AN INQUIRY OF SPACE ARCHITECTURE: DESIGN CONSIDERATIONS AND DESIGN PROCESS

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ABSTRACT

AN INQUIRY OF SPACE ARCHITECTURE: DESIGN CONSIDERATIONS AND DESIGN PROCESS

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Space architecture is a newly emerging field with the focus of designing human habitats for out of the boundaries of Earth. Due to the extremity of the environmental conditions in Space, the architectural product defines the whole accessible environment of the user. In addition, Space habitats are high-risk and high-cost projects, addressing rather unexplored issues. As a result, unquestioned preconceptions or assumptions are needed to be avoided. This situation requires comprehensive research on human – environment interaction. Furthermore, the complexity of the design problem necessitates contribution from various disciplinary fields, calling for interdisciplinary design approaches. It might be argued that hitherto realized designs of Space habitats are under the influence of excessive technical and cost constraints, and being formed by engineering-dominated design approaches. Whereas the inclusion of the architects to the spacecraft design had been to provide an environment to support human well-being, the research area of the field has been expanded since. This thesis is an inquiry of Space architecture through its design considerations and design process, hoping to find potential reflections both on architecture and on Space architecture, in means of design approaches and understanding of human – environment interaction.

Keywords: Extreme environments design, interdisciplinary design, space architecture, human factors and habitability.

ÖZ

UZAY MİMARLIĞI ÜZERİNE BİR ARAŞTIRMA: TASARIM KRİTERLERİ VE TASARIM SÜRECİ

Yeğen, Ece
Yüksek Lisans, Mimarlık
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Uzay mimarlığı, insanın uzay ortamında yaşayabileceği mekanların tasarