Thagard, 1995)	x		
		ISS: The labels and interfaces follow mainly 2 different standards: Russian and American.	x		x
RESTRAINTS		Mir: Handrails used for feet (Thagard, 1995).			x
		Mir: I needed a flat surface to work on with Velcro® on both sides (Lucid, 1996)	x		x
		Mir: The German chair thing was big, it was clumsy, and it was over-engineered (Lucid, 1996)	x		
LOGISTICS		Mir: I wore the same blue jumper every day for 188 days (Lucid, 1996)		x	x
		Mir: Shortage of wet towels (Thagard, 1995).	x		
		Mir: We ran out of dry towels, too many wet towels. (Lucid, 1996)	x		
Index: x=problems ; v= support					

Physical Problems

Table 0.9: Physical problems in space missions (Behar, 2006; Häuplik-Meusburger, 2011; Lucid, 1996; Mars 500, 2011; Messerschmid, 2008; Musser Shiner, 2006; Thagard, 1995)

Physical (Environmental, Physiological)					
	Hazard	Example	Usability	Livability	Flexibility
ENVIRONMENTAL CONTROLS		Mir: Uncontrollability of the system. Noisy ventilator fan, and too warm temperature, the range of adjustment is not great (Thagard, 1995).	x	x	X
		Mir: Uncontrollability of the system. In solar orbit, it was pretty warm, difficulties in sleep (Lucid, 1996).	x	x	x
PHYSIOLOGICAL		Mir: I think the temperature probably caused some little sleep loss in the crew quarter (Thagard, 1995)		x	x
		Mir: Noise was not a problem but I find degradation in my hearing when I got back (Lucid, 1996).		x	x
		Mir: The doctors recommended wearing ear protection at night because of noise; those were uncomfortable and created sleep loss. Noise was chronic, apparently mildly exceeding the recommended industrial noise level.	x	x	x
		ISS: It is hard to force yourself to do exercise. We like the treadmill because it supports a variety of exercises	x	x	v

		(Lebedev, 1990 p. 168)			
NOISE		Shuttle and Mir: Could be very noisy e.g. toilet, crew quarters fan, regenerative system. There was no sound meter (Thagard, 1995)		x	x
LIGHT	x	Mir: In the night light is turned on to be reactive for emergency (Thagard, 1995)		x	
		Mir: Power was a big concern. So a lot of times we had to work in semidarkness (Lucid, 1996).	x		x
DECOR		Mir: I do not remember (Thagard, 1995)		x	
WATER		Mir: I need a lot of water (Lucid, 1996).	x		
		Mir: I did not drink a lot of water because of another shortcoming of our experimental food system. No drink bags were provided. The condensate system, with 25 milliliters at a time, was only used to rehydrate drink bags and food (Thagard, 1995).	x	x	x
Index: x=problems ; v= support					

Psychological Problems

Table 0.10: Psychological problems in space missions (Behar, 2006; Häuplik-Meusburger, 2011; Lucid, 1996; Mars 500, 2011; Messerschmid, 2008; Musser Shiner, 2006; Thagard, 1995)

Psychological (User)					
	Hazard	Example	Usability	Livability	Flexibility
PSYCHOLOGICAL SUPPORT		Mir: With windows in the crew quarter you did not feel to be like inside a tin can (Thagard, 1995).		v	
		ISS: During the ESA mission private psychological support, with astronaut's agreement, are performed with personal conversation from 10 min to 1 h (Dietrich Manzey, lecture communication, TU Berlin, 2009).		v	
		ISS: After exercise I have a sense of psychological satisfaction, I did not believe in endorphins on Earth (Whitson, 2008)			
FUN		Solyut: Turning the vacuum cleaner between the legs, you flew like a rocket inside the stations (Prunariu, 2011 cited after Häuplik-Meusburger, 2011)		v	
		Solyut: "Swimming" in weightlessness is a lot of fun (Lebedev, 1990 p. 216)		v	
CONFLICTS	x	Apollo 9: Constant quarrelling within crew, creates conflicts with ground control (Messerschmid, 2008)			
	x	Biosphere 2: Unexpected deterioration of air also led to psychological problems. Bad crew selection led to bad group interaction. High expectations and public relations pressure increased stress (Messerschmid, 2008)		x	

		Crew request me to not use the motor and the ground wanted me doing that (Lucid, 1996)			
COMMUNI-CATION	x	Mir: Problems with air to ground communication; it was practically impossible for me to hear what the person was saying (Lucid, 1996).	x	x	
		Mir: The second communication channel allows you to provide news, and things that are appropriate for culture, background and nationality		v	
		Mir: The time delay in communication was very frustrating (Thagard, 1995)	x		
		Mir: Hearing another crew member's speech without the use of an intercom between compartments is next to impossible (Thagard, 1995)	x	x	x
		ISS: He called me from ISS and I was hearing him perfectly (Häuplik-Meusburger, 2011 p. 275)			
HIERARCHY		Mir: Conducting experiments, I had the lowest priority for communications, the work associated with EVA's or Station maintenance had to take precedence (Thagard, 1995)		x	
PRIVACY		Mir: You're just talking about basically a little alcove with no door on it (Thagard, 1995)		x	
		Mir: Mir is big, privacy is something you necessarily seek out on large crews and longer period of time (Thagard, 1995)		x	
		Mir: It was just nicer having a little place where you could be a little more by yourself sometimes. To go look out a window most of time you would be by yourself (Lucid, 1996).		x	v
		Mir: Ulf Merbold commented too, you don't get the same sense of privacy with the video two-way that you do with audio (Thagard, 1995)		x	
		Mir: I wrote my diary on time for myself (Thagard, 1995)		v	
		Mir: In private conference with family you see somebody walk across and adjust the microphone, I would prefer to do audio only (Thagard, 1995)		x	
		Mir: Personal cleaning in public space made using big shirt to cover nude part (Lucid, 1996).		x	x
PERCEPTION	x	Mir: The helmet got fogged up on EVA, it was dangerous (Musser Shiner, 2006, p. 33).			
		ISS: Up and down and orientation may be problematic (Astronaut personal courtesy communication, ILA, Berlin 2008).		x	
		Mir: I didn't notice any change in taste, smell, vision, anything apart from that loss in hearing capacity (Lucid, 1996).			
MOTIVATION		Mars500: Capacity of **adaptation, mission relevance,** support through **twitter, website and relatives and friends via e-mails** help to hold on**.**		v	x

		Alexey Sitev (crew commander): We became accustomed to everything. Dropped into rhythm. Sukhrob Kamolov (crew physician): The fact that we do all this is not in vain. That one day our knowledge will be needed and some experimental results can probably be used even now. And of course I understand how much efforts and money were invested in this Project; I guess all this helps us to hold on. Romain Charles (flight engineer) My 5 crewmates help me to bear with this long duration isolation study. We are on the same boat together. I also receive a lot of support through e-mails from my family, friends and from our ESA representative. Diego Urbina (researcher) The support from my family, my friends and from people that encourage us through means like websites or twitter. Wang Yue (researcher) My crew, my family, my friends, and all the people supporting us.			
STIMULI AGAINST BOREDOM	x	Salyut 6: Yuri “Romanenko's EVA was entirely impromptu” without safety tethers, because of exhilaration (Musser Shiner, 2006, p. 33; Messerschmid, 2008).	x	x	x
		Mars 500: The most impressive event was **the Mars landing simulation but the rest of the mission is understimulating.** Sukhrob Kamolov: It is difficult to say that I was impressed by some events very much. Of course the participation in such project is probably the most impressive event. Diego Urbina (researcher): The Mars walks and the rover driving on the surface are pretty high on the list, they brought some adrenaline with them! Then maybe the power cut, it caught us by surprise, and in spite of the “risks” it brought us together and was something very different.		x	x
		ISS: Physical exercises are boring and monotonous and heavy work. I love it on Earth, I hate it here, Valery Ryumin (Blut & Helppie, 1986)			
		ISS: You will never get tired to look at Earth out of the window, in long duration missions that will be not possible (Williams, 2007)		x	x
		ISS: If you have open space you can do advanced acrobatics (Chamitoff, 2008)		x	x
Index: x=problems ; v= support					

Socio-Cultural Problems

Table 0.11: Socio-cultural problems in space missions. (Behar, 2006; Häuplik-Meusburger, 2011; Lucid, 1996; Mars 500, 2011; Messerschmid, 2008; Musser Shiner, 2006; Thagard, 1995)

	Hazard	Example	Usability	Livability	Flexibility
CREW		Mir: You couldn’t have asked for nicer people to work with on a long term basis (Lucid, 1996)		v	
		ISS: Living and working together with only two other people for several months is challenging (Bursch, 2002)		x	x
EAT		Mir: We ate all our meals together (Lucid, 1996)		v	
		Mir: About half the time we ate together (Thagard, 1995)		x	
		Mir: Supplementary food system allows you a lot of flexibility (Thagard, 1995)			v
		Mir: We were not tested on that experimental food system in the training (Thagard, 1995)	x	x	x
CULTURAL ACTIVITIES		Mir: We circle around the cosmic dancer (Space Art) and he circles around us (Polischuk, 1993 cited after Häuplik-Meusburger)		v	
PREFERE-NCES		Mir: Food was good, you could get different tastes by mixing different stuff together (Lucid, 1996)		v	
	x	Mir: The experimental food was picked by someone who had no idea what we liked. It was stuff I didn’t normally eat. I was losing protein, as well as fat. One of the things that saved us was the presence of all of this food, most of which was left over from previous crews (Thagard, 1995)		x	x
		Mir: Small amount of fresh food: apples, oranges, garlic, and onions, and a little bit of keilbasa, coleslaw or Russian sausage (Thagard, 1995)			x
		Mir: Obviously, your preferences are for things with which you’re familiar (Thagard, 1995)			x
RITUAL		Mir: Friday night or something, we’d get together, and we’d break out some of the sausage and cheese. The wardrobe table has a fan in it to attract crumbs and loose particles, we would turn that fan on, and that would allow us to hold things to the table (Thagard, 1995)			x
		Mir: Russians feel very strongly about their saunas, I would not have missed that, also it was very difficult to use (Thagard, 1995)	x	v	
		Mir: Friday and Saturday nights, before the EVA's started, we would watch movies on video (Lucid, 1996)		v	
		Mars 500: About ritual, there is a routine that can be broke with personal activity. Romain Charles (flight engineer) I don't know if we can call it a ritual but I always do the same thing in the morning. From the moment when I wake up until the breakfast, I'm doing the same tasks at the same time almost every day. I don't have any routine for the rest of the day. Diego Urbina (researcher) Not really, I like to change the routine as much as I can. Maybe watching an episode of some series with the guys after a hard day’s work, we do			x

		that often. Wang Yue (researcher): Ritual? Maybe you mean individual habit? I think practicing calligraphy is my special one.			
LEISURE		Mir: Psychologically you need to be reasonably busy with meaningful work, you find projects that you are interested in doing (Lucid, 1996)		x	x
		Mir: CD player did not work in microgravity (Lucid, 1996)	x	x	x
		Mir: Mostly look out the window (Lucid, 1996)		v	
		Mir: Leisure activity start to loom larger over a longer period of time: 6 months or 1 year mission (Lucid, 1996)		x	
		Mars 500: Favorite leisure activities are reading books, playing computer games, doing sports to relax, studying to keep the brain active, writing to relatives, practicing calligraphy.		v	x
PERSONALITY AND PERSONAL NEEDS	x	Mercury 7: Unplanned maneuvering using manual altitude control jets to get pictures of beautiful sunsets. Almost made return impossible.			
		Mars500: Crew misses nature, direct interactions with family and friends, their own national food. Romain Charles (flight engineer) It's always better to talk to someone directly and to have an immediate feedback than to write a letter and wait several days for the answer. Diego Urbina (researcher) The blue sky and meeting new people. Wang Yue (researcher) For me, I guess it should be the food, my national food. Because of my stomach's protest.		x	x
		Mir: Wife´s e-mails are like a present or a chocolate (Foale, 1999, p. 80 cited after Häuplik-Meusburger, 2011)		v	
Index: x= problems; v= support					

Appendix F refers to 4.2.1 IDP Application Process

Table 0.12: Comparison of IDP positions applied during the conceptual phase of a space project: ESA (Bandecchi et al. 2000, ESA, 2007 cited after Johansson; ESA 2011b), HMM (Bessone and Vennemann; 2004, Imhof personal communication 2011), SSDW (SSDW, 2009), HSI (Johansson, 2010)

TEAM POSITIONS	Proposed	Actual	Experimental	Experimental	Proposed
	IDP	ESA	HMM ESA	SSDW	HSI
Management Positions					
A. CDF Manager	x	x	x	X	
B. Team Leader	x	x	**x**	**X**	
C. Technical Author / Editing	x	x	**x**		
D. Systems Specialist	x	x	**X**		
E. Systems Assistant	x	x	**X**		

Position Disciplines					
1. Acceleration	x			V	Part of HSI
2. Attitude and Orbit Control	x	x		V	
3. Aerothermodynamics	x		**x**	V	
4. Configuration (*Habitat System and Architecture)	**X***	Part of Structures	**X**	v	
5. Command and Data Handling	x	x		v	
6. Cost	**x**	x	x	x	
7. Communications System	**x**	x	x	x	
8. Crew Escape Facility	**x**			v	Part of HSI
9. Crew Performance	**X**			vPart of HF	
10. Cultural Theorist (space cultural application)	**X**				
11. Data Handling		x	x		
12. Exploration Scientist	x		Part of others		
13. Environment	x		Part of others	x	
14. Future Options and Developments	x			xv	
15. Ground Systems and Operations (*Ground segment)	x	x	X*		
16. Guidance Navigation Control (GNC)	x		x		
17. HF(* and Habitability, ** and Crew Performance)	**X***		**X**	**X****	
18. HIS (Human System Integration)	x			v	**X**
19. Instruments	x	x		v	
20. Life Support (*ECLSS)	**X**		**x**	**x***	
21. Marketing	x			Part of outreach	
22. Mechanisms (*and Pyrotechnics)	x	x *	x		
23. Mission Analysis	x	x	x		
24. Noise	x				Part of HSI
25. Outreach and Marketing	x			x	
26. Operation (*and Utilization & Risk Analysis)	**X**			X*	
27. Physiologist/Psychologist (Medicine)	**X**		Part of others		
28. Power (*EPS: Electrical Power System)	x	x	x	X*	
29. Propulsion	x	x	**x**		
30. Pyrotechnics	x	Part of mechanisms			
31. Propulsion	x	x	x		
32. Programmatic	x	x	x		
33. Requirement	x				Part of HSI
34. Resource	x			X*	

(*In-situ Resource Utilization)					
35. Radiation	x		**x**	x	Part of HSI
36. Risk/Safety (*Risk Assessment)	x	X*	**x**	Part of operations	
37. Robotics, Mobility &EVA	x			x	
38. Science and Physics	x		Part of others		
39. Simulation	x	x	**x**		
40. Systems	x	x	x		
41. Structure (* and Configurations)	**X**	X*	**X**	**X***	
42. Thermal (*TCS: Thermal Control System)	x	x	**x**	X*	
43. Telemetry Tracking and Command	x	x			
44. Trajectories	x		x		
45. Transportation & Logistics	x			x	
46. Visibility (PR)	**X**			Part of outreach	
47. Workload	x				Part of HSI
48. User: Astronaut	**X**			v (Frank de Winne was present but not listed as a participant)	
49. Others	x	X *Instrument design activities have specialized teams with disciplines such as: Receiver, Optics etc.	**x**		
Index: Marked = new disciplines, x = concurrent design position, **x** Bold= position related to Human Factors, **X** = position that works in close relation with Human Factors. Acronyms: HF (Human Factors), IDP (Integrated Design Process), ESA (European Space Agency), HMM (Human Mars Mission), SSDW (Space Stations Design Workshop), HSI (Human Systems Integration), ECLSS: Environmental Control & Life Support System					

Table 0.13: Hf relevance for possible IDP Concurrent Design positions.

IDP Concurrent Design HF POSITION	Relevance to Habitability Factors					Relevant to all the *Hf*	Strongly related to HF
	Hf_p		Hf_{ps}	Hf_{sc}	Hf_o		
	Hf_e	Hf_{ph}					
Management functions							
CDF Manager	Concurrent Design coordinators are Human Centered					x	
Team Leader							
Technical Author /Editing							
Systems Specialist							
Systems Assistant							
Disciplines							
Aerothermodynamics	x						

Configuration (Habitat System)	x	x	x	x	x	x	x
Cost					x		
Communications System			x		x		
Crew Escape Facility	x		x		x		
Crew Performance	x	x	x	x	x	x	x
Cultural Theorist (space cultural application)			x	x	x		x
Exploration Scientist					x		
Environment	x						
Future Operations and Developments					x		
Ground Systems and Operations (Ground Segment)					x		
HF / Habitability	x	x	x	x	x	x	x
Life Support (ECLSS: Environmental Control and Life Support System)	x	x					x
Operation					x		x
Physiologist/Psychologist (Medicine)		x	x	x			x
Physical HF (Radiation, Temperature, Noise, Acceleration)	x	x					
Resource (In-situ Resource Utilization)					x		
Radiation		x					
Risk/Safety			x		x		
Science and Physics	x				x		
Simulation	x	x			x		
Systems	x	x			x		
Structure	x	x	x		x		x
Thermal (TCS: Thermal Control System)	x	x			x		
Visibility (PR)	x	x	x	x	x	x	x
Workload		x	x		x		
User: Astronaut	x	x	x	x	x	x	x
Others							

Index: **text** Bold = new disciplines
Habitability Factors index: Hf_p(Physical Factors): Hf_e (Environmental Factors),Hf_{ph} (Physiological Factors); Hf_{ps} (Physiological Factors); Hf_{sc} (Socio-Cultural Factors); Hf_o (Operational Factors).

Table 0.14: Focus Interrelation and Relevance of IDP Elements

IDP Components	Focus	Project
HOLISTIC METHODOLOGY		
HME (Human-Machine-Environment)	Holistic design	TU-Berlin
MD (Multidisciplinary Design)	Multidisciplinarity	MDRS Extreme-Design
CD (Concurrent Design)	All design phases	Moon Base
USER-CENTERED APPROACH		

PD (Participatory Design)	User in the design	User Analysis
UE (User Experience)	Qualitative dimensions	MDRS Stimuli
ED (Empathetic Design)	Simulates user	MDRS-Cromos

Element Interrelations in the IDP

IDP			USER-CENTERED APPROACH		
			PD	UE	ED
			User in the design	Qualitative dimensions	Simulates user
HOLISTIC METHODS	HME	Holistic approach	V	V	V
	MD	Multidisciplinarity	V	V	V
	CD	All design phases	V	V	V

Index: V= apply

Relevance in the IDP

IDP			USER-CENTERED APPROACH			HOLISTIC METHODOLOGY		
Components	Relevance	Elements	PD	UE	ED	HME	MD	CD
HOLISTIC METHOD	5/6	**HME**						
	3/6	MD						
	2/6	CD						
USER-CENTERED APPROACH	3/6	PD						
	4/6	**UE**						
	3/6	ED						

Index: Dark Gray= Full focus; Gray = Partial focus, White= Slightly considered;

Acronyms: HME (Human Machine Environment Systems), MD (Multidisciplinary Design), CD (Concurrent Design), PD (Participatory design), UE (User Experience), ED (Empathetic Design)

Table 0.15: Interrelations in the IDP and the projects

IDP Goal: increase of habitability		Relevance							
PROJECTS		FOCUS	**HME**	MD	CD	PD	**UE**	ED	TEAM
THA LES	USER ANALYSIS (Space-Haven)	One element study\design							User-Designer
UNITO-TU	µGORIENTING (Cromos-WIUD)	One element study							Mixed Team
QUALITY OF LIFE	MDRS HABITABILITY	One element design							Humanities Team
MOON BASE	SSDW MOON BASE	System design							Engineer Team

	MOON LIFE	System design							Humanities Team
TU-BERLIN	HOLISTIC SOLUTIONS	Elements design							Engineers
	HABITABILITY SOLUTIONS	Elements design							Humanities
	STORAGE SYSTEM	One element design							Engineer Team
Index: Dark Gray= Full focus; Gray = Partial focus, White= considered Acronyms: HME (Human Machine Environment Systems), MD (Multidisciplinary Design), CD (Concurrent Design), PD (Participatory design), UE (User Experience), ED (Empathetic Design)									

Table 0.16: Interrelations in the IDP methodologies and the projects

IDP		Projects	USER ANALYSIS - SPACE-HAVEN	µGORIENTING CROMOS	µGORIENTING WIUD	MDRS EXTREME-DESIGN	MDRS STIMULY and CREATIVITY	MDRS HABITABILITY	SSDW MOON BASE	MOON LIFE	HOLISTICH SOLUTIONS	HABITABILITY SOLUTIONS	STORAGE SYSTEM
Elements		Application to Mission Design	THA LES	µG		QUALITY OF LIFE			MOON BASE		TU-BERLIN		
PD	HME	Astronauts (users) are involved in: Holistic design.	+					-	+				+
	MD	Astronauts contribute to the multidisciplinary team on each, particularly to HF team.							+				+
	CD	Astronauts take part in the CD meeting							+				
	PD	Astronauts contribute to the design process	+					-	+				
	UE	Astronauts contribute to defining the qualitative dimension and needs.	+	-	-		-	-	+				+
	ED	Designer and astronaut together experience astronaut condition or simulation condition		+			-	-					
UE	**HME**	**Astronauts' qualitative experience is supported by holistic design**											
	MD	Multidisciplinary team contributes to the astronauts' qualitative experience											
	CD	Astronauts' qualitative experience is supported with CD											
	PD	= PD-UE											
	UE	To guarantee the increase of knowledge also from the humanities perspective, qualitative experiences are:											

			USER ANALYSIS - SPACE-HAVEN	µGORIENTING CROMOS	µGORIENTING WIUD	MDRS EXTREME-DESIGN	MDRS STIMULY and CREATIVITY	MDRS HABITABILITY	SSDW MOON BASE	MOON LIFE	HOLISTICH SOLUTIONS	HABITABILITY SOLUTIONS	STORAGE SYSTEM
		- supported and investigated by the designer - performed and communicated by the astronaut											
	ED	Qualitative dimensions are experienced by the designer in user condition or simulation condition		+	-		-	-	-	-			-
ED	HME	Designer experiences the system holistically					-	-					
	MD	Designer experiences the user condition from a multidisciplinary perspective		+				-					
	CD	Design team experiences each aspect of the mission						-					
	PD	= PD-ED											
	UE	= UE-ED											
	ED	Designer experiences the user condition and/or simulation condition to deeply understand user needs and identify latent needs		+	-		-	-	-	-			-

Index: Dark Gray= Full focus; Gray = Partial focus, White= considered
- =Astronaut / environment are simulated; + =Astronaut / environment are real)

Acronyms: HME (Human Machine Environment Systems), MD (Multidisciplinary Design), CD (Concurrent Design), PD (Participatory design), UE (User Experience), ED (Empathetic Design)

Table 0.17: Interrelations in the IDP approach and the projects

IDP		Projects	USER ANALYSIS - SPACE-HAVEN	µGORIENTING CROMOS	µGORIENTING WIUD	MDRS EXTREME-DESIGN	MDRS STIMULY and CREATIVITY	MDRS HABITABILITY	SSDW MOON BASE	MOON LIFE	HOLISTICH SOLUTIONS	HABITABILITY SOLUTIONS	STORAGE SYSTEM
Elements		Application	THALES	µG		MDRS QUALITY OF LIFE			MOON BASE		TU-BERLIN		
HME	HME	Design focus on the holistic design, considering the system in its complexity and the relations between the system's elements											
	MD	The multidisciplinary team applies holistic design											
	CD	Holistic design is applied to all mission phases											
	PD	=PD-HME											
	UE	=UE-HME											
	ED	=ED-HME											
MD	HME	=HME-MD											

	MD	The team is composed of experts in engineering, scientific and humanistic fields to support functional and qualitative dimension of the mission.					
	CD	The CD team is multidisciplinary					
	PD	=PD-MD					
	UE	=UE-MD					
	ED	=ED-MD					
CD	HME	=HME-CD					
	MD	=MD-CD					
	CD	The team works concurrently on different aspects and phases of the mission design.					
	PD	=PD-CD					
	UE	=UE-CD					
	ED	=ED-CD					

Index: Dark Gray= Full focus; Gray = Partial focus, White= considered
- =Astronaut / environment are simulated; + =Astronaut / environment are real)

Acronyms: HME (Human Machine Environment Systems), MD (Multidisciplinary Design), CD (Concurrent Design), PD (Participatory design), UE (User Experience), ED (Empathetic Design)

Appendix G refers to 5.1.1 SSDW Design Process

From the HF perspective, the SSDW space habitat design methodology is advanced regarding the current ESA methodology. In particular, the IDP methodology has been applied in 2009, increasing the HF results even more with particularly innovative ideas for improving habitability. Below are reported the detailed data of the SSDW 2009.

MISSION STATEMENT

Mission Statement: "Outline a comprehensive study of an international lunar outpost concept, with the potential to be installed within one decade, to provide sustained surface exploration capabilities and growth potential towards a permanent lunar base. The outpost shall allow for extensive manned and robotic surface exploration in its first phase, enabling new insights into the Earth-Moon system and its development as well as technology demonstration and maturation for future human surface activities on Moon and Mars. It shall stimulate commercial partnerships as early in the program as possible, while specifically focusing on extending exploitation capabilities and commercial partnerships in its further development and continued operation after 2030" (SSDW, 2009).

Task at SSDW 2009: "The objective of the conceptual study is to define an evolutionary lunar base concept in an international lunar exploration scenario. In particular, the Moon Base shall:

- Provide initial habitation capabilities for extended surface stays no later than 2025
- Accommodate a crew of at least 4 astronauts for missions to the lunar surface of up to 180 days at assembly complete
- Provide safe haven capabilities for a crew of 4 astronauts for up to 14 days

- Provide growth potential towards a sustainable permanent lunar base including commercial partners after 2030
- Offer the possibility to conduct research on human aspects as well as on technology for long-term surface operations on Moon and Mars
- Outline a significant contribution and visibility of Europe in the international program" (SSDW, 2009).

Table 0.18: HF Work package
(Universität Stuttgart, IRS, SSDW09_WP_HumanFactors.doc, 16.06.2009)

Irene Schlacht: Preparation Work Package **HUMAN FACTORS**
1. Introduction
"Ergonomics" is a scientific discipline investigating the interactions between humans and other elements of a system (e.g. interfaces), in order to design and optimize human-machine interaction and overall system performance. This concept clearly focuses on a working human being, while the definition of "Human Factors" is wider and addresses also important parts of the environment and how acceptable it is to humans ("Habitability"). Habitability issues are part of the Human Factors design. Work/rest cycle, illumination, color scheme, internal decor, noise variation, physical-psychological stress, are all factors that have to be considered and planned in the habitat design. For example ergonomic interfaces are relevant in both short and long term missions, minor things as the presentation of food as a cultural ritual "will assume considerable significance to insure adequate habitability of a lunar base" (Koelle, 2003) in the long duration missions. Human Factors Engineering aims at integrating knowledge in the field of Human Factors into a human spaceflight project, thus is "is applied to enhance astronaut performance during space flight using human centered technologies" (aerospace Human Factors association). Considering the complexity of an extreme and isolated environment Human Factors Engineering is essential to guarantee human safety, efficiency, comfort, and mission success.
2. Task Description
1. List the scientific disciplines related to the Human Factors approach. 2. Summarize the main physical and psychological stressors of the space environment and space missions. 3. Identify the astronauts' needs from Human Factor perspective considering: a. Short Duration Mission scenario (2 weeks) b. Long Duration Mission scenario (months/years) 4. Describe briefly three examples of habitat design elements to avoid stressors affecting human performance in long-term space missions. 5. Summarize the parameters that can be used to evaluate the habitability quality following a human centered approach.
3. Potential Reference Readings
[1] Larson, W.J.; Wertz, J.R. (eds.): Human Spaceflight – Mission Analysis and Design, Space Technology Series, McGraw-Hill Companies Inc., Crawfordsville, 1999; in particular chapter 6 (Book). [2] Messerschmid, E.; Bertrand, R.: Space Stations – Systems and Utilization, Springer, Berlin, 1999 (Book). [3] Harrison, A.; Connors, M.; Akins, F.: Living Aloft. (Updated: August 6, 2004). http://history.nasa.gov/SP-483/cover.htm, in particular chapters 3.2 (Habitability: The Physical Environment) and 4.4 (Performance: Issues in Astronaut Work Regimes). [4] NASA: NASA-STD-3000 Man-System Integration Standards, Volume 1, Section 5 and 7, Johnson Space Centre, NASA, http://msis.jsc.nasa.gov/. [5] NASA: Guidelines and Capabilities for Designing Human Missions, NASA/TM-2003-210785, January 2003 (PDF on FTP). [6] Kanas, N.; Manzey, D.: Space psychology and psychiatry, Springer, The Netherlands, Dordrecht, 2008; in particular chapter 2 (Book).

[7] NASA: ISS Interactive Reference Guide, Release 2.3, 2009, http://www.nasa.gov/externalflash/ISSRG/.
4. Expected Output
The expected output is a document of 2 to 3 pages summarizing the answers to the above mentioned tasks. The document shall be produced in Microsoft Word (.doc) or PDF (.pdf) format.
5. General Info
A central FTP site has been established to facilitate the distribution of reference material and to allow you to upload your output documents

Table 0.19: Analysis of the HF work package results (Universität Stuttgart, IRS, 16.06.2009)

Irene Schlacht: Analysis of work package task results by two team members **HUMAN FACTORS**				
HF QUESTION	**Member Background: HF**		**Member Background: Architecture**	
1. HF disciplines related	Psychology - Engineering Science - Neuroscience - Cognitive Science - Informatics - Architecture and Design - Ergonomics - Medicine	+-	Philosophy / epistemology - esthetics - semiotics - ecology - anthropology - sociology - psychology - physiology - anthropometrics - architecture - ergonomics - medicine - cognitive sciences.	+
2. Stressors in space a. physical	Weightlessness, altered natural dark- light cycle, radiation	+	Vacuum ▪debris ▪gravity ▪solar radiation ionizing radiations	-
2. Stressors in space b. psychological	Restricted environmental cues, high workload, lack of privacy, separation of the usual social network	-	Spatial orientation and temporal confusion ▪isolation ▪reduced habitability ▪life in group - reduced privacy / personal space - territoriality ▪autonomy ▪non-gustatory food	+
3. Astronauts' needs: a. Short Duration Mission	Primary needs (eating, sleeping…) and: loss muscle and space motion sickness countermeasures - privacy - clear schedule.	+	More needs with time The need to compensate for an inadequate environment & need for countermeasures against an unsatisfactory environment The need being able to innovate, improvise and develop to go beyond mere survival and predefined mission accomplishments.	+
3. Astronauts' needs: b. Long Duration Mission LTM	Crew cohesion, family communication, psychological support, private space, intelligent medical system, physical exercise	-		
4. Three examples of good habitat design for LTM.	In the rest room: privacy, visual and acoustic shielding, adjustable warming, comfortable sleeping bags, audio and video devices, Good storing, adjustable décor, outside view, recreation devices, …	-	1. Artificial Gravity SICSA 1987 2. Cupola observatory from ISS 3. SICSA Habitability project	+
5. Requirement to evaluate the habitability	Simplicity, variety, personalization, safety, body posture, light.	+	Crew safety, health satisfaction and performance	+
Index: +=good reply, +-=medium reply, -=a deeper research is suggested				

Table 0.20: HF Recipe. (Universität Stuttgart, IRS, SSDW09_WP_HumanFactors.doc, 16.06.2009)

Irene Schlacht: Recipe **HUMAN FACTORS AND CREW PERFORMANCE**

1. Motivation and Objective (long duration mission)

The motivation and objective presented focused on human centered design able to increase crew performance, well-being and mission accomplishment through a rich experience. The crew will live on board the lunar base you are designing for a prolonged period of time. They will constantly have to deal with high workloads, a high-risk, technology-dominated environment and the effects of the environmental condition (gravity variation, stress, confinement and isolation).

Therefore, as a designer, you need to take into account all we know about Human Factors i.e. topics ranging from overall module configuration to interior layout to crew time scheduling. These insights must begin during the very early phase of the spacecraft design.

Your task is to make sure that your team's moon base is designed and will be operating in a way that is supportive of the human presence, providing an efficient working and living environment, able to increase crew performance, well-being and mission accomplishment through a rich experience.

Several everyday life habits, rituals and customs will be impossible but considering the extreme human capability to adjust its own ritual behavior in relation to new environments, new approaches will be develop (how can it be the meal ritual in 1/6 g, sleeping, using the toilet ?... Which social play may be developed to increase crew motivation?...).

2. Keywords

Sustainability, Flexibility-Variability-Adaptability, Cognitive Design Strategies, holistic approach, local environment feature.

3. Approach

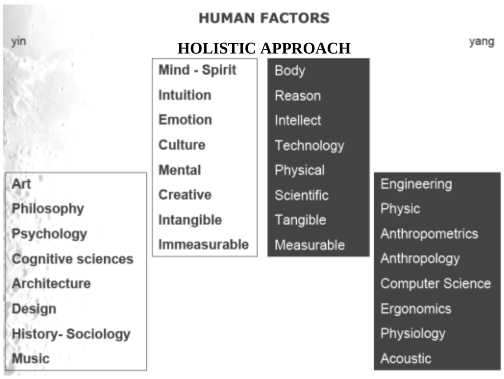
To help you to meet the objective, here are some hints for your design:

- Habitability aspects: Mental map of > Needs, cultural and place experience, aesthetics, harmonies, atmosphere (place spirit), values.
- Module configuration aspects: Pattern sketch of > Window locations, Earth orientation, access and egress paths, zoning and space distribution (activities, territoriality, walking-access path, visual field, privacy, group activities, noise, odors).
- Interior design: Design sketch of > lighting, colors, decors, ergonomics (moon walk), psycho and physiological stress countermeasure and storage system.
- Operations and scheduling: Conceptualization of > Crew division, work shifts, free time, private and group and recreational activity (also as interior configuration facilities), duration of stay.
- Social structure: Conceptualization of > Crew composition-selection, on-board chain of command, jurisdiction, ground station contact and support (ex. psychological).
- Life Support: Sketch and conceptualize of > Food preparation (also as recreational activity), rescue, radiation shelters, contamination control, and noises-odors screen.

4. Human Factors Heuristics and Design Hints

Human Factors must be considered both from an engineering point of view – i.e.: allowing for applying specific numbers and sizing correlations - and an architectural one – i.e.: allowing for an holistic approach, that refers to issues not directly related to numerical values, but which is still greatly important for the quality and completeness of the overall system concept.

However, experiences from previous human space programs, systems, and studies allow for the formulation of lessons learned in selected areas. Some of these are summarized in the following table. Please use those as a guidance where suitable, but carefully check their relevance and applicability to your specific design.



5. Human Factors Results documentation

- Document your design considerations, choices and justifications. Proposed "tangible results" of your work, as Human Factors team specialists, should include:
- Maps of Habitability requirement: needs analysis, moon constraints and environmental qualities (regolith, reduced weight, solar energy…), …
- Views and sketches of the station interior concept. Detail relevant aspects.
- Representations of: zoning, communication and translation paths.
- External views with emphasized HF influences.
- Crew schedules, on-board activity schedules (consolidate with Operations team).

6. Reference
[0] Heinz-Hermann, K. (2003). Lunar bases. Shaker Verlag: Aachen, Germany.
[1] Imhof, B., Mohanty, S., Adams, C., Häuplik, S., Stiefel, H., Fairburn, S. (2004). Space Architecture. Bundeskanzleramt: Wien.
[2] Mahnke, F., Mahnke, R., (1987). Color and Light in Man-made Environments. Van Nostrand Reinhold Company: New York, USA.
[3] Messerschmid, E.; Bertrand, R.: Space Stations – Systems and Utilization, Springer, Berlin, 1999. Cap.11
[4] Osburg, J.: An Interdisciplinary Approach to the Conceptual Design of Inhabited Space Systems, Dissertation, University of Stuttgart, 2001 (Basics, Tables 5, 6, 7, 8).
[5] NASA: NASA-STD-3000 Man-System Integration Standards. Volume 1, Section 5 and 7, Johnson Space Centre, NASA, http://msis.jsc.nasa.gov/.

Table 0.21: HF Requirements. (Universität Stuttgart, IRS, SSDW09_WP_HumanFactors.doc, 16.06.2009)

Irene Schlacht: Requirements

Heuristics and lessons learned for selected areas of Human Factors engineering

Aspect	Design Rules	Importance
Environment	Allows the use of local environment features: • Solar energy and illumination • Gravity reduction (possibility to jump, climb, move more weight, more flexibility for positioning payloads) • Consider use of Regolith. • Support Earth observation, astronomical observation and telecommunications (Earth provides reference for crew orientation (EVA)) because it is stationary in the lunar landscape).	B
Habitability	• Habitability requirements increase with mission duration, risk, degrees of isolation and confinement • Increase comfort, provide customizable elements of the environment • Permit the crew to behave in ways that are innate to them to remove numerous minor stressors from their daily routine	A
Interior Configurations	• Study redundant access and escape routes • Design territoriality distribution, private and public areas • Provide separate habitation areas, for quiet/individual activities and for group activities. • Deliberately use architectural space inside the modules, instead of giving the crew whatever is left over after fitting all hardware in. • Identify required degree of proximity of modules/functions. • Enable interior configuration modifications • Provide enough space to leave equipment that is in regular use (exercise, dinner table, etc.) deployed • Dinner/conferencing table and surrounding area must be large enough to accommodate entire crew	B
Perception	• Check field of view and shading for payloads, crew privacy, communication, … • Provide some long line-of-sight distances in local “horizontal” direction • Cluster and isolate noisy equipment, bad odors, vibration, etc. far from habitation zone and in relation with the area function	B
Windows	Provide accessible windows for Earth/Space viewing • Preferred window locations: conference/dining area, exercise area, quiet/recessed area; • In relation with radiation exposure, avoid windows in locations where crew must spend more than two hours each day (e.g. sleep quarters, laboratory)	B

Crew dynamics	• Design countermeasures for physical and emotional stressors, isolation and confinement (ex. Psychological support, gym, ...)	C
	• Interpersonal and leadership-acceptance problems, as well as problems between crew and ground support, increased with mission-elapsed time • Establishing pre-mission relationships reduces crowding problems • Consider crucial “everyday” conflict issues: stowage, food, acoustics, trash management, inventory system, hygiene, distribute within the crew the “housekeeper” functions.	B
	• Design crew autonomy and teamwork into system for increased productivity	A
	• Available space and spatial arrangements can indicate or influence hierarchy; must therefore be congruent with actual hierarchy structures	B
Activities and Schedule	• Schedule frequent regular group – social – recreational activities (dinner, conferences, music listening) to keep morale and productivity high • Provide marker events (holidays, celebrations) to structure long missions	B
Privacy	Privacy issues are twofold: among crewmembers (provide opportunities for retreat as well as openness), and between crew and ground (avoid one-way surveillance) • Crew selection for agreeableness and flexibility should mitigate cross-cultural issues • Provide secure channels, e.g. via encrypted e-mail, for personal communications of crew with family on ground • Offer area for person-to-person meetings, with privacy level. • Crowding is influenced by the flow of information between people, through vision, hearing, smell, and touch. Mitigation of crowded conditions therefore means reducing signal strength • Ability for crewmembers to withdraw to private quarters is extremely important to mitigate effects of transient negative moods on group morale • Provide space/technology for crew to store some personal items (music, images, books)	B
Index: relative importance”: A = most important, B = less important, C: least important		

Appendix H refers to 5.1.3 SSDW Result Validation

Table 0.22: IDP Result Evaluation (SSDW 2009)

		IDP (TEAM BLUE SSDW2009)					IDP (TEAM RED SSDW2009)			
	ELEMENT	KEY ELEMENTS	Usability	Livability	Flexibility	ELEMENT	KEY ELEMENTS	Usability	Livability	Flexibility
		MOON BASE (180 DAYS), 6 CREW MEMBWERS					MOON BASE (180 DAYS), 6 CREW MEMBERS			
Human Factors	Hfo Hfp Hfp	Human Factors become notably important when considering crew surface stays of 180 days and more.	'	YES	'	Hfo Hfp Hfps	Human Factors Engineering is essential in the design of long duration surface infrastructures, where an ideal habitat system should support human experiences allowing the active gain of further knowledge.	YES	YES	YES

Innovation	Hfo Hfp Hfps Hfsc	Thus, human experience and human-centered design have to be combined with latest technology developments.	YES	YES	YES	Hfo Hfp Hfps Hfsc	Many creative ideas and the use of modern technology have been introduced to avoid the psychological and functional problems of confined space and outward visibility	YES	YES	YES
Configuration	Hfp Hfo Hfp Hfps	The racetrack configuration of the lunar base reflects historical human dwellings and creates a feeling of safety against a potentially harmful environment, supporting psychological well-being. Local materials are used to protect the base from radiation, with regolith covering reaching up to about 2 m.	YES	YES	YES	Hfo Hfp Hfp Hfps	While the allocation of windows was rejected for safety and cost reasons, the walls between crew quarters and walkways are made of “liquid crystal intelligent glass” to simulate windows. Light colors and intensity can automatically change for day/night simulation or animation. Floors are flexible to allow for increased comfort of movement and relaxation. The “Camera Obscura” provides a really innovative idea, where little holes in the wall of a dark module sealed with lenses will create the inverted projection of the external environment.	YES	YES	YES
Interior	Hfo Hfp Hfps Hfsc	In the interior, dynamic multi-purpose furniture, ambient lighting and quarter`s walls folding systems, allow each person to be an active creator of his/her own place and space, providing the possibility to arrange the modules in almost countless combinations. This configuration also provides an effective guard against boredom and depression due to monotony. The six crew quarters provide 11 m^2 (27 m^3) each and are distributed in the two habitation elements.	YES	YES	YES	Hfo Hfps Hfsc	In crew quarters, the use of periscopes supports an individual place of exploration and a spiritual and meditative dimension. The crew quarters are distributed in two highly personalized habitation modules, also featuring personal communication centers based on augmented reality foldable touch screens.	YES	YES	YES
Crew		Not described				Hfp Hfps	The composition, of the crew of four, is assumed to comprise a commander (pilot & management), an engineer (pilot & servicing tasks) and two scientists (research), where gender mix is possible for psychological balance.	YES	YES	YES
Schedule		Not described				Hfp Hfo Hfps Hfsc	The crew timeline for working days is divided into sleep, task, hygiene and health, social activities and meals. One day off per crew member and week is envisioned in accordance with the activity schedule. Crew	YES	YES	YES

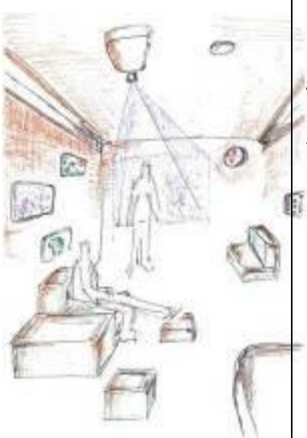
							operations will be more extensive during the lunar day			

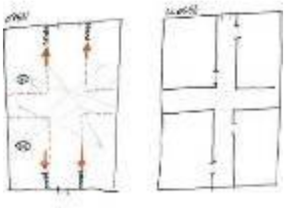
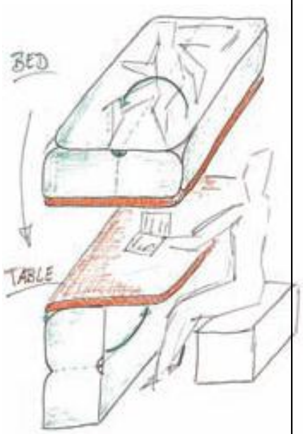
Table 0.23: Validation group result evaluation (SSDW, 2010)

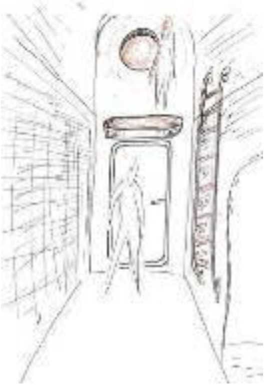
		VALIDATION GROUP (TEAM BLUE SSDW2010)					VALIDATION GROUP (TEAM RED SSDW2010)			
	ELEMENT	KEY ELEMENTS	Usability	Livability	Flexibility	ELEMENT	KEY ELEMENTS	Usability	Livability	Flexibility
		NEAR EARTH ASTEROIDS MISSION					NEAR EARTH ASTEROIDS MISSION			
Human Factors	Hfp	Asteroid Spacecraft (139/365 days), 3 crew members	-	-	NO	Hfp	Asteroid Spacecraft (180/317 days), 3 crew members	-	-	NO
Innovation		Not described					Not described			
Configuration	Hfps	The compartments are arranged keeping human factors engineering at its core and allocating open compartments for minimal confinement.	NO	NO (Bad Privacy)	NO	Hfp	In total, the human factor equipment accounts for a mass of 1.8 t, comprising hygiene items such as towels and clothing, medical devices, and exercise equipment.	YES	NO	NO
Interior	Hfp	The interior design of the Mother Vehicle provides a very low degree of isolation, but since there are only 3 crew members, isolation is not a major issue.	NO	NO (Social and environmental isolation)	NO	Hfp Hfo Hfps	Human factors issues include suitable zoning of spacecraft interior and proper color and illumination schemes as well as ergonomic work stations. Zoning allocates areas for social, private, and work activities. Exercise equipment on board includes the Advanced Resistive Exercise Device (ARED) and a COLBERT treadmill & vibration reducing rack. Both enable µg countermeasures.	YES	YES	NO
Crew		Not described				Hfsc	A crew social structure is proposed, as one serves as the commander, whereas the other two crewmembers have an equal standing in the hierarchy. From the professional point of view the crew is made up of a pilot, a scientist, and a robotic controller. Coming from a military background, the pilot also acts as commander of the spacecraft.	YES	-	NO (Ethical social relationship)

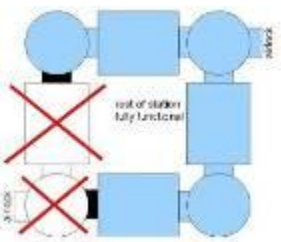
Schedule	Hfo	The daily crew schedule allots 8.5 hours for work, including planning and coordination as well as daily systems operation tasks. Another 8.5 hours are allowed for sleep. The remaining time is used for exercise, meals, and personal hygiene.	YES	YES	NO	Hfo	The crew schedule is arranged in a “round robin” format, a rotating schedule that allows alternating rest and work phases of the individual crewmembers. The crew works ten-hour days during the week and five-hour days on weekends. Eight hours are allocated for sleep and the remaining time is available for exercise, leisure, and social activities.	(No concurrent work) NO	(No free day) NO	NO

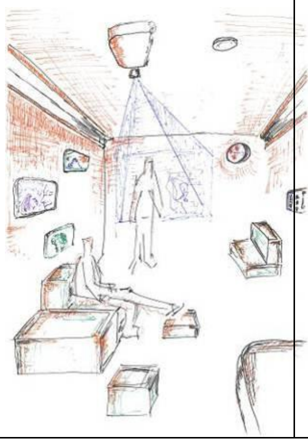
Table 0.24: Analysis example of IDP HF solutions (SSDW, 2009)

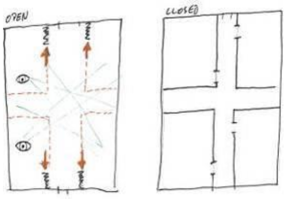
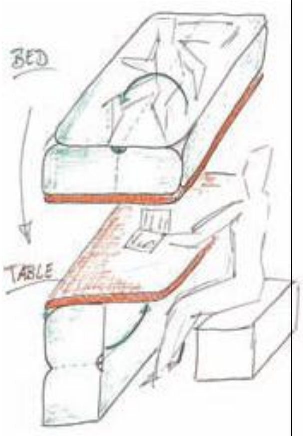
IDP	TEAM BLUE HF REPORT (SSDW, 2009b) HF Specialist: Jan Grippenkoven; HF Tutor: Irene Schlacht	
HME	HOLISTIC METHODOLOGY Human-System elements	In general, you can describe Human Factors as a discipline concerning all physical, psychological, and social characteristics of the human which influence or are influenced by socio-technical systems. Human Factors is a science which deals with the role of the human in complex systems, the design of technical equipment and facilities as well as with the adaptation of the working environment with the aim to increase comfort and safety (Kanas & Manzey, 2008). In an extreme and complex environment like a lunar base, the field of human factors is of particular importance. The following section contains a detailed overview of the most important influences of living and working in a lunar station on the human being, as well as considerations of how you can design the environment in such a way that it fits to specific human needs (p. 12).
MD	ENVIRONMENT ISRU, Architecture history Anthropology Psychology Poetry	The Loretta moon base follows the most basic construction principles of human civilization history: -ISRU and -anthropological history of building habitats in a ringlike configuration. This specific configuration creates a feeling of being protected from a potential harmful environment, so it probably subserves the psychological wellbeing of the crew. By closing the ring construction of our station on the Moon, we also close the metaphorical ring between human history and future. (p. 12)
UE	PRIVACY Stress countermeasures  (Crew quarters, G. Grippenko0ven)	As major psychological stressors in a space station, we consider the restricted range of environmental cues, the specific high workload of astronauts, the lack of privacy due to enforced social contact with other crew members, and the separation from the usual social network. We try to solve these problems by setting up private rooms for each crew member, which include specific customizable elements, the possibility to listen to music or watch movies, and the opportunity to communicate with family, friends or a psychiatrist in a private way (pp. 14-15).

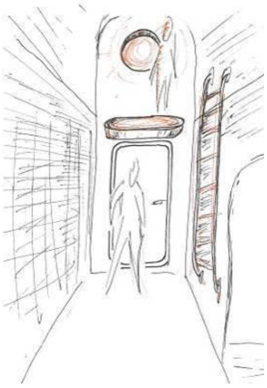
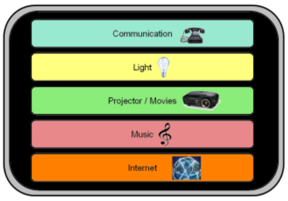
UE	HABITABLE VOLUME Flexible zoning 	Taking into account that the human missions to the Loretta base will last for at least 180 days, it is of specific importance to provide enough living space for each astronaut. Crew quarters have a size of approximately 11 m² (27m³), (p. 12). To provide even more space, a special folding system of the quarter's walls has been implemented. By folding the walls, it is possible to open up all personal rooms of the four-person group quarter module to get a maximum size of almost 66m² just in one module. This enables a great amount of movement for all astronauts, as well as a larger distances and angles of sight. If the walls are closed, each crewmember has his own privacy -visual and acoustic isolation-, which is very important on a long term space mission. Besides the private quarters, in our two living modules we implemented public space into habitat 2, where the crew will eat, have conferences, play (the table is a "virtual touchscreen playing table") and train (p. 12).
UE	INTERIORS Flexible interior design  (*multi-purpose furniture, Meander&Ottoman*)	Each room contains several customizable elements. One part of that is a furniture system, based on the Meander&Ottoman multi-purpose furniture. It involves each individual as an active creator of his environment, by providing the possibility of arranging the modules in almost countless combinations. Through this dynamic, the multi-purpose furniture is a part of the environment, which is meant to effectively counteract boredom and depression due to monotony. By that it also meets the NASA Man-Systems Integration Standards (p. 16). With ambient light we try to let the individual rooms appear in a color that suits individual preferences. The light is also adjustable in terms of brightness. The brightness in the working modules of our station can change to compensate for the lack of a natural night and day cycle. To maintain the human circadian rhythm, the light on our station can be adjusted up to a brightness that impacts the pineal gland of the human brain in a way that allows it to produce the same amount of melatonin that it would produce under sunlight conditions (p. 18).
UE	CREW QUARTERS Flexible interior design  *(Bed-Table-Module, J. Grippenkoven)*	Another important piece of furniture in the personal rooms is the new "Bed-Table-Module". As the name says, this is one more multi-purpose design, which can be used as a bed as well as a table (p. 16). A second customizable feature in the individual quarters consists of the use of virtual picture frames. Each astronaut can save a huge number of pictures of family members, nature or other content which reminds him of earth. It is even possible to receive new pictures from earth because Internet is provided on our Moon Base. In addition to the multi-purpose furniture, the virtual picture frames provide a nice additional possibility to create a constantly changing environment on the moon (p. 16).
UE HME	LIGHT Personalization and circadian cycle. 	The lighting used in the quarters of the Loretta moon station is based on an indirect ambient lighting system, which can make the room appear in different colors and brightness following individual preferences. The appearance of our lighting is comparable to the Sivra lamp of I. Guzzini. (p. 18) The light is also adjustable in terms of brightness. The brightness in the working modules of our station can change to compensate for the lack of a natural night and day cycle. To maintain the human circadian rhythm, the light on our station can be adjusted up to a brightness that impacts the pineal gland of the human brain in such a way that it is able to produce the same amount of melatonin that it would produce under sunlight conditions (p. 18).

	 *(Sivra, I Guzzini)*	
	WINDOW  *(Panorama window, J. Grippenkoven)*	From the human factors perspective, one of the most important features of our station is the implementation of windows in our station. The reason our station includes windows in all modules is to serve the psychological well-being of the crew, to initially counteract the feeling of being "locked up" in the station, which can lead to severe depressive feelings (Kanas & Manzey, 2008). It is important to have the possibility to take a look outside at the moon, to observe the other crew members during EVAs (this is also important for safety reasons), or to have a look at earth. Thus, we did not only include one window in each single member's room, but we also constructed a bigger "panorama window" in both of the living modules. Several problems connected to the construction of windows had to be solved in the early planning stages. In the construction of our base, the covering with regolith is crucial as a protection against radiation. To guarantee that the regolith does not cover the windows, we had to build all the windows in a tunnel fashion. This raises the next problem that the angle of sight is reduced significantly. To deal with this, we will build a quadratic mirror construction on the inside of the "window tube" to widen the angle. Still, a window does not protect the base from radiation as well as regolith shielding does, so we had to use special double glassed nano-structures (as described in the Section "Structure"). Additionally, we constructed a special window shutter on the outside of the station, which can be closed to minimize the impact of radiation and also serves as a light shielding to support recreative sleep (p. 18).
	CONTROL PANEL 	To control all the interior electricity of the private group quarters, we designed a special control panel (Fig.9). With this touchscreen panel it is possible to control all communication systems, the lighting, the projector inside the room, music and the Internet. The projector is able to project a normal computer desktop on the wall as well as live streams for dialogs with family, friends, or a psychiatrist. For the audio signals we use a wireless headset with an attached microphone, so none of the other crew members will be disturbed by communications or understand the content of private conversations. The headset is also used if the astronauts want to listen to music or watch movies inside their quarters. The adjustment of appropriate temperature in line with individual preferences is subserved by another (manual) control. Individual temperature adjustment is important, for example, in order to guarantee comfortable sleep (Manzey, 2008). We have chosen an extra manual control because if the touchscreen fails, the temperature, which must be adjustable, can still be controlled (p. 20).
	WORKING SCHEDULE	To deal with the high workload, we set up a clear schedule per day, to guarantee enough sleep and time for leisure activities for each crew member. The schedule looks like this: 8.30 h bed-time (8.00 h total sleep) 8.00 h work 2.00 h workout / training 0.30 h talk with psychiatrist 3.30 h free time for social and private activities (including hygiene) 1.30 h eating If a crew member is involved in EVAs, the workout time can be reduced. If a crew member has to work overtime, it is important that he can make up for this on the next day. Working overtime should not result in sleep deprivation. If a crew member sleeps less than eight hours, extra sleeping time has to be included. A tradeoff between the member's free time for social /

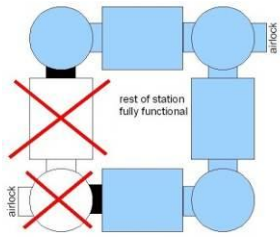
		private activities and eating time is acceptable if necessary. Missing the half hour of everyday private audiovisual conferencing with the mission psychiatrist is not acceptable (pp. 22-23).
	CREW COMPOSITION	In case of medical incidents, at least one of the astronauts should have some knowledge of medicine. In the composition of the crew, the personalities of the members and the hierarchy structure between the members are facts that are considered as well. A total number of six people is important to run the station effectively, to be able to meet the requirements of explorations (part of the group explores while another part stays in the base), to have some diversity in social relationships, to be able to conduct research in an appropriate way, and to be able to do secondary tasks, such as cleaning (etc.). Furthermore, a crew size of six members will enable all crewmembers to work according to their work-rest cycles. Six members would enable very efficient shift work. (p. 22)
HMS	AESTHETICS	To make the Loretta base a bit greener, an algae containing photo-bio reactor will be installed in the public space near the kitchen (fig. 11). Additionally, a salad machine will be used to enable the crew to grow and eat their own salad. We hypothesize that a lunar base will become more comfortable if plants are included. To shield against the light of the photo-bio reactor, we put a closable curtains in front of it, that it can be shaded if the crew does not want to look at it (p.23)
	Physical needs  	To prevent the loss of skeletal musculature that is typical in space environments, the base contains training opportunities in addition to some room to move around in. This includes two treadmills and a ring-shaped sports structure in the middle the four-quarters module. This “ring” was inspired by a comparable structure from Spacelab (p. 23). *(ring-shaped training structure on Spacelab)*
	HF HAZARD	Relating to the older Soyuz and Space Shuttle missions, the risk of crew conflicts can be assumed to be high enough to end up in a catastrophic case with the loss of crew members. Due to that fact it is necessary that one of the crew members is well trained in active conflict solving. Additionally, the LORETTA base provides for each crew member a room to rest. This also relaxes the relations, because the astronauts don’t have to see each other when they don’t want to. For aggressive single men, futile fixture straps are stored in the module. For serious injuries, the basic module contains complete operation instrumentation. For serious illnesses, a module can be locked to create a quarantine section. Because a malfunction of the toilet would lead to critical hygienic conditions, it has to be redundant. Additionally, the base contains hygiene bags for 14 days. (Messerschmid, 2009, p. 66)
	SAFETY  (Loretta Safety, Team Blue)	It has to be ensured that in case a module or node gets completely depressurized and excluded from the rest of the base, the crew always has access to any of the air locks. In fact, the ring configuration with two air locks in diagonal opposite positions fulfills this requirement. It is also guaranteed that every other module can be reached in case of exclusion.

	FUTURE DEVELOP-MENT & PR	There are several possibilities of how the LORETTA project may be implemented in commercial activities. The most promising options are listed below: Education: It is important to educate the public about going to the Moon and on to Mars. This will ensure public support in the future. Team up with schools and universities to provide information about life outside Earth Research: Provide research opportunities/ suggestions for experiments Public: Allow the public to submit possible contributions. Provide access for the public to view mission control. Live video feeds from the moon. Emphasize the global cooperation between nations in order to boost enthusiasm and public moral. Ex. A "One World" campaign of advertisements which emphasizes international collaboration, and moving beyond our planet. Commercial: Tourism as a long-term goal. Eventually, we hope to sell commercial flights to the moon. Lunar funeral: Send a family member's ashes to the Moon and have a video ceremony. Sponsorships: Sell naming rights for the different modules to companies, e.g., The McDonald's Research Module. Visual advertisements on the outside of all available surfaces. Data Storage: Back up essential and cultural information in a database on the Moon to protect it from war or natural disaster.
IDP	TEAM BLUE HF REPORT (SSDW, 2009b) HF Specialist: Jan Grippenkoven; HF Tutor: Irene Schlacht	
HME	HOLISTIC METHODOLOGY Human-System elements	In general, you can describe Human Factors as a discipline concerning all physical, psychological, and social characteristics of the human which influence or are influenced by socio-technical systems. Human Factors is a science which deals with the role of the human in complex systems, the design of technical equipment and facilities as well as with the adaptation of the working environment with the aim to increase comfort and safety (Kanas & Manzey, 2008). In an extreme and complex environment like a lunar base, the field of human factors is of particular importance. The following section contains a detailed overview of the most important influences of living and working in a lunar station on the human being, as well as considerations of how you can design the environment in such a way that it fits to specific human needs (p. 12).
MD	ENVIRONMENT ISRU, Architecture history, Anthropology, Psychology, Poetry.	The Loretta moon base follows the most basic construction principles of human civilization history: -ISRU and -anthropological history of building habitats in a ringlike configuration. This specific configuration creates a feeling of being secured against a potential harmful environment, so it probably subserves the psychological wellbeing of the crew. By closing ring construction of our station on the moon we also close the metaphorical ring between human history and future. (p.12)
UE	PRIVACY Stress countermeasure 	As major psychological stressors in a space station, we consider the restricted range of environmental cues, the specific high workload of astronauts, the lack of privacy, due to enforced social contacts with other crew members and the separation of the usual social network. We try to solve these problems by setting up private rooms for each crew member, which include specific customizable elements, the possibility to listen to music or watch movies and the opportunity to communicate with the family, friends or a psychiatrist in a private way (pp.14-15).

	(Crew quarter, G. Grip-penko0ven)	
UE	HABITABLE VOLUME Flexible zoning 	Taking into account, that the human missions to the Loretta base will endure at least 180 days, it is of specific importance to provide enough space of living for each astronaut. Crew quarters have a size of approximately 11 m² (27m³), (p.12). To provide even more space, a special folding system of the quarter's walls has been implemented. By folding the walls, it is possible to open up all personal rooms of the four-member-group quarter module to reach to a maximum size of almost 66m² just in one module. This enables a great amount of movement for all astronauts, as well as a larger distance and angle of sight. If the walls are closed each crewmember has his own privacy -visual and acoustic isolation-, which is very important on a long term space mission. Besides the private quarters in our two living modules we implemented public space into habitat 2, where the crew will eat, have conferences, play (the table is a "virtual touchscreen-playing-table") and train (p.12)
UE	INTERIORS Flexible interior design  (*multi-purpose furniture, Meander&Ottoman*)	Each room contains several customizable elements. One part of that is a furniture system, based on the Meander&Ottoman multi-purpose furniture. It involves each individual as an active creator of his environment, by providing the possibility of arranging the modules in almost countless combinations. By this dynamic, the multi-purpose furniture is a part of an environment, which is meant to countervail boredom and depression due to monotony in an effective way. By that it also meets the NASA Man-Systems Integration Standards (p. 16). With ambient light we try to let the individual rooms appear in a color, due to individual preferences. The light is as well adjustable in terms of brightness. The brightness in the working modules of our station can change to compensate for the lack of a natural night and day cycle. To keep the human circadian rhythm upright, the light on our station can be adjusted up to brightness that impacts the pineal gland of the human brain in a way that it is able to produce the same amount of melatonin it would produce under sunlight conditions (p.18)
UE	CREW QUARTERS Flexible interior design  *(Bed-Table-Module, J. Grippenkoven)*	Another important piece of furniture in the personal rooms is the new "Bed-Table-Module". As the name says, this is one more multi-purpose design, which can be used as a bed as well as a table (p.16). A second customizable feature in the individual quarters consists in the use of virtual picture frames. Each astronaut can save a huge number of pictures of family members, nature or other content which reminds him of earth. It is even possible to receive new pictures from earth because internet is provided on our moon base. In addition to the multi-purpose furniture, the virtual picture frames provide a nice additional possibility to create a constantly changing environment on the moon (p.16).
UE HME	LIGHT Personalization and circadian cycle. 	The lightning used in the quarters of the Loretta moon station is based on an indirect ambient lightning system which can make the room appear in different colors and brightness follow individual preferences. The appearance of our lightning is comparable to the Sivra lamp of I. Guzzini. (p.18) The light is as well adjustable in terms of brightness. The brightness in the working modules of our station can change to compensate for the lack of a natural night and day cycle. To keep the human circadian rhythm upright, the light on our station can be adjusted up to brightness that impacts the

	 *(Sivra, I Guzzini)*	pineal gland of the human brain in a way that it is able to produce the same amount of melatonin it would produce under sunlight conditions (p.18).
	WINDOW  *(Panorama window, J. Grippenkoven)*	From the human factors perspective, one of the most important features of our station is the implementation of windows in our station. The reason our station includes windows in all modules is to serve the psychological well-being of the crew, to initially counteract the feeling of being "locked up" in the station, what can lead to severe depressive feelings (Kanas & Manzey, 2008). It is important to have the possibility to have a look out on the moon, to observe the other crew members during EVA's (this is also important for safety reasons) or to have a look back home to earth. Thus, we did not only include one window in each single member's room, but we also constructed a bigger "panorama window" in both of the living-modules. Several problems connected to the construction of windows had to be solved in the early planning stages. In the construction of our base, the covering with regolith is crucial as a protection against radiation. To guarantee that the regolith does not cover the windows, we had to build all the windows in a tunnel fashion. This raises the next problem, that the angle of sight is reduced significantly. To deal with that, we will build a quadratic mirror construction on the inside of the "window tube", to broaden the angle. Still, a window does not protect the base from radiation as well as regolith shielding, so we had to use special double glassed nano-structures (as described in the Section "Structure"). Additionally, we constructed a special window shutter on the outside of the station, which can be closed to minimize the impact of radiation as well as to serve as a light-shielding to support a recreative sleep (p. 18).
	CONTROL PANEL  	To control all the interior electricity of the private group quarters, we designed a special control panel (Fig.9). With this touchscreen panel it is possible to control all communication systems, lightning, the projector on the inside of the room, music and internet. The projector is able to project a usual computer desktop on the wall as well as live streams for dialogues with family, friend or a psychiatrist. For the audio signals we use a wireless headset with an attached microphone, so no one of the other crew members can be disturbed by communications or understand the content of private dialogues. The headset is also used if the astronauts want to listen to music or watch movies inside their quarters. The adjustment of an appropriate temperature due to individual preferences is subserved by another (manual) control. Individual temperature adjustment is for example important to guarantee for a comfortable sleep (Manzey, 2008). We have chosen an extra manual control because if the touchscreen fails, the temperature which is very important to be adjustable, can still be controlled (p.20).
	WORKING SCHEDULE	To deal with the high workload we set up a clear schedule per day, to guarantee enough sleep and time for leisure activities for each crew member. The schedule contains: 8.30 h bed-time (8.00 h total sleep) 8.00 h work 2.00 h workout / training 0.30 h talk with psychiatrist 3.30 h free time for social and private activities (including hygiene) 1.30 h eating

		If a crew member is involved in EVA's, the time of workout can be reduced. If a crew member has to overwork, it is important that he can catch up for this on the next day. Overworking should not result in sleep deprivation. If a crew member sleeps less than eight hours, extra sleeping time has to be included. A tradeoff between the member's free time for social / private activities and eating time is acceptable if necessary. Missing the half hour of everyday private audiovisual conferencing with the mission psychiatrist is not acceptable (pp.22-23)
	CREW COMPOSITION	In case of medical incidents at least one of the astronauts should have some knowledge of medicine. In the composition of the crew, the personalities of the members and the hierarchy structure between the members are facts that are considered as well. A total number of six people is important to run the station effectively, to be able to meet the requirement of explorations (part of the group explores while another part stays in the base), to have some diversity in social relationships, to be able to conduct research in an appropriate way, and to be able to do secondary tasks, such as cleaning (etc.). Furthermore, a crew size of six members will enable all crewmembers to work accordingly to their work-rest cycles. Six members would enable very efficient shift work. (p.22)
HMS	AESTHETICS	To make the Loretta base a bit greener, an algae containing photo-bio reactor will be installed in the public space near the kitchen (fig. 11). Additionally a salad machine will be used to enable the crew to grow and eat their own salad. We hypothesize that a lunar base will become more comfort
	Physical needs   *(ring shaped training structure on Spacelab)*	To prevent the space environment-typical loss of skeletal musculature, besides some room to move the base contains training opportunities. Parts of this are two treadmills and a ring shaped sport structure in middle the four quarter module. This "ring" is inspired from a comparable structure of Spacelab (p.23)
	HF HAZARD	Relating to the older Soyuz and Space Shuttle missions the risk of crew conflicts can be assumed to be high enough to end up in a catastrophically case with loss of crew members. Due to that fact it is necessary that one of the crew members is well trained on active conflict solving. Additional the LORETTA base provides for each crew member a room to rest. That also relaxes the relations, because they don't have to see each other when they don't want. For aggressive single man futile fixture straps are stored in the module. For hazardous injury the basic module contains complete operation instrumentation. For serious illness a module can be locked to create quarantine. Because a malfunction of toilet would lead to critical hygiene, it has to be redundant. Additional the base contains hygiene bags for 14 days. (Messerschmid, 2009, p.66)
	SAFETY	It have to be ensured that in case a module or node gets completely depressurized and excluded from the rest of the base the crew has always access to any of the air locks. If fact the ring configuration with two air locks on the diagonal opposite position provides this requirement. It is also guaranteed to reach every other module in case of exclusion.

	 (Loretta Safety, Team Blue)	
	FUTURE DEVELOPMENT & PR	There are several possibilities how the LORETTA project may be implemented in commercial activities. The most promising options are listed below: Education: It is important to educate the public about going to the Moon and onto Mars. This will ensure public support in the future. Team up with schools and universities to provide information about life outside Earth Research: Provide research opportunities/ suggestions for experiments Public: Allow public to submit possible contributions. Provide access for public to view mission control. Live video feeds from the moon. Emphasize the global cooperation between nations in order to boost enthusiasm and public moral. Ex. A „One World" campaign of advertisements which emphasizes international collaboration, and moving beyond our planet Commercial: Tourism as a long term goal. Eventually, we hope to sell commercial flights to the moon. Lunar Funeral: Send a family member's ashes to the Moon and have a video ceremony. Sponsorships: Sell naming rights of the different modules to companies, e.g. The McDonald's Research Module. Visual advertisements on the outside of all available surfaces Data Storage: Back up essential and cultural information in a data base on the moon to protect from war or natural disaster

Appendix I refers to 5.2.2 MDRS Research Results

In order to provide sensory stimulation for the astronaut experience, stimuli need to be effective culturally, creatively, and emotionally, involving the astronauts actively. One of the main references is natural stimulation. The following sections review the aspects that formed the basis for the selection of colors, plants, fragrances, and natural sound stimuli investigated in the experiment.

Sensory stimuli such as colors, plants, sounds, and fragrance samples were selected for their properties. Color gradations evoke visual pleasure and satisfaction. Plants provide tactile interaction and establish a connection with natural materials and other forms of life, stimulating feelings of pleasure. Natural sounds relax and stimulate the imagination, and fragrances evoke past experiences and memories. Gustative stimulation was not performed in order to avoid the problem of interaction with the "Food Study" research by Kim Binsted (University of Hawaii) and Jean Hunter (Cornell University), which is based on the food assumption. An additional neutral stimulus with a totally neutral and mechanical task acted as a reference for comparing the results of the creative and sensory stimulations. The validation task selected was to copy and mirror a list of surnames (e.g., surname_1= 1_*emanruS*). The sensory experience experiment initiated by Irene Lia Schlacht was realized with the contribution of Ayako Ono (sounds, colors), Scott Bates (plants), Regina Peldszus and Franca Stricker (fragrances) (Schlacht et al., 2010c).

Tasks focusing on creative performance and mood analysis were completed after the administration of the stimulus in order to verify whether it had increased creative performance.

Table 0.25: Sensory experience experiments

ORGANS	STIMULI	EFFECTS
Visual	Color graduations	Pleasure and satisfaction
Tactile	Plants	Pleasure, connection with nature/ other forms of life
Auditive	Natural sound	Relax and stimulate the imagination
Olfactive	Evoke past experiences and memories	Evoke past experiences and memories
Gustative	Part of Food Study	Research not performed to avoid study influences
Validation Test	Mechanical test	

Experiment Methodology

The experiment procedures were the following:

1. Mood analysis (before the stimulus)

2. Sensory experience (10 min. of stimulus interaction)

3. Mood analysis (after the stimulus)

4. Creative performance task (10 min.)

The goal of the test was to stimulate sensory activity, well-being, and creativity. The subjects were able to perform the test autonomously following instructions.

The mood analysis was performed using two methodologies: the first one was quantitative with a subjective rating scale on feelings, and the second one was qualitative with open questions and behavioral observation. The quantitative investigation aimed to confirm mood effects, and the qualitative one aimed to discover new effects (Howitt, 2010, p. 10). The open questions were:

- What is your personal opinion on the stimulus that you had?
- What is the cause of your feeling at this moment?
(i.e. I'm happy because of the sun, I'm frustrated because my PC is slow.)

The behavioral observation focused on the individual preference order in which the test was performed; in other words, for each test, the subject decided with which stimuli to interact, and the chosen order was used as preference data. The mood scale of Bond & Lader (1974) was used to assess the effects on subjective mood. This scale has been used before to monitor the mood and well-being of an astronaut on a short-duration space mission (Manzey et al., 2000). A scale from 1 to 7 was applied to rate the pairs of opposing attributes.

Following the factor analysis by Bond & Lader, the results are grouped on the basis of three main factors:

- Factor 1 shows arousal on a scale from 1 to 7, where the value 1 implies the adjectives alert, attentive, energetic, clear-headed, well-coordinated, quick-witted, strong, interested, and proficient, and 7 implies the opposite.
- Factor 2 shows friendliness on a scale from 1 to 7, where the value 1 implies the adjectives happy, amicable, tranquil, content and gregarious and 7 implies the opposite.
- Factor 3 shows relaxing on a scale from 1 to 7, where the value 1 implies the adjectives calm, relaxed, and 7 implies the opposite.

Table 0.26 & 0.27: Questionnaire to rate subjective feelings from the Mars Habitability Project (left). Bond and Lader (1974), Factors for rating subjective feelings from the Mars Habitability Project (right). (Schlacht et al., 2010c)

How do you feel now?		
Alert	○ ○ ○ ○ ○ ○ ○	Drowsy
Calm	○ ○ ○ ○ ○ ○ ○	Excited
Strong	○ ○ ○ ○ ○ ○ ○	Feeble
Muzzy (confused)	○ ○ ○ ○ ○ ○ ○	Clear-headed
Well-coordinated	○ ○ ○ ○ ○ ○ ○	Clumsy
Lethargic	○ ○ ○ ○ ○ ○ ○	Energetic
Content	○ ○ ○ ○ ○ ○ ○	Discontent
Troubled	○ ○ ○ ○ ○ ○ ○	Tranquil
Mentally Slow	○ ○ ○ ○ ○ ○ ○	Quick-witted
Tense	○ ○ ○ ○ ○ ○ ○	Relaxed
Attentive	○ ○ ○ ○ ○ ○ ○	Dreamy
Incompetent	○ ○ ○ ○ ○ ○ ○	Proficient
Happy	○ ○ ○ ○ ○ ○ ○	Sad
Antagonistic	○ ○ ○ ○ ○ ○ ○	Amicable
Interested	○ ○ ○ ○ ○ ○ ○	Bored
Withdrawn	○ ○ ○ ○ ○ ○ ○	Gregarious

Factors analysis variable to rate subjective feeling		
MOOD	**FACTORS**	**VARIABLE**
1 Alert 2 Calm 3 Strong *4 Clear-headed* 5 Well-coordinated *6 Energetic* 7 Content *8 Tranquil* *9 Quick-witted* *10 Relaxed* 11 Attentive *12 Proficient* 13 Happy *14 Amicable* 15 Interested *16 Gregarious*	**Factor 1 (Arousal)**	1 Alert 3 Strong 4 *Clear-headed* 5 Well-coordinated 6 *Energetic* 9 *Quick-witted* 11 Attentive 12 *Proficient* 15 Interested
	Factor 2 (Friendliness)	7 Content 8 *Tranquil* 13 Happy 14 *Amicable* 16 Interested
	Factor 3 (Relaxing)	2 Calm 10 *Relaxed*

Experiment Result

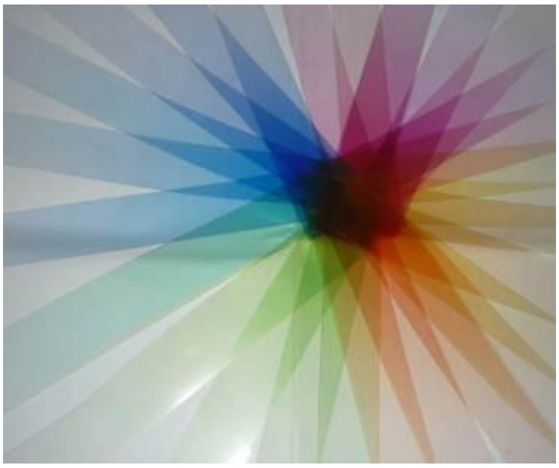


Figure 0.12: Color strips composition by one crew member for the Mars Habitability Project at MDRS. (Schlacht et al., 2010c)

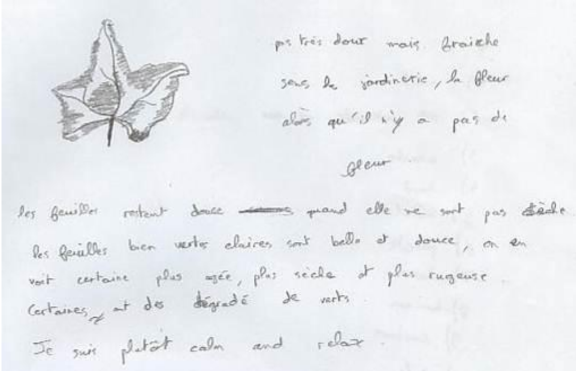


Figure 0.13: Plant interaction result from one subject of the Mars Habitability Project at MDRS.

Figure 0.14: IFF Fragrances for the Mars Habitability Project. (Peldszus, 2010, IFF London)

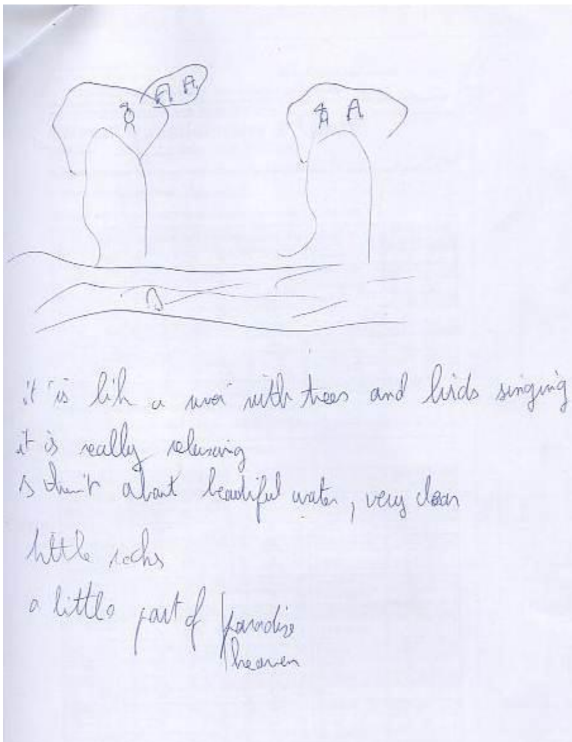


Figure 0.15: Sound interaction result from one subject of the Mars Habitability Project; in particular, this subject overcame the barrier of drawing to express his emotions and sensations.

Astronauts are required to approach problems creatively and adaptively in space exploration. However, in long duration missions in isolation and confinement, psychological stressors can negatively affect the performance of cognitive and creative tasks.

The Extreme-Design group hypothesized that a space habitat system with varied sensory and creative stimulation would result in sustained performance, well-being, and reliability. This increases overall habitability and further facilitates and maintains the mental activity necessary for the performance of research and exploration duties.

In the *Mars Habitability Project*, four types of sensory stimuli were investigated during the 2010 EuroMoonMars mission campaign simulation at MDRS. Quantitative and qualitative data were collected and the analysis showed different results.

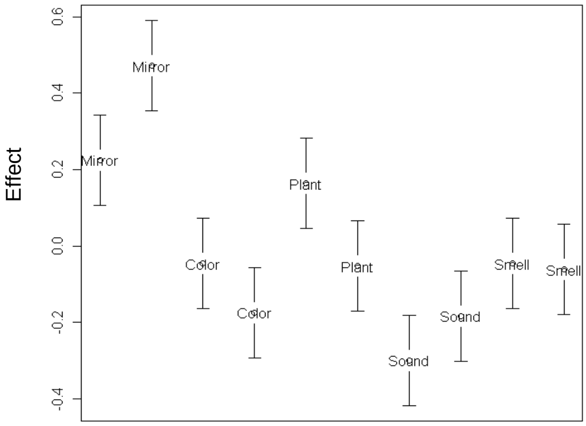
The quantitative analysis is based on the comparison between the questionnaire on the subjective rate feeling filled in before the sensory experience and the same questionnaire filled in after the sensory experience.

The resulting values do not express any relevant effect on the overall subjective mood. In fact, the Wilcox test for non-parametrical samples gives resulting values higher than 0.05. This means that the stimuli did not change the overall mood, but stimulated experiences related to them.

A neutral test of a mechanical task was performed as a reference for the sensory experiences. The neutral test was called *mirror*, mirroring a list of surnames, affecting the overall mood, decreasing happiness (Factor 2) and calm feeling (Factor 3), and decreasing alertness (Factor 1).

Factor 1 Arousal:

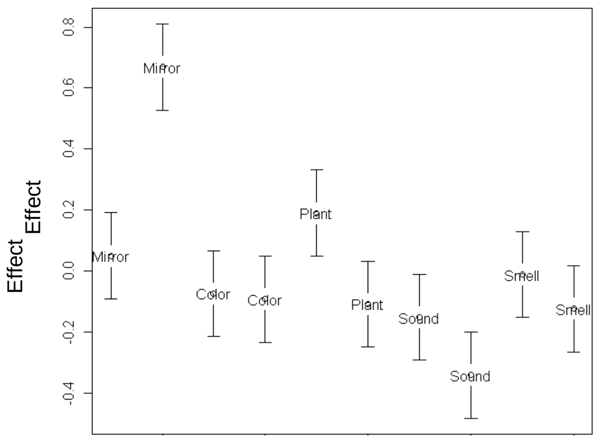
Alert



Drowsy

Factor 2 Friendliness:

Happy



Sad

Factor 3 Relaxing:

Calm

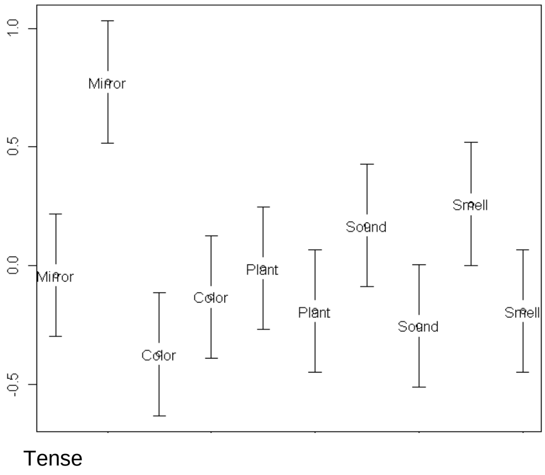


Figure 0.16, 0.17 & 0.18: Factors' error bars after and before the stimulus, referring to the quantitative analysis for the Mars Habitability Project at MDRS. The bars refer to standard errors of posterior distributions of a multivariate multilevel model in which the time- and type-specific effects were modeled as random intercepts. The diagrams are the results of the preliminary study; a verification study will be performed in the future.

Factor 1, associated mainly with *alertness*, has a value with the plant and color stimuli. Plants and colors have a tendency to increase the feeling of being awake, even when they do not change the overall subject state.

Factor 2, related mainly to a positive and *happy* feeling, has a low value with the plant and sound stimuli, showing that these stimuli tend to increase a positive feeling. Particularly the mechanical neutral stimulus *mirror* shows a decrease in happiness.

Factor 3, related mostly to a *calm* feeling, has a low value with sounds and fragrances, showing that these stimuli tend to increase a calm feeling. Particularly the mechanical neutral stimulus *mirror* shows an increase in tenseness.

However, the quantitative analysis shows no statistical relevance.

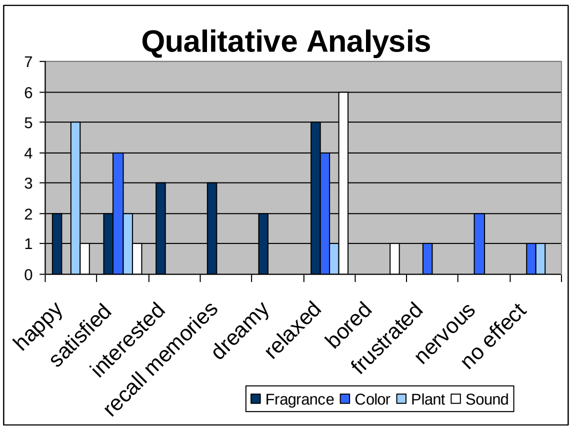


Figure 0.19: *Qualitative analysis of Mars Habitability experiment at the MDRS.*

The qualitative data show how the stimuli effect itself was perceived. The most evident effect is related to natural sound interaction for its relaxation effect; also evident is the memory and relaxation effect from the fragrances interaction, the positive effect from plants, and the feeling of satisfaction from colors. In comparison to the quantitative analysis, the qualitative analysis shows statistical relevance. Also, these results are not in contradiction with those of the quantitative analysis.

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Appendix J refers to 5.2.2 MDRS Research Results, part Habitability Analysis

EuroMoonMars campaign manager: Prof. Bernard Foing.

Mars Habitability Project leader: Irene Lia Schlacht.

Mars Habitability Experiment

Coordinators: Irene Lia Schlacht: crew 91; Marie Mikolajczak: crew 92; Guerric de Crombrugghe: crew 94.

Stimuli Experts: Dr. Scott Bates, Ayako Ono, Regina Peldszus, Irene Lia Schlacht, Prof. Franca Stricker.

Supervisors: Prof. Matthias Rötting, Prof. Melchiorre Masali, Prof. Luigi Bandini Buti.

Consulting: Prof. Alessandro Angrilli, Dr. Monica Argenta, Liuccia Buzzoni, Cian Curran, Prof. Dietrich Manzey, Prof. Enrica Fubini, Prof. Shin Fukudo, Dr. Noel Gazzano, Jan Grippenkoven, Dr. Margherita Micheletti, Arch. Giorgio Musso, Prof. Alessandra Re.

- Project Motivation

Astronauts suffer from insomnia, depression, and stress because of the isolated conditions of artificial habitats. These negative effects influence crew performance such as creativity. Amongst the abilities implied by the term ‘positive crew performance’, creativity is particularly relevant to astronauts because creativity is required to solve unforeseen problems.

The hypothesis is that in order to achieve efficiency, reliability, and well-being, humans need variability of sensory stimuli such as occurs in the natural environment; for example, seasonal change. During isolation in an artificial environment, such as in a space dwelling, monotonous sensory stimuli may create mental drowsiness and decrease creative performance.

The Extreme-Design group set out to verify that by introducing sensorial and affective stimulations – like plants, colors, circadian light variation – creative performance and habitability levels may be significantly improved.

- Experiment Methodology

The Mars Habitability experiment investigated sensory experience.

Sensory stimuli, such as displays and interaction with colors, plants, sound, and fragrance samples, were prepared by specialists to be investigated during the experiment.

Five experiment sessions of 30 minutes each were performed with one of the following contents in random order for each experiment session:

- Color gradation (used to evoke visually aesthetic feelings)
- Plants (used to stimulate a connection with the natural elements and tactile interaction)
- Listening to natural sounds (used to relax and to stimulate the imagination)
- Smelling fragrances (used to evoke past experiences and memories)
- Neutral stimuli (used for comparative data)

As an appendage to the experiment, focused tasks on creative activity and mood analysis were used to measure the effect of sensory stimulation on performance.

The experiment consisted of:

1. Questionnaire on present state of the mood
2. One sensory experience task (10 min.)
3. Questionnaire on present state of the mood
4. Creative performance task (10 min.)

The goal was to stimulate sensory activity (to fight mental drowsiness), well-being, and creativity, as these elements may be extremely relevant for the success of long duration missions.

- Other Investigations

Other activities of the Mars Habitability project were:

- Observations and interviews
- Questionnaires
- Collective debriefing

Specific observations and interviews were performed with crew 91 and are reported in the following paragraph on behavioral observation. The crew journalist’s parallel activity provided strong support for this investigation. The questionnaires focusing on mood and habitability will be analyzed together with the experiment at the end of the campaign. In order to actively involve the crew in the habitability problem analysis, a collective debriefing (45 minutes) with the entire crew was conducted either at the end of the mission or, for logistical reasons, a maximum of three days before the end of the mission.

- Debriefing procedures

The debriefing included:

1. Mars Habitability Project objective and motivation (10 min.).
2. Habitability concept definition and short discussion (5 min.).
3. Crew investigation of habitability needs (25 min.).

The debriefing was performed to motivate and support the crew in the investigation of habitability needs. Habitability was defined as “usability of the environment” aimed to:

- Decrease human error.
- Increase safety.
- Decrease human effort.
- Increase performance.
- Decrease frustration.

Habitability examples consist of four key elements:

- System interface
- Environmental condition
- Working and living space
- Adaptability.

Research Results

As an example, the detailed results of the habitability analysis of crew 91 are reported here. Direct data collection provided indications that previous activities, personal relations, and mood may have affected the data outcomes. An increased occurrence of these events observed in younger members of the crew needs to be verified. However, direct data collection was a big challenge for the crew in terms of experiment-schedule flexibility.

- Result summary

- OPERATIONAL: Problems related to the maintenance system were focused on by the crew during the debriefing. In particular, the absence of appropriate interfaces increases errors in managing the habitability system (potable tank water level, diesel and propane tank level, gray water level). Toilet and greenhouse system needs automation. Storage system should be improved (difficulties in finding objects).

- ENVIRONMENTAL: Problems related to mood and usability were focused on during the observation. In particular, EVA visibility needs to be increased (helmet fog and decrease of visibility increases frustration); visual contact with the habitat increases self-confidence. The equipment has low usability in the EVA context, dedicated instrumentation is missing.

- SOCIAL: Crew cohesion and knowledge are needed before the mission. A solution proposed by the crew during the debriefing was live voice chat for half an hour each week for one month before the mission.

- PHYSICAL: During the debriefing, the crew underlined the need to eat more meat.

- Crew behavioral observation in detail

Behavioral factors are described by means of human factors observations and crew-focused interviews.

- Subjects: The crew was composed of three males and three females, aged between 20 and 30; three military and three civilian scientists, all healthy, all students in the space field and space enthusiasts.

- Organization: Thanks to the military attitude of half of the members, the crew quickly created a good but also rigid and focused organization for system maintenance and daily life schedule. The daily life schedule was: Two people each day for a 2-minute shower, two for cooking, and two for cleaning. Cooking and cleaning in teams of two helped socialization, saved time, and helped to improve the mood. For the first three days, the crew worked mainly on organization, getting to know each other, communication with mission support, adapting to the new conditions (time, routine, etc.) and making the Hab system work. Problems with low water levels in the tank drove the crew to adopt a rigid water saving attitude: No shower was permitted, no washing-up took place, and no shaving was allowed (creating a particular mood among the military members who normally shaved every day). After the water problem was solved, on the third day, the water saving attitude remained. This led to less gray-water production and, as a consequence, created problems with the health of the greenhouse plants and problems in the production of water for flushing the toilet. 'No shower equals no flush', concluded the engineers. Habitability really depends on a delicate equilibrium and being stingy with resources could also be wrong!

- Stress management: Unexpected tasks were carried out properly with short group plans and actions. However, some unexpected tasks were done only by females (inventory documentation, abstract submission, …) and other tasks were done mainly by the males (technical problems with the Hab caused by power problems, stormy weather, …).

- Deprivation: The major frustrations noted only in the first week were: lack of freedom to go outside; lack of free, instinctive, and autonomous decision making; and the impossibility to wash after physical activities and not only when scheduled. The desire for sweet food and physical activity was exhibited by all members. As a consequence, a positive mood and an increase in friendliness emerged with the consumption of "Nutella®" during social time and collective pushups performed to music background.

- Communication with family: In the habitat, no phone calls were possible and communication was by email and live web chat when time allowed. The absence of voice-to-voice communication and separation from family and friends was not a problem. However, the needs for increased intimacy and friendship between the crew members emerged as a task (see also "cohesion" paragraph below). The crew discussed the potential of military camp communities and families for a space settlement (American military camps in other countries are like closed and autonomous settlements). The idea of using family or friend groups as crew members was already tested in the MDRS; also in the EuroMoonMars-3 the crew is composed of friends.

- Privacy: Overcrowding was found not to be relevant nor was territoriality: 'Normal' sensibility was observed for private quarters. The need for increased privacy or an isolated place was felt by the females, who spent more time doing activities inside the habitat. As a possible solution, a sound-proof room was proposed for private conversations. After the first few days, the webcams were not perceived as intrusive, maybe because images were only recorded every three to five minutes. Perhaps contradictorily, the cameras were utilized in a positive way to stay in contact with family, friends, and ground support. Various public and private messages were often posted in front of the webcam (for example, a memory object from a loved person, greetings to friends, acknowledgments to ground support).

- Cohesion: The group showed cohesion particularly through helpfulness and collaboration on mutual projects, by sharing food, and by timing their breakfast, lunch, and dinner. However, during social time, non-native English speakers who shared the same language tended not to speak English, which created some tension within the crew. The tendency to do activities together was particularly noted between members who had already been in a relationship before the mission. They shared: Intra-Vehicular activity (IVA), Extra-Vehicular activity (EVA), ATV excursion (by motorbike), and social activity. This phenomenon created a problem for overall group unity. The problems emerged as a challenge that called for improvement. To improve intimacy and friendship between all the group members, the crew decided to enforce different table positions on each other for the meals on the very last day (it is never too late!). In the habitability debriefing, the need for opportunities for pre-mission crew interaction was reported as relevant to improve crew unity and a feeling of friendship.

- Post-Mission: The data from the three males were not available. The data of all three females show high and low rates of stress after traveling only during the first week after the mission.

Appendix K refers to 5.2.3 MDRS Result Validation

The EuroMoonMars-1 mission was performed by crew 91 (from 20 February to 6 March 2010) and controlled externally by campaign director Prof. Bernard Foing (ESA RSSD Chief Scientist and ILEWG Executive Director), mission director Artemis Westenberg, and mission support from ”Earth” as in the simulation logic. In order to verify the IDP in an analog mission simulation, the MDRS-IDP research was performed and compared with the MDRS-HC research based on a different methodology.

The MDRS-IDP project is composed of:

- HF investigation, focusing on habitability investigation:

  Habitability experiment

  Habitability debriefing

  Dust control

  Food study

  Ethospace study (ethological study)

- Field experiment, focusing on:

  Geology, Rover exploration

  Field procedures and communication to support these field experiments

The MDRS-HC project is composed of:

- HF investigation, focusing on human crew-related investigation:

  Crew schedule

  Habitat functions and interfaces

  Equipment and human-machine interfaces

- Field experiment, focusing on:

  Geology, astrobiology

  Technology and network to support these field experiments

Appendix L refers to 5.4.2 CEF Workshop Result

This part is related to the results of the Concurrent Engineering workshop at DLR, where the IDP was applied to the first ever human habitat project carried out at the Concurrent Engineering Facility of DLR.

- Isolation countermeasures

Dimensional Confinement

- Constrained visual field: Myopia -> Cupola in living module and arboretum
- Claustrophobia -> Open space in arboretum
- Limited movement -> Exercise facility
- Privacy problem-> Personal crew quarters and storage

Demotivation

- Decline in motivation -> Support of cultural activities for personal development
- Depression -> Contact with plants and fish (personal plants to take care of)
- Exhilaration -> Psychological support, one session per week

Isolation

- Lack of stimuli variation -> Arboretum
- Circadian cycle-> Visual contact with natural sun cycle or artificial mimicry of sun cycle
- Feeling of contact with the outside

Windows and Cupola

- Human anthropometry
- Outside view and long distance view against myopia
- Psychological well-being
- Countermeasures against claustrophobia
- Safety, e.g., fire outside
- Human relies on him-/herself
- Direct contact with the exterior without media gives feeling of safety

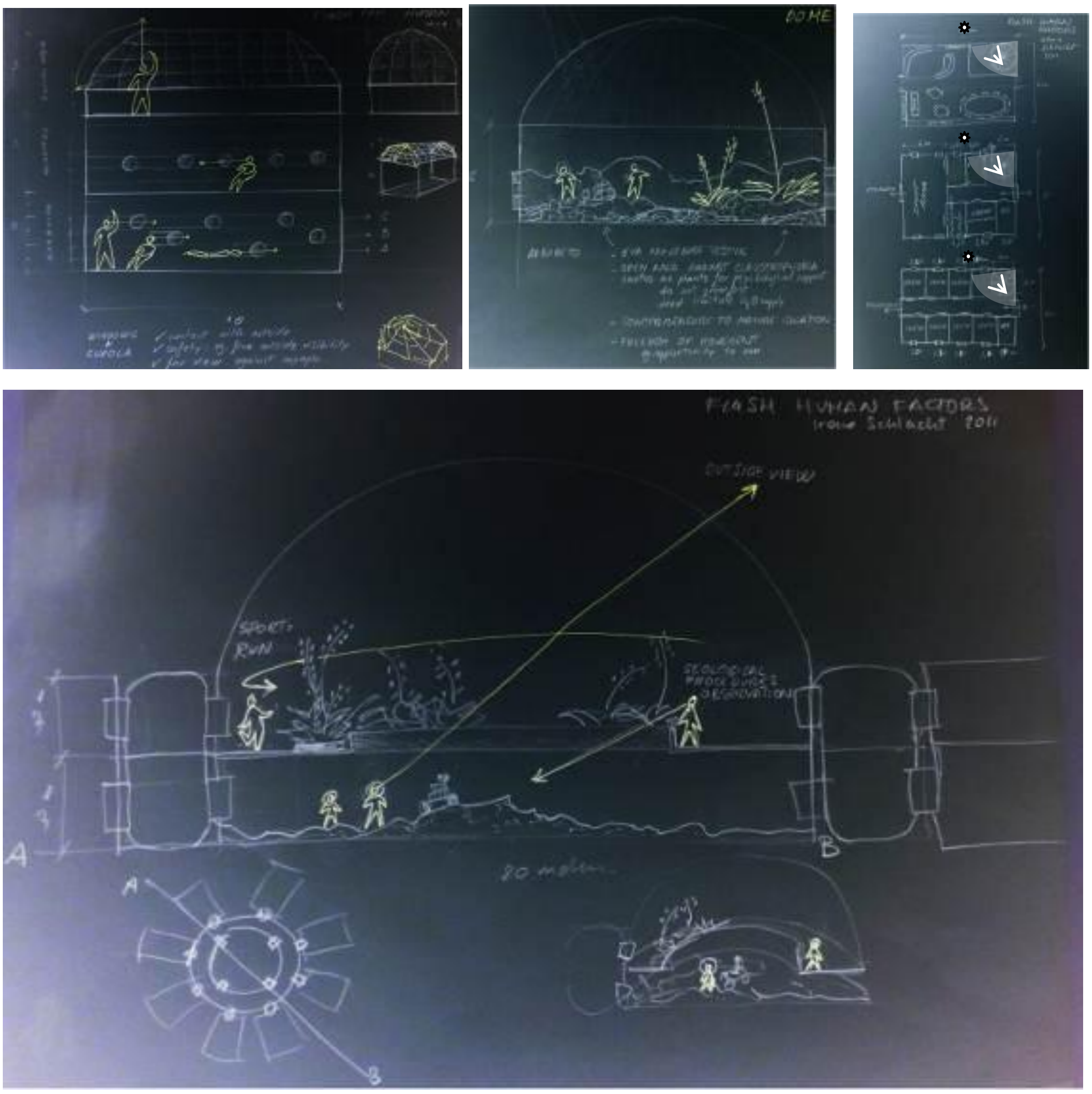


Figure 0.20, 0.21, 0.22 and 0.23: Draws for HF studies, FLaSH facility isolation countermeasures.

Psychological Factors

Table 0.28: Habitability – psychological factors FLaSH study (DLR, 2011)

Psychological and socio-cultural factors	**Minimum**	**Maximum**	**Optimal**
Visual Privacy	Toilet		flexible
Odor privacy	Toilet		flexible
Noise privacy	Toilet, crew quarters	Everywhere	flexible
Communication privacy	Sick bay	Dedicated place	flexible
Far view meters	7	20	10
Reliability of crew members	8	12	12
Personal plants in crew quarters	1	2	1 per person
Motivation	Activity and psychological support		Personal Devel-opment

Socio-cultural Factors

Socio-Cultural	Minimun	Maximun	Optimal
Ethics	person are voluntary		
Religion	privacy consideration	dedicate space	support
Cultural Activity Research	database of publications		Internet
Cultural Activity Free time	Hobbies support		Hobbies support
Cultural Activity support instruments	computer		Personal items
Meal			Ethnical meal
Personal Development			Personal items
Crew composition			Mix gender
Crew nationality			Mix
Flexible on personal request of the crew members	Recreational facilities		
	Supplementary food		
	Time schedule		
	Religious activities and facilities		
	Celebrations activities and facilities		

Environemntal Factors

Table 0.29: Habitability – environmental factors FLaSH study (DLR, 2011)

Environmental Constraint (Natural env.)	Minimun	Maximun	Optimal
Natural light			circadian rythem
Pressure Bar			1
Earthly Rain			To be considered
Earthly Wind			To be considered
Eartly Snow			To be considered
Winter Temperature			To be considered
Summer Temperature			To be considered
Humidity Temperature			To be considered

Physiological Needs

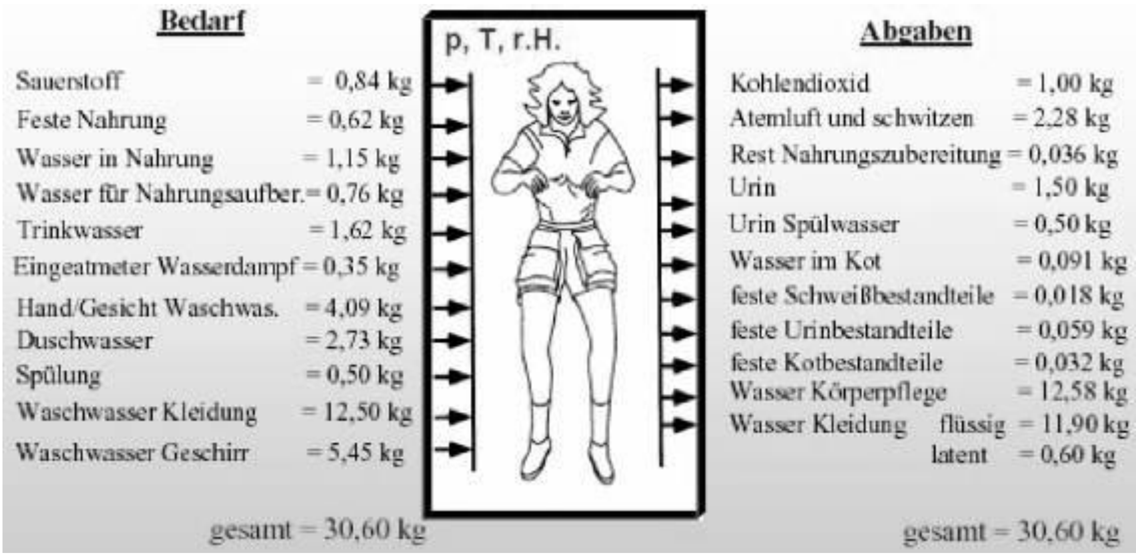


Figure 0.24: FLaSH research of input and output (DLR, 2011)

Table 0.30: Habitability – physiological factors FLaSH study (DLR, 2011)

Physiological Needs								
Input per day per person	**Min**	**Max**	**Applied**	Crew of 8		Output per day per person		Crew of 8
Oxygen kg			0.84	6.72		Carbon dioxide kg	1	8
Water kg (without food water)			2	16		Water kg (Res-Perspiration)	1.83	14.64
Personal cleaning water			6.8	54.4		Waste water	6.8	54.4
Emergency dry food (require 3.55 liters of water)			0.64	5.12		Feces (100gr; 350 gr)	0.253	2.024
Normal food			1.9	15.2		Urine	1.63	13.04
Food kcal Man 75 kg			2,971	23768				
Food kcal Women 60 kg			2,160	17280				
Flush Water x 4 times a day	2.5	10				Flush water x 4 times a day	2.5	10
Person‘s height	1.53	1.85	1.75	14				
Shoes			3	24				
Clothes			10	80				
Shoes kg			3	24				
Clothes kg			20	160				
Clothes per week number			3	24		Dirty clothes per week Kg	6	48
Washing machine week number			7	7		Gray water washing machine per day		7,13

Operational Factors

Table 0.31, 0.32, 0.33: Habitability – operational factors FLaSH study (DLR, 2011)

ENVIRONMENTAL CONTROL and STRUCTURE	Minimum	Maximum	Optimal
Natural light	Circadian rhythm		
Light Work light FLULLY ADJUSTABLE Lux			750
Light Walk Way FULLY ADJUSTABLE Lux			50
Light Crew FULLY ADJUSTABLE Lux			300
Air Velocity cm per second			10

Humidity			50%
Space square meters per day per person	17		
Temperature in Celsius (optimal=ISS)	13	29.4	23.8
Constant noise Indoor dB	45		
Odor (NASA rate from 1undetectable to 4 revolting)	2.0		
Vibration (m/s2)	0.1		
Air Velocity cm per second			

SCHEDULE CREW OF 8	Activity h	Free day	Emergency
Authonomy supports	Automatic interface	Only Check Linst	Emergency signal
MAINTENANCE H (with safety check list and reports)	Daily	1Free day pro week	Emergency
Air	01:00	00:40	03:00
Water	00:40	00:30	04:30
Animal	02:30	00:45	10:00
Sickbay	01:30	00:00	07:00
Green house 1 and 2	18:00	02:00	06:00
Workshop	00:00	00:00	03:00
ISRU	01:00	00:00	08:00
Living Unit	00:30	00:00	00:30
Food Processing	06:00	00:30	02:00
Arboreum	00:30	00:00	02:00
General Maintenance	00:20	00:00	01:00
Ground Control			01:00
Total maintenance per day per crew	32:00:00	4:25:00	48:00:00
TOTAL MAINTENANCE PER DAY PER PERSON	04:00	00:33	06:00
WORK ACTIVITY H	Daily	1Free day pro week	Emergency
Work (Research, EVA, Experiments, ISRU, PR)	04:00	00:00	00:00
TOTAL WORK PER DAY PER PERSON	08:00	00:33	06:00
OTHER ACTIVITY H	Daily	1Free day pro week	Emergency
Transaction between module	00:30	00:30	00:45
Eat	02:10	02:10	00:00
Sleep	08:00	08:00	08:00
Personal hygiene/Care	00:45	01:00	01:00
Gymnastic	00:50	00:00	00:00
Pubblic/private relation (with outside)	00:45	02:00	01:00
FREE TIME (Personal/social activities, relax, free activity)	03:00	00:00	00:00
TOTAL	24:00:00	14:13:07	16:45:00

LIVING STORAGE (eg. furniture)			

Living Unit Excel file			
STRUCTURE REQUIREMENT			
Pathway cm			90 minimum
Chair height			adjustable
Table height			adjustable
Habitable ceiling height	2.25	4.5	3.50
Structural ceiling height	2.50		
Step inclination cm			17High x 29 Bright
Space square meters per day per person	17		
Safety	**Minimum**	**Maximum**	**Optimal**
Emergency fire safety system water liters	100	10000	5000
Fire protection system	on every floor		
Emergency Exit	on every floor		1,20 bright

Environment Simulation (pssible consideration)			
Radiation			
Difference of Gravity			
Mars Dust Storm			

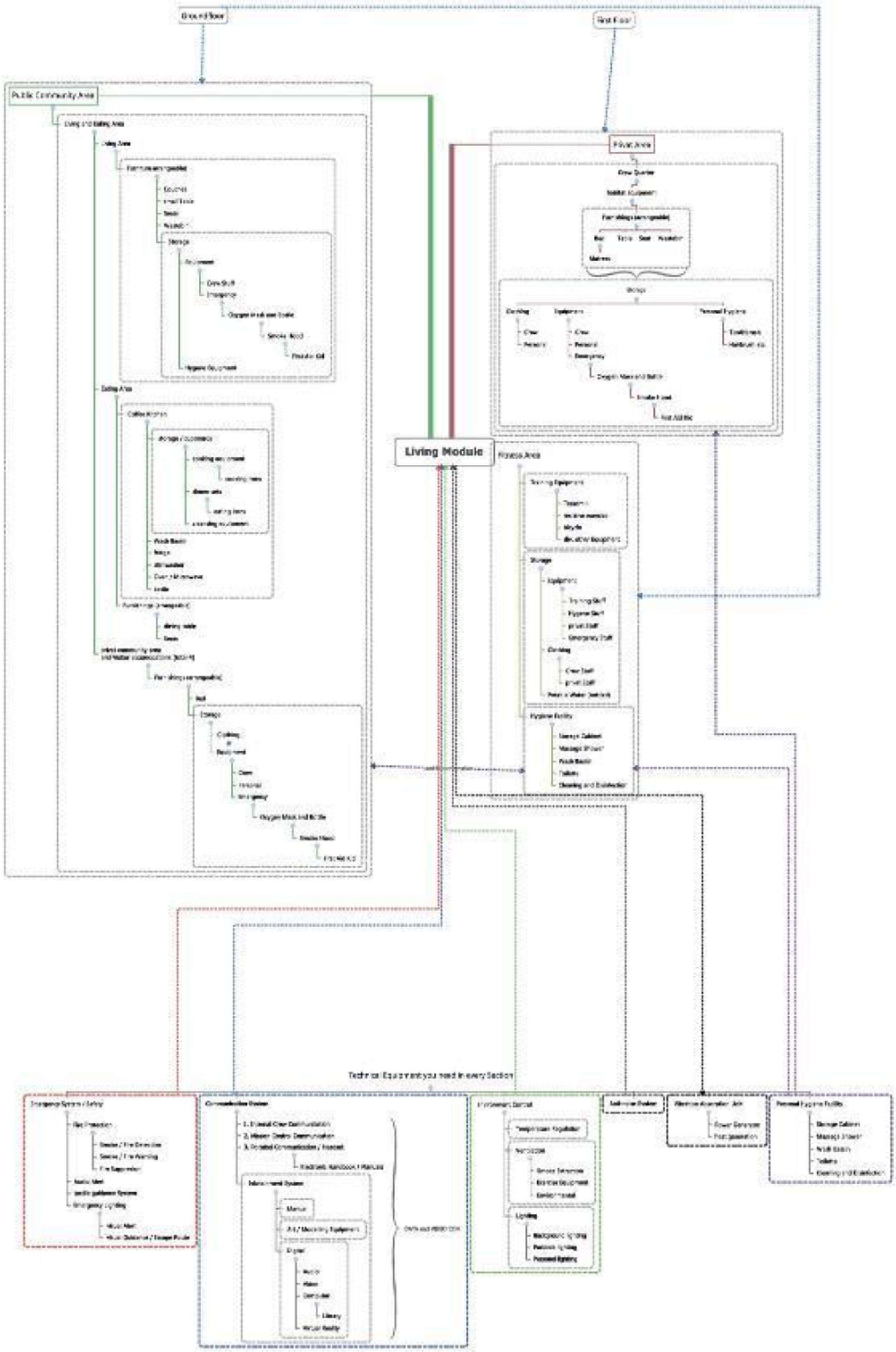


Figure 0.25: FLaSH Living Module breakdown structure by Kiell Hermann (DLR FLaSH study in 2011)

Parameter SUM	Summe	Air Module	Animal Module	Food Processing Facility	Greenhouse Module	ISRU Module	Living Module	Sickbay	Waste Module
total H2	0,00	0	0	0	0	0	0	0	0
total anorganic solid waste	-1,79	0	0	0	0	0	0	0	-1,79
total Ar	-0,24	0	0	0	0	-0,24	0	0	0
total C	0,00	0	0	0	0	0	0	0	0
total C6H12O6	0,01	41,304	-6,4545	-34,84	0	0	0	0	0
total CH4	1,81	0	0	0	0	1,81	0	0	3,45
total CO	6,37	0	0	0	0	6,37	0	0	0
total CO2	-15,23	-60,58	52,1	0,6	-16,45	-15,24	8	0	5,544
total drinking water	-77,02	-24,7824	-960,48	-50	557,71	17,15	-153,6	0	-23
total Evaporated Water	2,05	-28,099994	8,5	6,8	0	0	14,452	0	0
total fertilizer	0,00	0	0	0	-46	0	0	0	46
total food	0,55	0	2,35	-28,15	26,35	0	0	0	0
total green water	-1,00	0	720	0	-720	0	0	0	0
total grey water	-8,73	28,099994	240	43,2	123,81	0	58,72	0	51,92
total H2	-1,11	0	0	0	0	-1,12	0	0	0,0143
total liquid waste	-5,00	0	0	0	0	0	60	0	-60
total Mars atmosphere	0,51	0	0	0	0	0,51	0	0	0
total Mars soil	-15,00	0	0	0	0	-15	0	0	0
total N2	-0,26	0	0	0	0	-0,26	0	0	0
total O2	34,29	44,056	-34,4	0	11,96	36,82	-6,56	0	-2,584
total oil/brine	0,50	0	0	0	0	0	0	0	0
total organic solid waste	0,01	0	-92,919	33,5	57,63	0	1,8	0	0
total raw materisls	5,00	0	0	0	0	5	0	0	0
total regolith	-41,00	0	0	0	0	-41	0	0	0
total trace gas	0,00	0	-4,9998	0	5	0	0	0	0
total yellow water	0,00	0	0	0	0	0	12,92	0	-12,92

Table 0.34: FLaSH habitat matrix with ISRU (DLR Bremen 2011)

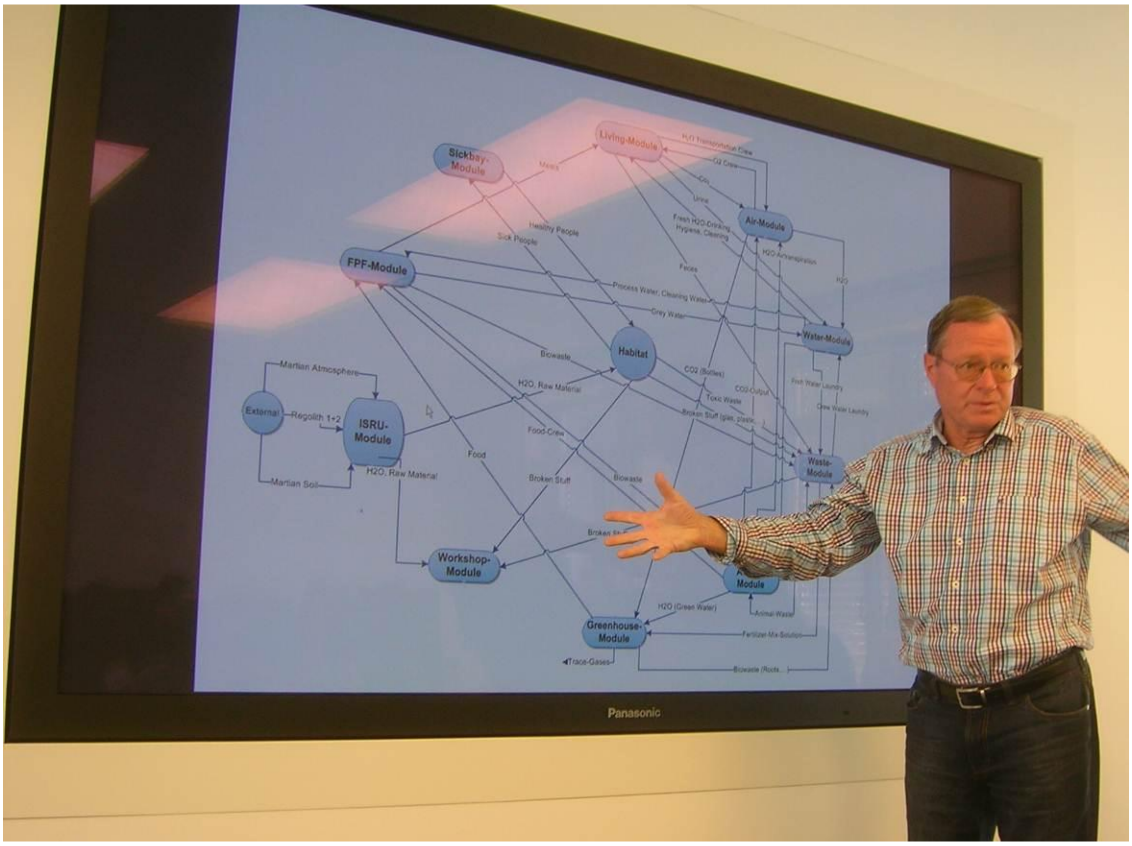
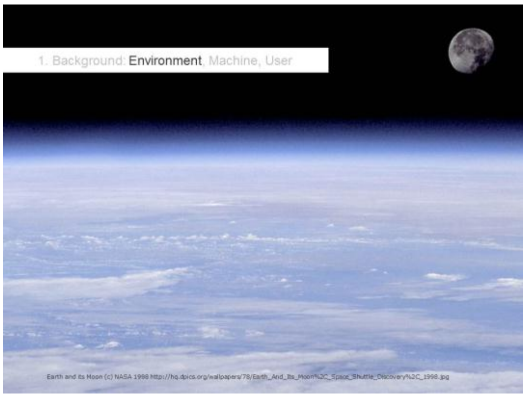
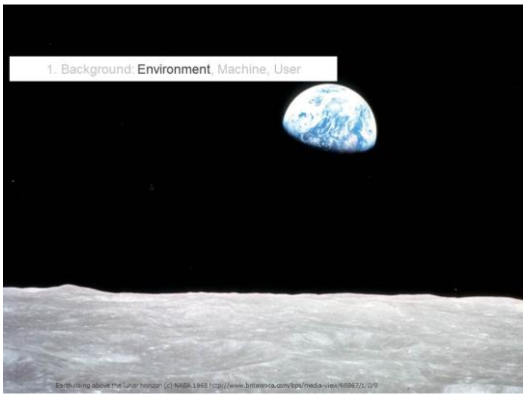
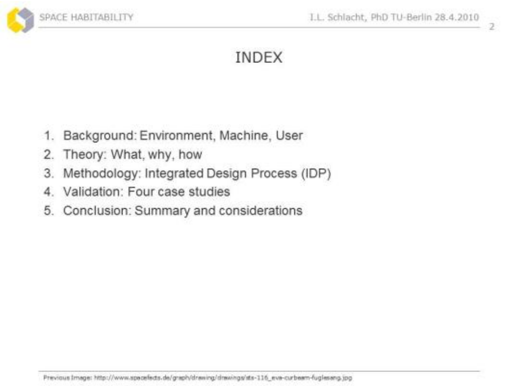


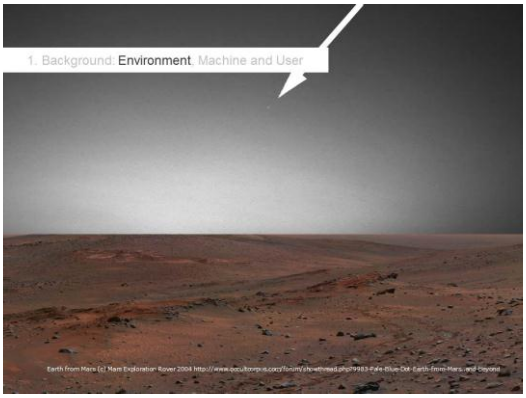
Figure 0.26: FLaSH habitat matrix representation discussed by the ISRU specialist Wolfgang Seboldt (DLR FLaSH study in 2011)

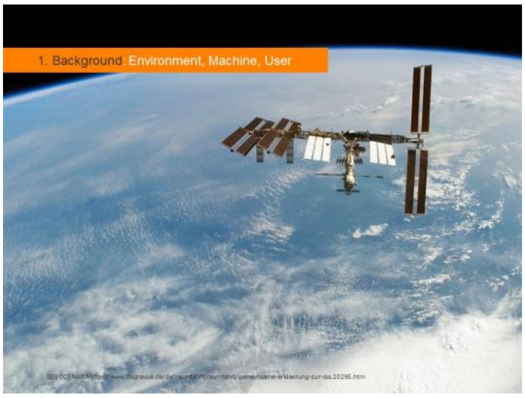
Presentation

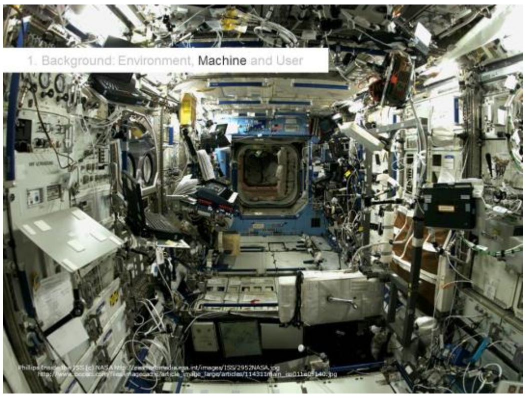


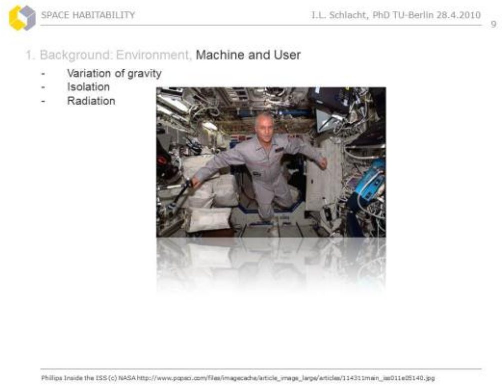


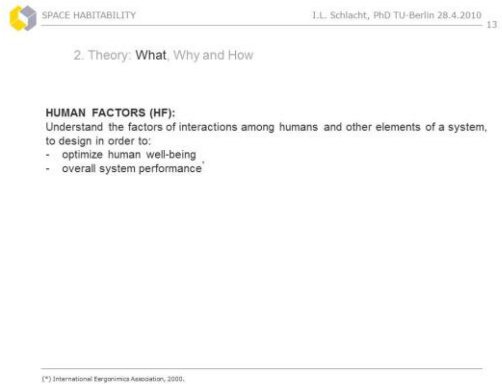


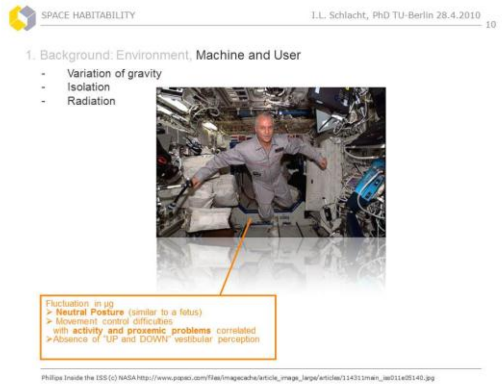







SPACE HABITABILITY
I.L. Schlacht, PhD TU-Berlin 28.4.2010
9
1. Background: Environment, Machine and User
- Variation of gravity
- Isolation
- Radiation
Phillips Inside the ISS (c) NASA http://www.popsci.com/files/imagecache/article_image_large/articles/114311main_iss011e05140.jpg


SPACE HABITABILITY
I.L. Schlacht, PhD TU-Berlin 28.4.2010
10
1. Background: Environment, Machine and User
- Variation of gravity
- Isolation
- Radiation
Fluctuation in μg
➢ Neutral Posture (similar to a fetus)
➢ Movement control difficulties
with activity and proxemic problems correlated
➢Absence of "UP and DOWN" vestibular perception
Phillips Inside the ISS (c) NASA http://www.popsci.com/files/imagecache/article_image_large/articles/114311main_iss011e05140.jpg


SPACE HABITABILITY
I.L. Schlacht, PhD TU-Berlin 28.4.2010
11
1. Background: Environment, Machine and User
- Variation of gravity
- Isolation
- Radiation
Earth environment confinement
(Isolation of the natural human environment)
➢ Sensory monotony (lack of stimuli variation)
➢ Social isolation
➢ Lack of expression
Dimensional confinement
➢ Privacy problem
➢ Claustrophobia
➢ Movement limitation
➢ Myopia
➢ fall of motivation
➢ Anemia
➢ Asthenia, sleep problems depression, Irritability, problem of concentration, headaches, ...
Stress (PSYCHOLOGICAL)
➢ Feeling of life risk
➢ Immune system repercussions
➢Renal calculus
➢ Exhilaration
Radiation
➢Cancer
μgravity
➢Muscle reduction
CICHEN LEGS
➢Bone Decalcification
Fluid redistribution
➢body shape modification
PUFFY FACE
➢brain congestion
Fluctuation in μg
➢ Neutral posture (similar to the fetal)
➢ Movement control difficulties
with activity and proxemics problems correlated
➢Absence of "UP and DOWN" vestibular perception
➢ Sensorial perception changes
➢ Changed body language and expressions
➢ Change of communication
Phillips Inside the ISS (c) NASA http://www.popsci.com/files/imagecache/article_image_large/articles/114311main_iss011e05140.jpg


SPACE HABITABILITY
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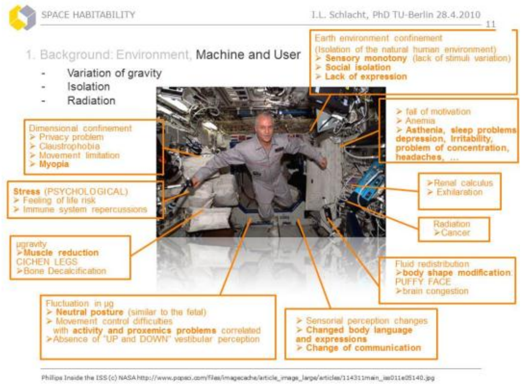
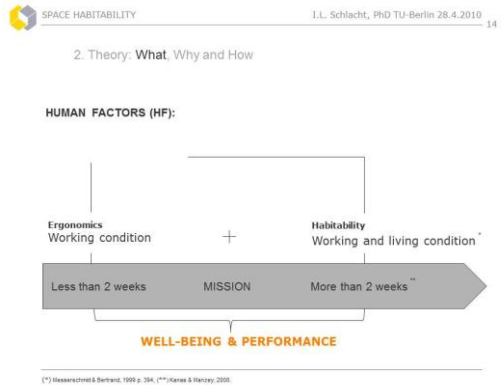
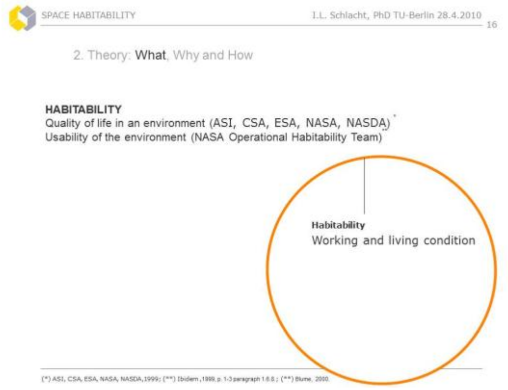
12
2. Theory: What, Why and How

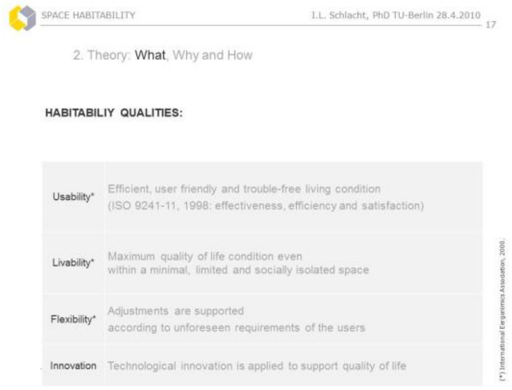

SPACE HABITABILITY
I.L. Schlacht, PhD TU-Berlin 28.4.2010
13
2. Theory: What, Why and How
HUMAN FACTORS (HF):
Understand the factors of interactions among humans and other elements of a system, to design in order to:
- optimize human well-being
- overall system performance*
(*) International Ergonomics Association, 2000.

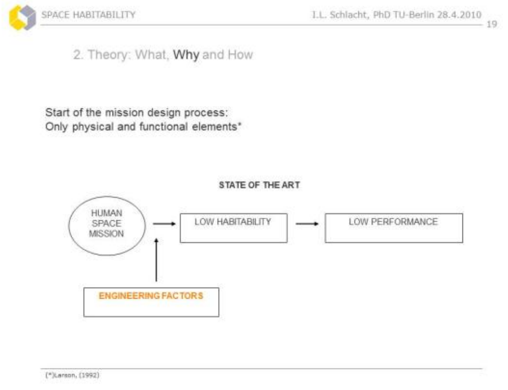

SPACE HABITABILITY
I.L. Schlacht, PhD TU-Berlin 28.4.2010
14
2. Theory: What, Why and How
HUMAN FACTORS (HF):
Understand the factors of interactions among humans and other elements of a system, to design in order to:
- optimize human well-being
- overall system performance*
HF is considered a "specific branch of Industrial Design" **, which integrates both quantitative and qualitative project variables in a multidisciplinary manner, supporting functional but also affective, emotional, and cultural user needs through a user-centered approach.
(*) International Ergonomics Association, 2000. (**) Ferrara, 2004 p. 22

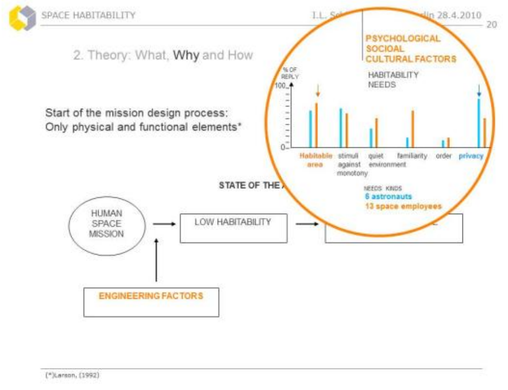

SPACE HABITABILITY
I.L. Schlacht, PhD TU-Berlin 28.4.2010
14
2. Theory: What, Why and How
HUMAN FACTORS (HF):
Ergonomics
Working condition
+
Habitability
Working and living condition*
Less than 2 weeks
MISSION
More than 2 weeks**
WELL-BEING & PERFORMANCE
(*) Messerschmid & Bertrand, 1999 p. 394, (**) Kanas & Manzey, 2008.

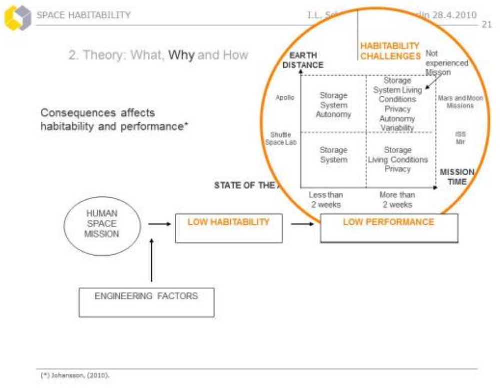

SPACE HABITABILITY
I.L. Schlacht, PhD TU-Berlin 28.4.2010
15
2. Theory: What, Why and How
HUMAN FACTORS (HF):
Ergonomics
Working condition
+
Habitability
Working and living condition*
Less than 2 weeks
MISSION
More than 2 weeks**
WELL-BEING & PERFORMANCE
(*) Messerschmid & Bertrand, 1999 p. 394, (**) Kanas & Manzey, 2008.

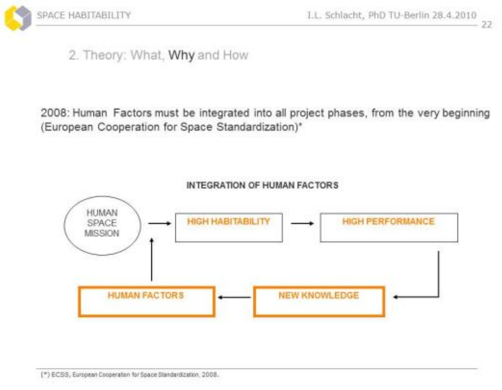

SPACE HABITABILITY
I.L. Schlacht, PhD TU-Berlin 28.4.2010
16
2. Theory: What, Why and How
HABITABILITY
Quality of life in an environment (ASI, CSA, ESA, NASA, NASDA)
Usability of the environment (NASA Operational Habitability Team)
Habitability
Working and living condition

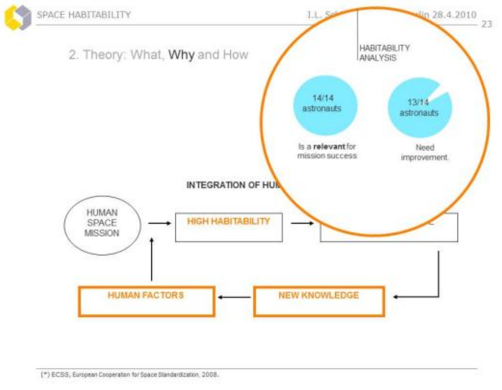

SPACE HABITABILITY
I.L. Schlacht, PhD TU-Berlin 28.4.2010
17
2. Theory: What, Why and How
HABITABILIY QUALITIES:
Usability*
Efficient, user friendly and trouble-free living condition
(ISO 9241-11, 1998: effectiveness, efficiency and satisfaction)
Livability*
Maximum quality of life condition even
within a minimal, limited and socially isolated space
Flexibility*
Adjustments are supported
according to unforeseen requirements of the users
Innovation
Technological innovation is applied to support quality of life
(*) International Ergonomics Association, 2000.

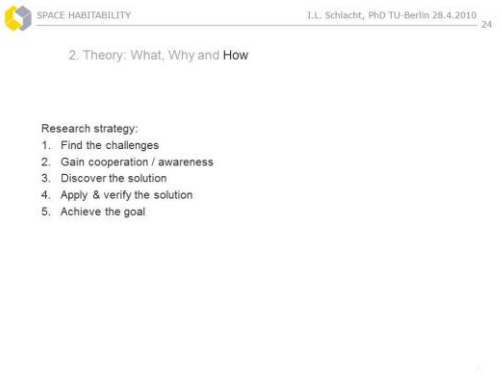

SPACE HABITABILITY
I.L. Schlacht, PhD TU-Berlin 28.4.2010
19
2. Theory: What, Why and How
Start of the mission design process:
Only physical and functional elements*
STATE OF THE ART
HUMAN SPACE MISSION
LOW HABITABILITY
LOW PERFORMANCE
ENGINEERING FACTORS
(*)Larson, (1992)


SPACE HABITABILITY
28.4.2010
20
2. Theory: What, Why and How
Start of the mission design process:
Only physical and functional elements*
STATE OF THE
HUMAN SPACE MISSION
LOW HABITABILITY
ENGINEERING FACTORS
PSYCHOLOGICAL
SOCIOAL
CULTURAL FACTORS
HABITABILITY NEEDS
100
0
Habitable area
stimuli against monotony
quiet environment
familiarity
order
privacy
6 astronauts
13 space employees
(*)Larson, (1992)


SPACE HABITABILITY
28.4.2010
21
2. Theory: What, Why and How
Consequences affects
habitability and performance*
EARTH DISTANCE
HABITABILITY CHALLENGES
Not experienced Mission
Apollo
Storage System Autonomy
Storage System Living Conditions Privacy Autonomy Variability
Mars and Moon Missions
Shuttle Space Lab
Storage System
Storage Living Conditions Privacy
ISS Mir
MISSION TIME
Less than 2 weeks
More than 2 weeks
STATE OF THE
HUMAN SPACE MISSION
LOW HABITABILITY
LOW PERFORMANCE
ENGINEERING FACTORS
(*) Johansson, (2010).


SPACE HABITABILITY
I.L. Schlacht, PhD TU-Berlin 28.4.2010
22
2. Theory: What, Why and How
2008: Human Factors must be integrated into all project phases, from the very beginning
(European Cooperation for Space Standardization)*
INTEGRATION OF HUMAN FACTORS
HUMAN SPACE MISSION
HIGH HABITABILITY
HIGH PERFORMANCE
HUMAN FACTORS
NEW KNOWLEDGE
(*) ECSS, European Cooperation for Space Standardization, 2008.


SPACE HABITABILITY
28.4.2010
23
2. Theory: What, Why and How
HABITABILITY ANALYSIS
14/14 astronauts
Is a relevant for mission success
13/14 astronauts
Need improvement.
INTEGRATION OF HU
HUMAN SPACE MISSION
HIGH HABITABILITY
HUMAN FACTORS
NEW KNOWLEDGE
(*) ECSS, European Cooperation for Space Standardization, 2008.


SPACE HABITABILITY
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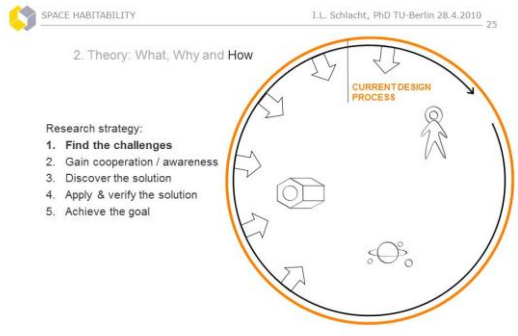
24
2. Theory: What, Why and How
Research strategy:
1. Find the challenges
2. Gain cooperation / awareness
3. Discover the solution
4. Apply & verify the solution
5. Achieve the goal


SPACE HABITABILITY
I.L. Schlacht, PhD TU-Berlin 28.4.2010
25
2. Theory: What, Why and How
CURRENT DESIGN PROCESS
Research strategy:
1. Find the challenges
2. Gain cooperation / awareness
3. Discover the solution
4. Apply & verify the solution
5. Achieve the goal


SPACE HABITABILITY
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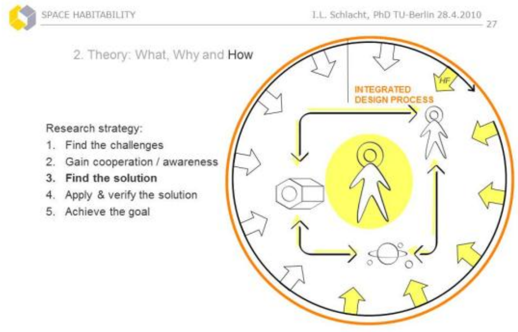
26
2. Theory: What, Why and How
NETWORKING
Research strategy:
1. Find the challenges
2. Gain cooperation/awareness
3. Find the solution
4. Apply & verify the solution
5. Achieve the goal
IMAGE: http://www.extreme-design.eu/group.html


SPACE HABITABILITY
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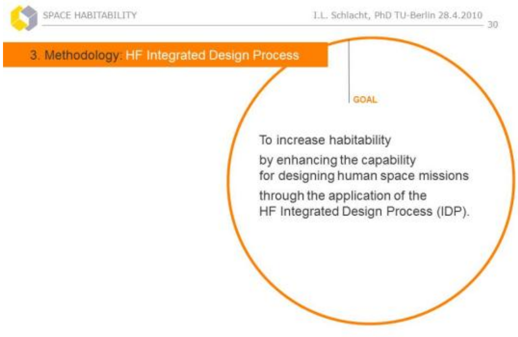
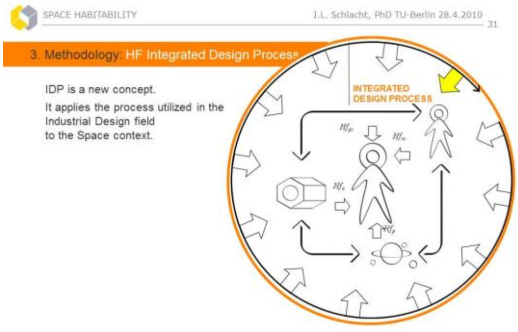
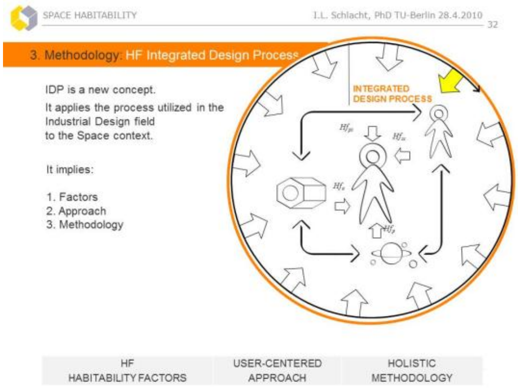
27
2. Theory: What, Why and How
INTEGRATED DESIGN PROCESS
HF
Research strategy:
1. Find the challenges
2. Gain cooperation / awareness
3. Find the solution
4. Apply & verify the solution
5. Achieve the goal

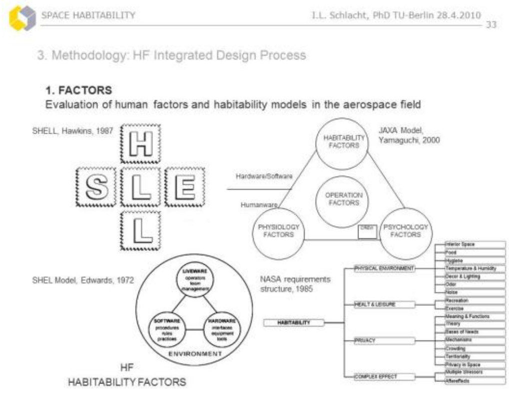

SPACE HABITABILITY
I.L. Schlacht, PhD TU-Berlin 28.4.2010
28
2. Theory: What, Why and How
FOUR CASE STUDIES
Research strategy:
1. Find the challenges
2. Gain cooperation / awareness
3. Find the solution
4. Apply & verify the solution
5. Achieve the goal
Image: SSDW (2009)


SPACE HABITABILITY
I.L. Schlacht, PhD TU-Berlin 28.4.2010
29
2. Theory: What, Why and How
GOAL
Research strategy:
1. Find the challenges
2. Gain cooperation / awareness
3. Find the solution
4. Apply & verify the solution
5. Achieve the goal
To increase habitability
by enhancing the capability
for designing human space missions
through the application of the
HF Integrated Design Process (IDP).


SPACE HABITABILITY
I.L. Schlacht, PhD TU-Berlin 28.4.2010
30
3. Methodology: HF Integrated Design Process
GOAL
To increase habitability
by enhancing the capability
for designing human space missions
through the application of the
HF Integrated Design Process (IDP).


SPACE HABITABILITY
I.L. Schlacht, PhD TU-Berlin 28.4.2010
31
3. Methodology: HF Integrated Design Process
IDP is a new concept.
It applies the process utilized in the
Industrial Design field
to the Space context.
INTEGRATED DESIGN PROCESS


SPACE HABITABILITY
I.L. Schlacht, PhD TU-Berlin 28.4.2010
32
3. Methodology: HF Integrated Design Process
IDP is a new concept.
It applies the process utilized in the
Industrial Design field
to the Space context.
It implies:
1. Factors
2. Approach
3. Methodology
INTEGRATED DESIGN PROCESS
HF HABITABILITY FACTORS
USER-CENTERED APPROACH
HOLISTIC METHODOLOGY


SPACE HABITABILITY
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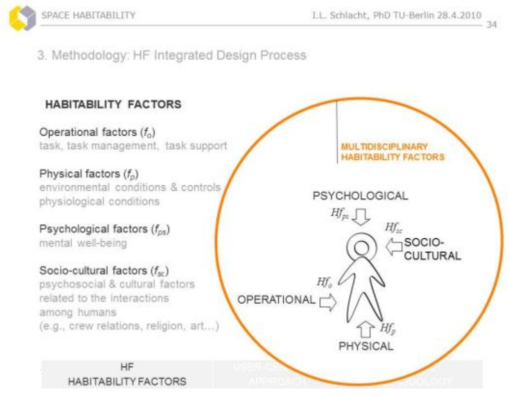
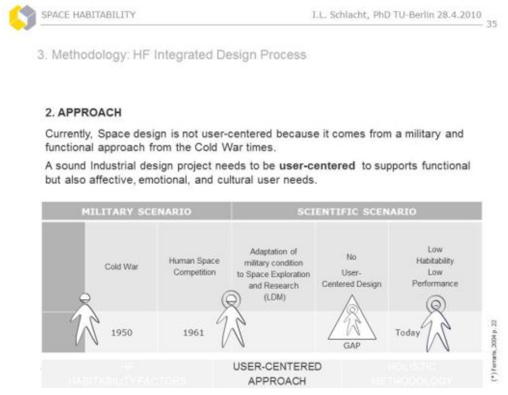
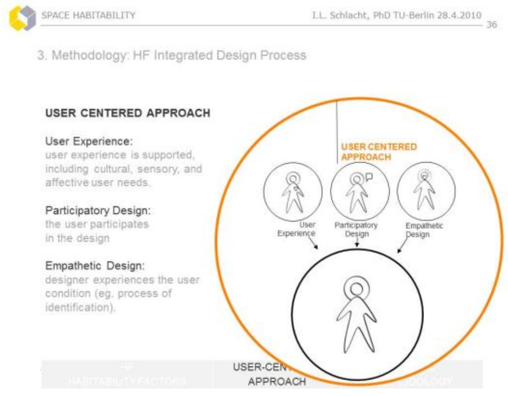
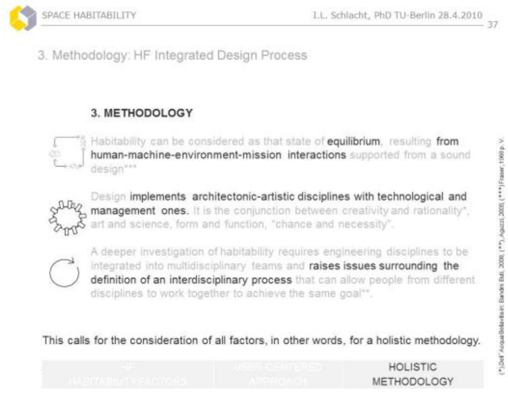
33
3. Methodology: HF Integrated Design Process
1. FACTORS
Evaluation of human factors and habitability models in the aerospace field
SHELL, Hawkins, 1987
JAXA Model, Yamaguchi, 2000
HABITABILITY FACTORS
OPERATION FACTORS
PHYSIOLOGY FACTORS
PSYCHOLOGY FACTORS
Hardware/Software
Humanware
SHEL Model, Edwards, 1972
NASA requirements structure, 1985
ENVIRONMENT
HF
HABITABILITY FACTORS


SPACE HABITABILITY
I.L. Schlacht, PhD TU-Berlin 28.4.2010
34
3. Methodology: HF Integrated Design Process
HABITABILITY FACTORS
Operational factors (f_o)
task, task management, task support
Physical factors (f_p)
environmental conditions & controls
physiological conditions
Psychological factors (f_{ps})
mental well-being
Socio-cultural factors (f_{sc})
psychosocial & cultural factors
related to the interactions
among humans
(e.g., crew relations, religion, art…)
MULTIDISCIPLINARY HABITABILITY FACTORS
PSYCHOLOGICAL
SOCIO-CULTURAL
OPERATIONAL
PHYSICAL
HF
HABITABILITY FACTORS


SPACE HABITABILITY
I.L. Schlacht, PhD TU-Berlin 28.4.2010
35
3. Methodology: HF Integrated Design Process
2. APPROACH
Currently, Space design is not user-centered because it comes from a military and functional approach from the Cold War times.
A sound Industrial design project needs to be user-centered to supports functional but also affective, emotional, and cultural user needs.
MILITARY SCENARIO
SCIENTIFIC SCENARIO
Cold War
Human Space Competition
Adaptation of military condition to Space Exploration and Research (LDM)
No User-Centered Design
Low Habitability Low Performance
1950
1961
GAP
Today
USER-CENTERED
APPROACH


SPACE HABITABILITY
I.L. Schlacht, PhD TU-Berlin 28.4.2010
36
3. Methodology: HF Integrated Design Process
USER CENTERED APPROACH
User Experience:
user experience is supported, including cultural, sensory, and affective user needs.
Participatory Design:
the user participates in the design
Empathetic Design:
designer experiences the user condition (eg. process of identification).
USER CENTERED APPROACH
User Experience
Participatory Design
Empathetic Design
USER-CENTERED
APPROACH


SPACE HABITABILITY
I.L. Schlacht, PhD TU-Berlin 28.4.2010
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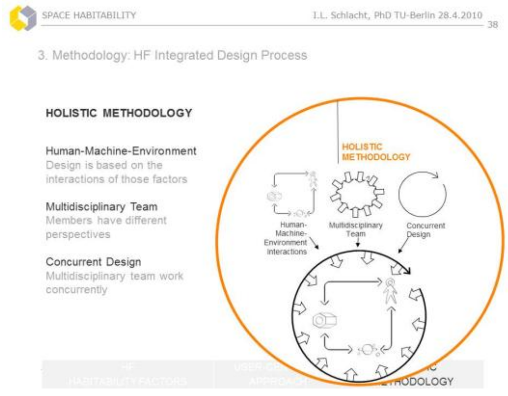
3. Methodology: HF Integrated Design Process
3. METHODOLOGY
Habitability can be considered as that state of equilibrium, resulting from human-machine-environment-mission interactions supported from a sound design***
Design implements architectonic-artistic disciplines with technological and management ones. It is the conjunction between creativity and rationality*, art and science, form and function, "chance and necessity".
A deeper investigation of habitability requires engineering disciplines to be integrated into multidisciplinary teams and raises issues surrounding the definition of an interdisciplinary process that can allow people from different disciplines to work together to achieve the same goal**.
This calls for the consideration of all factors, in other words, for a holistic methodology.
HOLISTIC
METHODOLOGY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38
3. Methodology: HF Integrated Design Process
HOLISTIC METHODOLOGY
Human-Machine-Environment
Design is based on the interactions of those factors
Multidisciplinary Team
Members have different perspectives
Concurrent Design
Multidisciplinary team work concurrently
HOLISTIC METHODOLOGY
Human-Machine-Environment Interactions
Multidisciplinary Team
Concurrent Design


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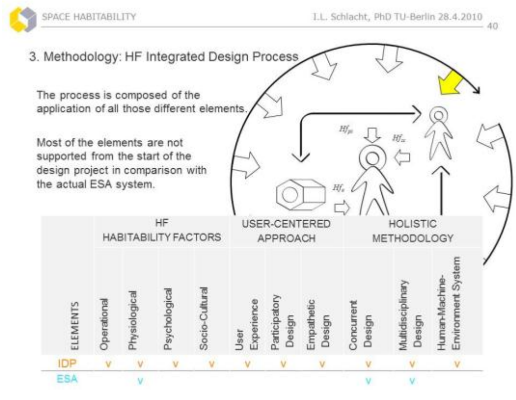
3. Methodology: HF Integrated Design Process
HOLISTIC METHODOLOGY
Human-Machine-Environment
Design is based on the interactions of those factors
Multidisciplinary Team
Members have different perspectives
Concurrent Design
Multidisciplinary team work concurrently
ARCHITECT
ANTHROPOMETER
PSYCHOLOGIST SOCIOLOGIST
HUMAN FACTORS DESIGNER
CULTURAL THEORIST


SPACE HABITABILITY
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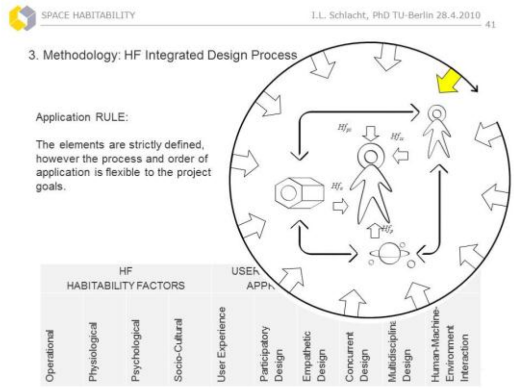
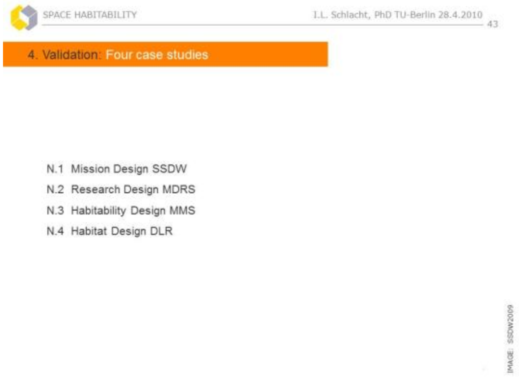
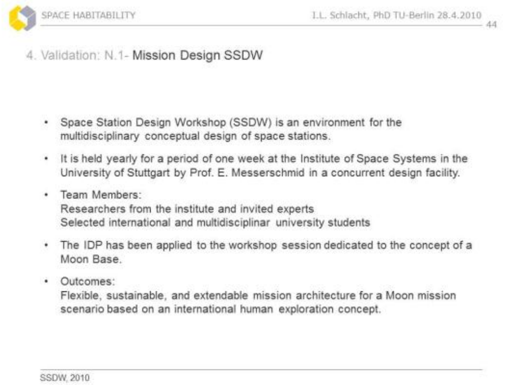
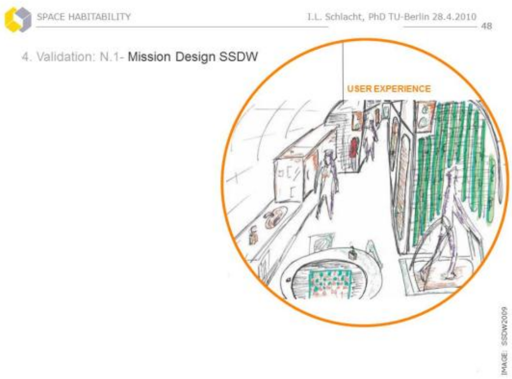
40
3. Methodology: HF Integrated Design Process
The process is composed of the application of all those different elements.
Most of the elements are not supported from the start of the design project in comparison with the actual ESA system.
HF HABITABILITY FACTORS
USER-CENTERED APPROACH
HOLISTIC METHODOLOGY
ELEMENTS
Operational
Physiological
Psychological
Socio-Cultural
User Experience
Participatory Design
Empathetic Design
Concurrent Design
Multidisciplinary Design
Human-Machine-Environment System
IDP v v v v v v v v v v
ESA v v v







Concurrent Design	SSDW IDP	ESA
Management Functions		
CDF Manager	v	v
Team Leader	v	v
Disciplines		
Cost	v	v
Communications System	v	v
Environment	v	v
Future Options and Developments	v	
HF / Habitability	v	
Life Support (ECLSS)	v	
Operation	v	
Power System	v	v
Resource (In-situ)	v	
Radiation	v	
Risk/Safety	v	v
Robotics, Mobility &EVA	v	
Structures and Configuration	v	v
Thermal	v	v
Transportation & Logistics	v	
Outreach, PR and Marketing	v	

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4. Validation: N.1- Mission Design SSDW
PARTICIPATORY DESIGN
IMAGE: SSDW2009


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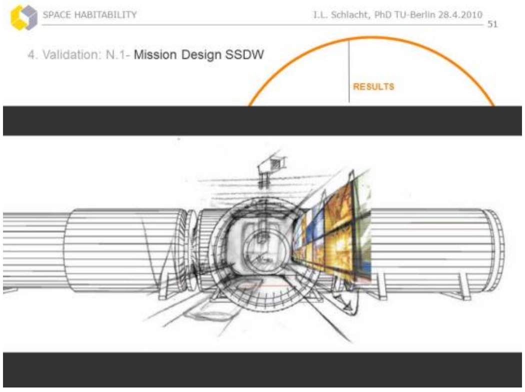
4. Validation: N.1- Mission Design SSDW
EMPATHETIC EXPERIENCE
IMAGE: SSDW2009 Soyuz-ISS docking


SPACE HABITABILITY
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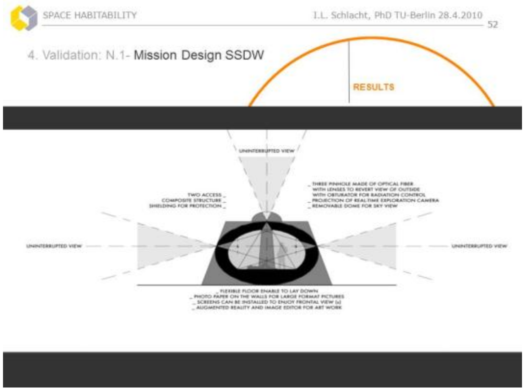
51
4. Validation: N.1- Mission Design SSDW
RESULTS


SPACE HABITABILITY
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52
4. Validation: N.1- Mission Design SSDW
RESULTS
UNINTERRUPTED VIEW
UNINTERRUPTED VIEW
UNINTERRUPTED VIEW


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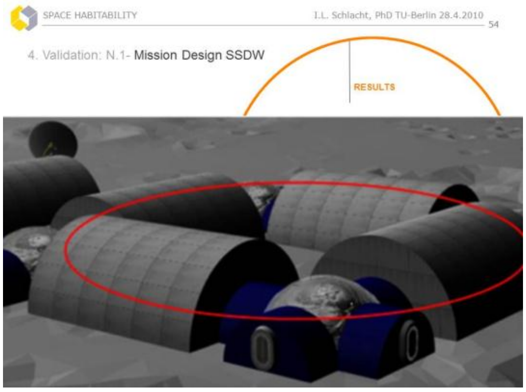
53
4. Validation: N.1- Mission Design SSDW
RESULTS


SPACE HABITABILITY
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4. Validation: N.1- Mission Design SSDW
RESULTS


SPACE HABITABILITY
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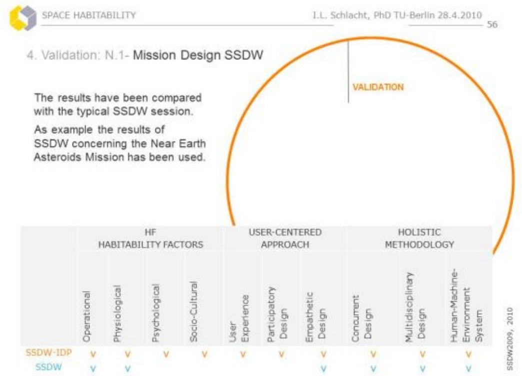
55
4. Validation: N.1- Mission Design SSDW
RESULTS
Mankind, with the target in mind to settle down on the moon, should not only rely upon the latest technology, but also on the experience of all of human existence
(J. Grippenkoven & I. Schlacht communication, 2009).
IMAGE: SSDW2009


SPACE HABITABILITY
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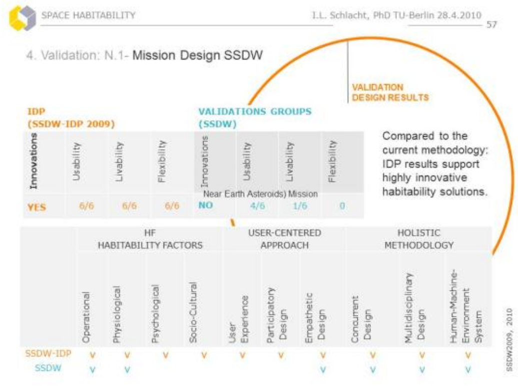
4. Validation: N.1- Mission Design SSDW
VALIDATION
The results have been compared with the typical SSDW session.
As example the results of SSDW concerning the Near Earth Asteroids Mission has been used.
HF HABITABILITY FACTORS: Operational, Physiological, Psychological, Socio-Cultural
USER-CENTERED APPROACH: User Experience, Participatory Design, Empathetic Design
HOLISTIC METHODOLOGY: Concurrent Design, Multidisciplinary Design, Human-Machine-Environment System
SSDW-IDP: V V V V V V V V V V
SSDW: V V (Operational, Physiological); V (Empathetic Design); V V V (Concurrent Design, Multidisciplinary Design, Human-Machine-Environment System)
SSDW2009, 2010


SPACE HABITABILITY
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57
4. Validation: N.1- Mission Design SSDW
VALIDATION DESIGN RESULTS
IDP (SSDW-IDP 2009)
VALIDATIONS GROUPS (SSDW)
Innovations
Usability
Livability
Flexibility
Innovations
Usability
Livability
Flexibility
Near Earth Asteroids) Mission
YES 6/6 6/6 6/6 NO 4/6 1/6 0
Compared to the current methodology: IDP results support highly innovative habitability solutions.
HF HABITABILITY FACTORS
USER-CENTERED APPROACH
HOLISTIC METHODOLOGY
Operational
Physiological
Psychological
Socio-Cultural
User Experience
Participatory Design
Empathetic Design
Concurrent Design
Multidisciplinary Design
Human-Machine-Environment System
SSDW-IDP V V V V V V V V V V
SSDW V V V V V V
SSDW2009, 2010


IMAGE: MDRS, ESA-ILEWG Mission 2010


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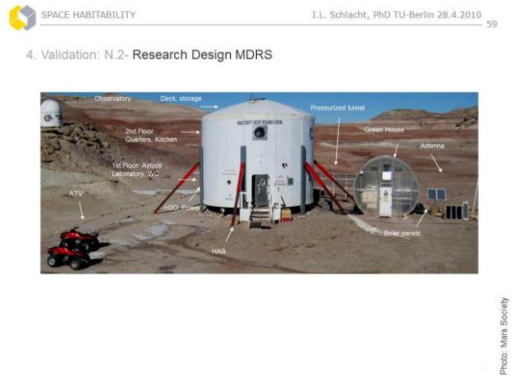
4. Validation: N.2 Research Design MDRS
Mars Desert Research Station (MDRS) is a facility for space mission simulation in the Utah desert from the Mars Society.
A mission campaign is held yearly by the ILEWG-ESA and directed by Prof. Bernard Foing.
Mission:
Composed by international researchers of the field
Duration of 2 weeks.
The IDP has been applied to the "Moon Mars Habitability Research":
Sensory Experience
Habitability Investigation
Creative Activities
Methodology: Questionnaires, interviews, observations, and collective debriefings. 18 Subjects; 3 Missions; 6 Crew members per mission.
Outcomes: Research concept of human aspects for a sustainable extra-terrestrial planetary exploration during a mission simulation


IMAGE: MDRS, ESA-ILEWG Mission 2010


SPACE HABITABILITY
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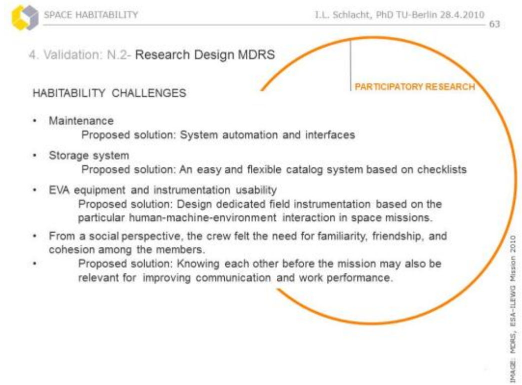
4. Validation: N.2- Research Design MDRS
Observatory
Deck: storage
Pressurized tunnel
2nd Floor Quarters, Kitchen
Green House
Antenna
1st Floor: Airlock Laboratory, WC
ATV
H2O Power
Solar panels
HAB
Photo: Mars Society


SPACE HABITABILITY
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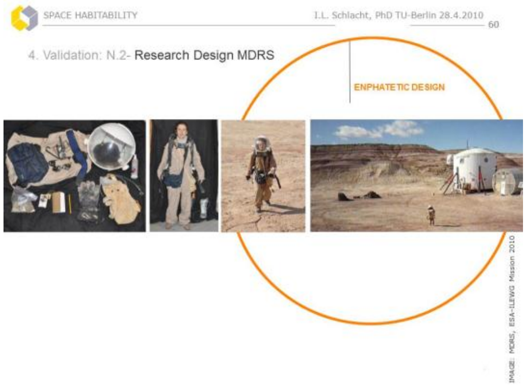
4. Validation: N.2- Research Design MDRS
PARTICIPATORY RESEARCH
HABITABILITY CHALLENGES
Maintenance
Proposed solution: System automation and interfaces
Storage system
Proposed solution: An easy and flexible catalog system based on checklists
EVA equipment and instrumentation usability
Proposed solution: Design dedicated field instrumentation based on the particular human-machine-environment interaction in space missions.
From a social perspective, the crew felt the need for familiarity, friendship, and cohesion among the members.
Proposed solution: Knowing each other before the mission may also be relevant for improving communication and work performance.
IMAGE: MDRS, ESA-ILEWG Mission 2010


SPACE HABITABILITY
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60
4. Validation: N.2- Research Design MDRS
ENPHATETIC DESIGN
IMAGE: MDRS, ESA-ILEWG Mission 2010


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64
4. Validation: N.2- Research Design MDRS
USER EXPERIENCE
IMAGE: MDRS, ESA-ILEWG Mission 2010

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4. Validation: N.2- Research Design MDRS

USER EXPERIENCE

The tasks stimulated sensory activity, creativity, and well-being.

The stimuli were felt to be a relevant factor for LDM;

Fragrance variation, in particular, had the strongest effect and was considered relevant to habitability. This is of interest in light of the current odor neutrality requirement for the ISS.

IMAGE: MDRS, ESA-ILEWG Mission 2010

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4. Validation: N.2- Research Design MDRS

ENPHATETIC DESIGN

- Color gradation: evokes aesthetic feeling
- Plants: connects with other forms of life
- Natural sounds: relaxes, stimulates imagination
- Fragrances: evoke experiences and memories
- Creative performance: relaxes and leads thinking

IMAGE: MDRS, ESA-ILEWG Mission 2010

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4. Validation: N.2- Research Design MDRS

VALIDATION RESERACH RESULTS

IDP (MDRS-IDP) Innovations	Usability	Livability	Flexibility	VALIDATIONS GROUPS (MDRS) Innovations	Usability	Livability	Flexibility
YES	6/6	6/6	6/6	Only Op. Ph.	4/4	1/4	1/4

Increasing awareness of and knowledge about habitability factors, sensory experiences and creative performances, expected to become relevant during long duration missions.

	HF HABITABILITY FACTORS				USER-CENTERED APPROACH			HOLISTIC METHODOLOGY		
	Operational	Physiological	Psychological	Socio-Cultural	User Experience	Participatory Design	Empathetic Design	Concurrent Design	Multidisciplinary Design	Human-Machine-Environment System
MDRS-IDP	V	V	V	V	V	V	V	V	V	V
MDRS	V	V				V	V			V

Schlacht et al., 2010; Thiel et al., 2011

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4. Validation: N.3 Habitability Design MMS

- At the Chair of Human-Machine Systems (MMS) the author guided 3 classes of students to the IDP.
- Classes:
  Composed by 26 students from different disciplines and countries.
  Duration of 6 months (90 h).
- The IDP has been applied to the workshop session dedicated to the concept of a Moon Base.
-
  Methodology: Guide the student to the acquiring of a specific field of expertise to create a multidisciplinary team context
- Outcomes: Iinnovative concept solutions to habitability problems in long duration missions exploration

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4. Validation: N.3- Habitability Design MMS

Project 1

Image: 'Apertura' Student: Johnston MMS TU-Berlin

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4. Validation: N.3- Habitability Design MMS

Project 2

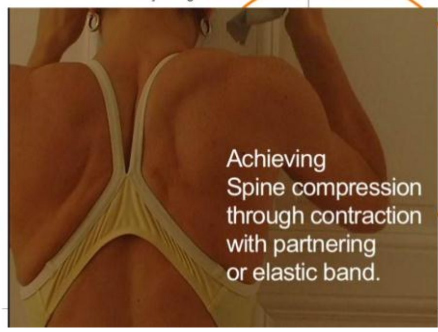

Image: "Video for space countermeasures" Student: Kavanaugh MMS TU-Berlin

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4. Validation: N.3- Habitability Design MMS

Project 5

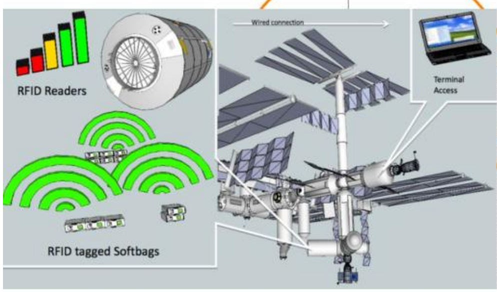

Image: Space Storage System MMS Students group TU-Berlin

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4. Validation: N.3- Habitability Design MMS

VALIDATION HABITABILITY RESULTS

IDP (SSDW-IDP 2009) Innovations	Usability	Livability	Flexibility
YES	5/5	4/5	5/5

Project 5 Storage System, the team did not consider psychological and socio-cultural habitability dimensions (see*). Instead, the team focused its research on the user-centered approach; this was demonstrated as not being sufficient to support an increase of habitability in the project.

	HF HABITABILITY FACTORS				USER-CENTERED APPROACH			HOLISTIC METHODOLOGY		
	Operational	Physiological	Psychological	Socio-Cultural	User Experience	Participatory Design	Empathetic Design	Concurrent Design	Multidisciplinary Design	Human-Machine-Environment System
MMS-IDP	V	V	v*	v*	V	V	V	V	V	V
ESA		V						V	V	

SSDW2009, 2010

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4. Validation: N.4 Habitat Design DLR

- The first human project for long duration missions was performed at the Concurrent Engineering Facility (CEF) of the DLR Institute of Space Systems in Bremen with the support of the IDP design model.
- Team Members:
  Employees from the DLR and invited experts from selected disciplines
  Workshop session of one week
- Concept: effective and self-sustainable artificial habitat for humans is essential to the exploration of the space hostile environment and also considering Earthly application as in megacities.
- Outcomes: ground-based laboratory facility to test new and innovative habitat technologies named "Facility of Laboratories for Sustainable Habitation" (FLaSH).

SSDW, 2010

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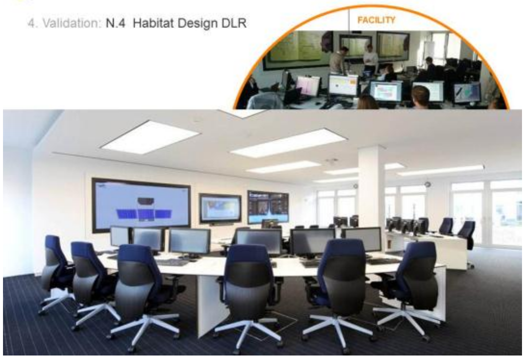
4. Validation: N.4 Habitat Design DLR



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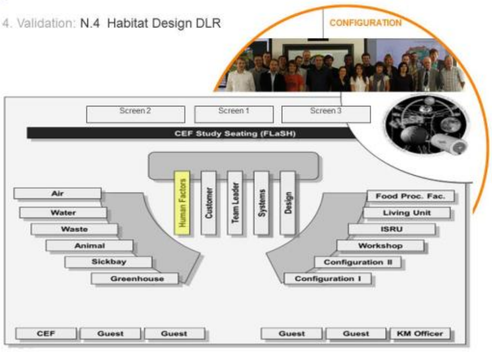
4. Validation: N.4 Habitat Design DLR



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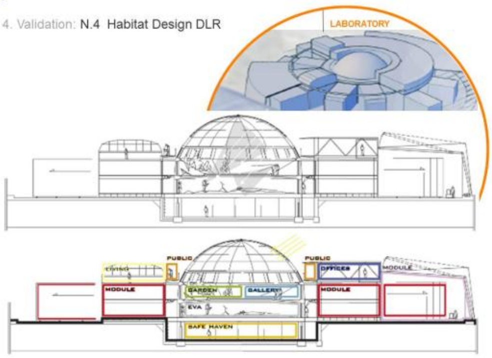
4. Validation: N.4 Habitat Design DLR



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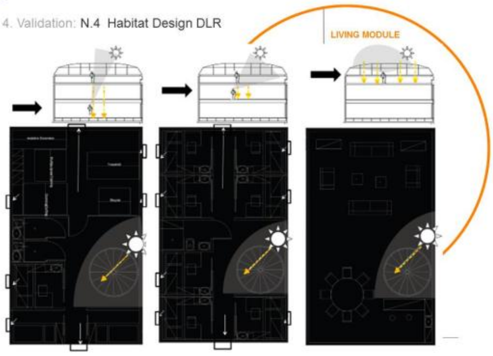
4. Validation: N.4 Habitat Design DLR



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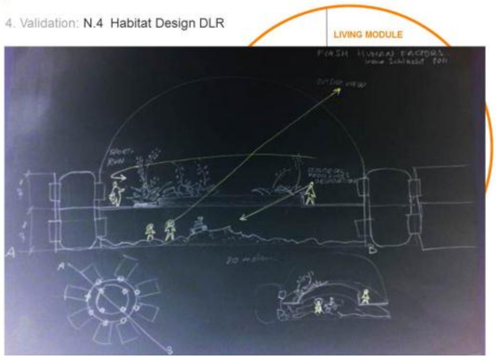
4. Validation: N.4 Habitat Design DLR



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4. Validation: N.4 Habitat Design DLR

SCHEDULE CREW OF 8	Activity h	Free day	Emergency
Authonomy supports	Automatic interf.	Only Check Linst	Emergency signal
MAINTENANCE H (with safety check list and reports)	Daily	1Free day pro week	Emergency
Air	01:00	00:40	03:00
Water	00:40	00:30	04:30
Animal	02:30	00:45	10:00
Sickbay	01:30	00:00	07:00
Green house 1 and 2	18:00	02:00	06:00
Workshop	00:00	00:00	03:00
ISRU	01:00	00:00	08:00
Living Unit	00:30	00:00	00:30
Food Processing	06:00	00:30	02:00
Arboreum	00:30	00:00	02:00
General Maintenance	00:20	00:00	01:00
Ground Control			01:00
Total maintenance per day per crew	32:00:00	4:25:00	48:00:00
TOTAL MAINTENANCE PER DAY PER PERSON	04:00	00:33	06:00
WORK ACTIVITY H	Daily	1Free day pro week	Emergency
Work (Research, EVA, Experiments, ISRU, PR)	04:00	00:00	00:00
TOTAL WORK PER DAY PER PERSON	08:00	00:33	06:00
OTHER ACTIVITY H	Daily	1Free day pro week	Emergency
Transaction between module	00:30	00:30	00:45
Eat	02:10	02:10	00:00
Sleep	08:00	08:00	08:00
Personal hygiene/Care	00:45	01:00	01:00
Gymnastic	00:50	00:00	00:00
Pubblic/private relation (with outside)	00:45	02:00	01:00
FREE TIME (Personal/social activities, relax, free activity)	03:00	00:00	00:00
TOTAL	24:00:00	14:13:07	16:45:00

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4. Validation: N.4 Habitat Design DLR

VALIDATION DESIGN RESULTS

Unlike the previous procedures, which had only been used for robotic missions prior to this study, a more dynamic approach was incorporated with descriptive and visual data, which fully integrated user-centered design and a holistic methodology.
The result considered the overall complexity of human needs and project qualities.

IDP (SSDW-IDP 2009)	Innovations	Usability	Livability	Flexibility
	YES	V	V	V

	HF HABITABILITY FACTORS				USER-CENTERED APPROACH			HOLISTIC METHODOLOGY		
	Operational	Physiological	Psychological	Socio-Cultural	User Experience	Participatory Design	Empathetic Design	Consumer Design	Multidisciplinary Design	Human-Machine-Environment System
CEF-IDP	V	V	V	V	V	V	V	V	V	V
CEF	V							V	V	

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5. CONCLUSION

IDP fully meets the objective of increasing the sustainability of habitability solutions for human space missions in the 4 case studies

	HABITABILITY QUALITIES				HF HABITABILITY FACTORS				USER-CENTERED APPROACH			HOLISTIC METHODOLOGY		
	Innovation	Usability	*Livability*	*Flexibility*	Operational	Physiological	*Psychological*	*Socio-Cultural*	*User Experience*	Participatory Design	Empathetic Design	Concurrent Design	Multidisciplinary Design	Human-Machine-Environment Interaction
Study 1														
SSDW-IDP	V	V	V	V	V	V	V	V	V	V	V	V	V	V
SSDW		V			V	V				V		V	V	
Study 2														
MDRS-IDP	V	V	V	V	V	V	V	V	V	V	V	V	V	V
MDRS-HC	V	V			V	V				V	V			V
Study 3														
MMS-IDP	V	V	V	V	V	V	V	V	V	V	V	V	V	V
ESA	V					V						V	V	
Study 4														
CEF-IDP	V	V	V	V	V	V	V	V	V	V	V	V	V	V
CEF	V				V							V	V	

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5. CONCLUSION: Summary

The current design process for human space missions does not properly integrate the basic principle of quality of life into the astronauts' environment according to HF principles.

Considering the need to integrate these principles from the start of the mission design, the Integrated Design Process is the concept of a design model that aims to fulfill this need.

This concept model has been used in different projects and experiments, in particular considering the context of long duration and long range missions.

The results increase the sustainability and quality of habitability solutions for human space missions in order to support astronaut performance and safety.

Moreover, further applications of the IDP methodology may also include retirement homes, prisons, research facilities in extreme environments, space tourism.

The rapid growth of the world's population and the proliferation of megacities also increase the need for sustainable human-machine-environment systems, making the IDP not only applicable in extreme environments but also in our daily lives.

T. Reiter (c) NASA 2005 http://www.esa.int/esaCP/SEM3S2815QE_Germany_1.html

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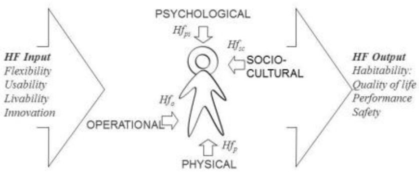
5. CONCLUSION

To integrate the HF in the design process we need to consider the whole: a holistic methodology.
Aristotle (300 B.C.): *The whole is more than the sum of its parts*



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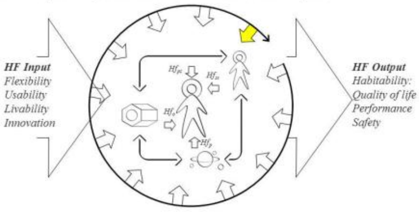
5. CONCLUSION

To integrate the HF in the design process we need to consider the whole: a holistic methodology.
Aristotle (300 B.C.): *The whole is more than the sum of its parts*



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For a more detailed bibliography please refer to the PhD Thesis

T. Reiter (c) NASA 2005 http://www.esa.int/esaCP/SEM3S2815QE_Germany_1.html

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- *How is the user safety supported?*
- *Difference between Ergonomics and Human factors? (Masali: Human factors come sinonimo dell'Ergonomia non lascia spazio all'abitabilitá)*
- *How to support different cultural needs in the international crew?*
- *How to select the quantity of the design team person? (follow the case)*
- *How may the interdisciplinary team be able to communicate using different discipline-language? (Imhof: Communicate the same value with different language. Masali: "Stabilire un ponte tra paradigmi")*
- *How to quantify the habitability level? (Experiment conducted at the MDRS with Habitability Debriefing Procedure)*

?

QUESTIONS

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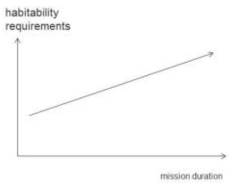
CHALLENGES ANALYSIS User Analysis

"Human factors and habitability requirements for space flights are driven by mission duration" (Woolford & Mount; 2006).



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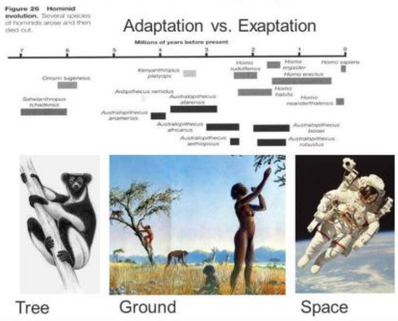
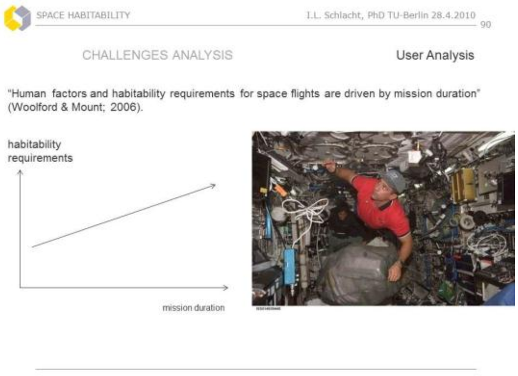
Human Evolution 7 Millions Altitudinal Selection for space 50 years

Adaptation vs. Exaptation

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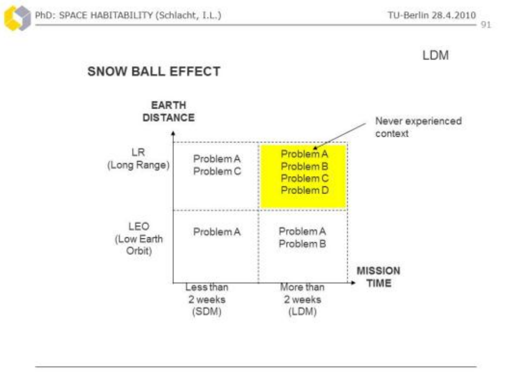
CHALLENGES ANALYSIS
User Analysis
"Human factors and habitability requirements for space flights are driven by mission duration" (Woolford & Mount; 2006).
habitability requirements
mission duration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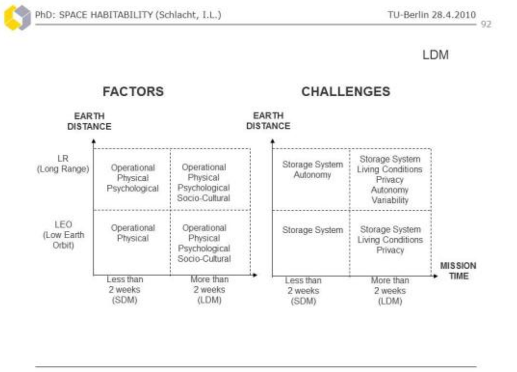
LDM
SNOW BALL EFFECT
EARTH DISTANCE
Never experienced context
LR (Long Range)
Problem A
Problem C
Problem A
Problem B
Problem C
Problem D
LEO (Low Earth Orbit)
Problem A
Problem A
Problem B
MISSION TIME
Less than 2 weeks (SDM)
More than 2 weeks (LDM)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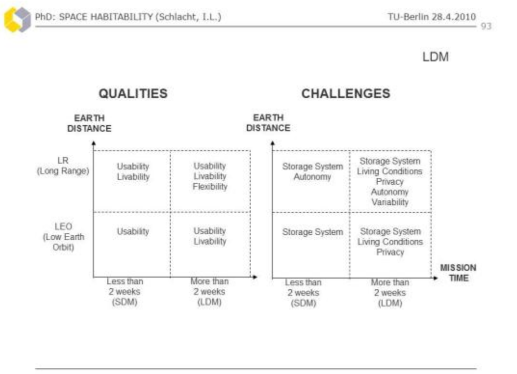
LDM
FACTORS
CHALLENGES
EARTH DISTANCE
LR (Long Range)
Operational Physical Psychological
Operational Physical Psychological Socio-Cultural
LEO (Low Earth Orbit)
Operational Physical
Operational Physical Psychological Socio-Cultural
Less than 2 weeks (SDM)
More than 2 weeks (LDM)
EARTH DISTANCE
Storage System Autonomy
Storage System Living Conditions Privacy Autonomy Variability
Storage System
Storage System Living Conditions Privacy
MISSION TIME
Less than 2 weeks (SDM)
More than 2 weeks (LDM)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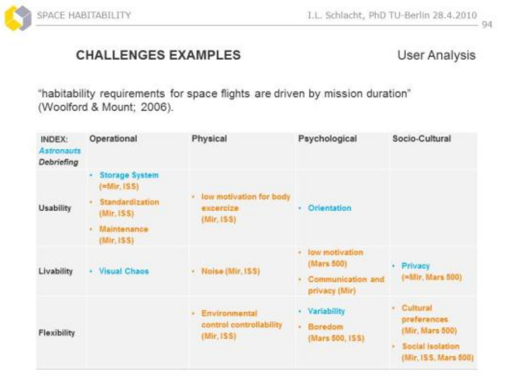
LDM
QUALITIES
CHALLENGES
EARTH DISTANCE
LR (Long Range)
Usability Livability
Usability Livability Flexibility
LEO (Low Earth Orbit)
Usability
Usability Livability
Less than 2 weeks (SDM)
More than 2 weeks (LDM)
EARTH DISTANCE
Storage System Autonomy
Storage System Living Conditions Privacy Autonomy Variability
Storage System
Storage System Living Conditions Privacy
MISSION TIME
Less than 2 weeks (SDM)
More than 2 weeks (LDM)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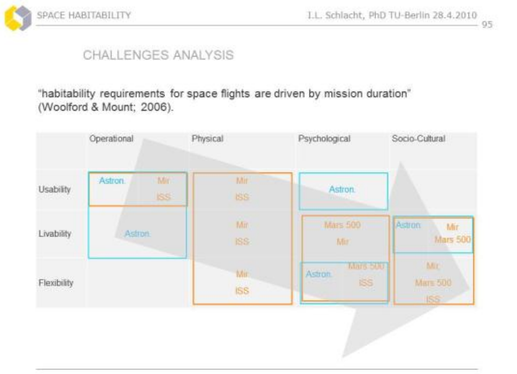
CHALLENGES EXAMPLES
User Analysis
"habitability requirements for space flights are driven by mission duration" (Woolford & Mount; 2006).
INDEX: Astronauts Debriefing
Operational
Physical
Psychological
Socio-Cultural
Usability
Storage System (=Mir, ISS)
Standardization (Mir, ISS)
Maintenance (Mir, ISS)
low motivation for body excercize (Mir, ISS)
Orientation
Livability
Visual Chaos
Noise (Mir, ISS)
low motivation (Mars 500)
Communication and privacy (Mir)
Privacy (=Mir, Mars 500)
Flexibility
Environmental control controllability (Mir, ISS)
Variability
Boredom (Mars 500, ISS)
Cultural preferences (Mir, Mars 500)
Social isolation (Mir, ISS, Mars 500)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CHALLENGES ANALYSIS
"habitability requirements for space flights are driven by mission duration" (Woolford & Mount; 2006).
Operational
Physical
Psychological
Socio-Cultural
Usability
Livability
Flexibility
Astron.
Mir
ISS
Mars 500


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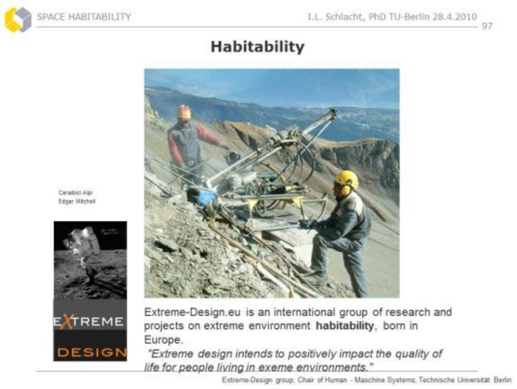
SOLUTION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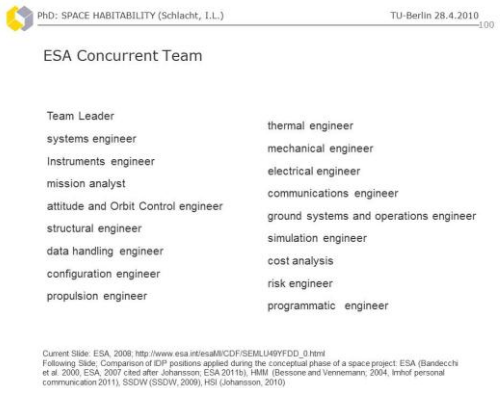
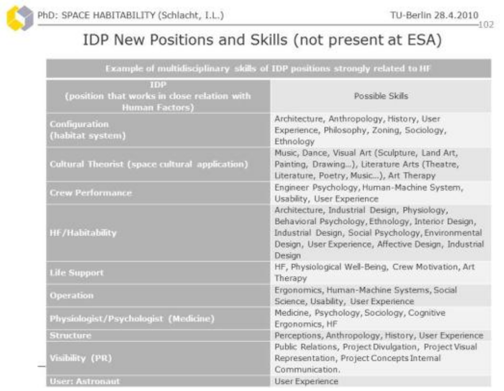
Habitability
EXTREME DESIGN
Extreme-Design.eu is an international group of research and projects on extreme environment habitability, born in Europe.
"Extreme design intends to positively impact the quality of life for people living in exeme environments."
Extreme-Design group, Chair of Human - Maschine Systems, Technische Universität Berlin





Example of multidisciplinary skills of IDP positions strongly related to HF	
IDP (position that works in close relation with Human Factors)	Possible Skills
Configuration (habitat system)	Architecture, Anthropology, History, User Experience, Philosophy, Zoning, Sociology, Ethnology
Cultural Theorist (space cultural application)	Music, Dance, Visual Art (Sculpture, Land Art, Painting, Drawing...), Literature Arts (Theatre, Literature, Poetry, Music...), Art Therapy
Crew Performance	Engineer Psychology, Human-Machine System, Usability, User Experience
HF/Habitability	Architecture, Industrial Design, Physiology, Behavioral Psychology, Ethnology, Interior Design, Industrial Design, Social Psychology, Environmental Design, User Experience, Affective Design, Industrial Design
Life Support	HF, Physiological Well-Being, Crew Motivation, Art Therapy
Operation	Ergonomics, Human-Machine Systems, Social Science, Usability, User Experience
Physiologist/Psychologist (Medicine)	Medicine, Psychology, Sociology, Cognitive Ergonomics, HF
Structure	Perceptions, Anthropology, History, User Experience
Visibility (PR)	Public Relations, Project Divulgation, Project Visual Representation, Project Concepts Internal Communication.
User: Astronaut	User Experience

IDP PROPOSED TEAM POSITIONS	Proposed	Actual	Experimental	Experimental	Proposed
	IDP	ESA	HMM ESA	SSDW	HSI
Management Positions					
CDF Manager	x	x	x	X	
Team Leader	x	x	x	X	
Technical Author / Editing	x	x	x		
Systems Specialist	x	x	X		
Systems Assistant	x	x	X		
Position Disciplines					
Acceleration	x			v	Part of HSI
Attitude and Orbit Control	x	x		V	
Aerothermodynamics	x		x	V	
Configuration (*Habitat System and Architecture)	X*	Part of Structures	X	v	
Command and Data Handling	x	x		v	
Cost	x	x	x	x	
Communications System	x	x	x	x	
Crew Escape Facility	x			v	Part of HSI
Crew Performance	X			vPart of HF	
Cultural Theorist (space cultural application)	X				
Data Handling		x	x		
Exploration Scientist	x		Part of others		
Environment	x		Part of others	x	
Future Options and Developments	x			xv	
Ground Systems and Operations (*Ground segment)	x	x	X*		
Guidance Navigation Control (GNC)	x		x		
HF(* and Habitability, ** and Crew Performance)	X*		X	X**	
HIS (Human System Integration)	x			v	X
Instruments	x	x		v	
Life Support (*ECLSS)	X		x	x*	

Index: Marked = new disciplines, x = concurrent design position, x Bold = position related to Human Factors, X = position that works in close relation with Human Factors.
Acronyms: HF (Human Factors), IDP (Integrated Design Process), ESA (European Space Agency), HMM (Human Mars Mission), SSDW (Space Stations Design Workshop), HSI (Human Systems Integration), ECLSS: Environmental Control & Life Support System

TEAM POSITIONS	Proposed	Actual	Experimental	Experimental	Proposed
	IDP	ESA	HMM ESA	SSDW	HSI
Management Positions					
Marketing	x			Part of outreach	
Mechanisms (*and Pyrotechnics)	x	x *	x		
Mission Analysis	x	x	x		
Noise	x				Part of HSI
Outreach and Marketing	x			x	
Operation (*and Utilization & Risk Analysis)	**x**			X*	
Physiologist/Psychologist (Medicine)	**x**		Part of others		
Power (*EPS: Electrical Power System)	x	x	x	X*	
Propulsion	x	x	**x**		
Pyrotechnics	x	Part of mechanisms			
Propulsion	x	x	x		
Programmatic	x	x	x		
Requirement	x				Part of HSI
Resource (*In-situ Resource Utilization)	x			X*	
Radiation	x		**x**	x	Part of HSI
Risk/Safety (*Risk Assessment)	x	X*	**x**	Part of operations	
Robotics, Mobility &EVA	x			x	
Science and Physics	x		Part of others		
Simulation	x	x	**x**		
Systems	x	x	x		
Structure (* and Configurations)	**x**	X*	**x**	X*	
Thermal (*TCS: Thermal Control System)	x	x	**x**	X*	
Telemetry Tracking and Command	x	x			
Trajectories	x		x		
Transportation & Logistics	x			x	
Visibility (PR)	**x**			Part of outreach	
Workload	x				Part of HSI
User: Astronaut	**x**			(De Winne unofficial)	
Others	x	X(*)	x		

(*)instrument design activities have specialized teams with disciplines such as: Receiver, Optics etc.

Acronyms

ASI	Italian Space Agency
AU	Astronomical Unit = Sun - Earth approximately distance (150 million km)
CD	Concurrent Design
CDF	Concurrent Design Facility
CHeCS	Crew Health Care System
CNSA	China National Space Administration
CSA	Canadian Space Agency
DLR	Forschungszentrum der Bundesrepublik Deutschland für Luft- und Raumfahrt
ECLSS	Environmental Control and Life Support System
ED	Empathetic Design
eHS	environmental Health System
ESA	European Space Agency
ELDO	European Launcher Development Organisation (sucessively ESA)
EVA	Extra Vehicular Activities
FAI	Fédération Aéronautique Internationale
FKA	Russian Federal Space Agency (Roskosmos)
GNC	Guidance Navigation Control
HF	Human Factors
HFD	Human Factors Design
Hf	Habitability Factors
Hf_{p}	Habitability Physical Factors
Hf_{e}	Habitability Environmental Factors
Hf_{ph}	Habitability Physiological Factors
Hf_{ps}	Habitability Physiological Factors,
Hf_{sc}	Habitability Socio-Cultural Factors
Hf_{o}	Habitability Operational Factors.
HME	Human Machine Environment
HME	Human Machine Environment Systems
HMS	Human-Machine Systems
IDP	Integrated Design Process
ILA	International Aerospace Exhibition (Berlin Air Show)
IRS	Institut für Raumfahrtsysteme

IVA	Intra Vehicular Activities
LDM	Long Duration Mission
LEO	Low-Earth Orbit
LRM	Long Range Mission
MDP	Mission Design Process
MD	Multidisciplinary Design
MDRS	Mars Desert Research Station
MMS	Mensch-Maschine-Systeme
μG	Microgravity
NACA	National Advisory Committee for Aeronautics (successively NASA)
NASA	National Aeronautics and Space Administration (USA)
NASDA	National Space Development Agency of Japan
NEO	Near-Earth Objects
QOL	Quality Of Life
PD	Participatory Design
JAXA	Japan Aerospace Exploration Agency
RGB	Red Green Blue
RKA	Russian Federal Space Agency (Roskosmos)
SDM	Short Duration Mission
SRM	Short Range Mission
SSDW	Space Station Design Workshop
TCS	Thermal Control System
TU	Technische Universität Berlin
UC	User-Centered
UCD	User-Centered Design
UE	User Experience
UNITO	Università di Torino
USA	United States of America

Declaration

I declare that this thesis is my own work and has not been submitted in any form for another degree or diploma at any university or other institution of tertiary education. Information derived from the published or unpublished work of others has been acknowledged in the text and a list of references is given.

Irene Lia Schlacht 20.9.2011, Berlin

"Even if somewhere in the bottomless sky
there are other stars just like Earth
there is only this one field of gravity and light
where we laugh and where we die
each of us holding within
a small universe of our own".
Motoo Ando, 2008

Author Bio

Irene Lia Schlacht is a European doctoral researcher in the field of Outer Space Habitability.

Currently, she is a doctoral research student at Technische Universität Berlin and is researching habitability in outer space, developing a methodology aimed at improving the living conditions of astronauts in long duration space missions.

Her objective is to apply human factors disciplines for improving human life conditions in extreme space environments. She has been working and doing research with multidisciplinary and international teams within both academic and industrial contexts in Europe.

As part of her PhD on "Space Habitability," she is currently researching and teaching at Technische Universität Berlin in the Chair of Human-Machine Systems under the tutelage of Prof. M. Rötting and with the mentorship of Prof. M. Masali at Università di Torino.

After an internship in Space Design at Thales Alenia Space, she was a Human Factors researcher for space at Università di Torino under Prof. M. Masali. In 2006, she graduated in Industrial Design from Politecnico di Milano with a thesis on "Color Requirement in Outer Space Habitats" supported by Prof. D. Riccò.

In the context of a European student team, she led the "CROMOS" experiment on color perception in microgravity. The experiment, which was conducted during parabolic flights with the ESA student campaign in September 2006, was given an award by ELGRA in 2007.

From 2005 until today, she has been leading international student groups in space habitat projects.

In 2010, she was invited by ILEWG (International Lunar Exploration Working Group) to investigate habitability during a Mars Mission simulation at the Mars Desert Research Station with support from SKOR (Foundation Art and Public Space).

Since 2008, she has been coordinating an international research group called Extreme-Design with outer space experts from various disciplines, including space art, space psychology, space ergonomics, space design, and space anthropology, as well as experts in sensory experiences applied to outer space habitats.

Her goal is to design space habitat systems using a holistic approach that includes scientific and humanistic disciplines.

間

The beauty of the moonlight
shining through an open gate.
Without the space between the gate,
the moonlight could not shine through,
and correspondingly, without the moonlight,
the space would take on less significance.
One cannot "be" without the other.
(Reischauer, 1970,
cited after Serejski 2011)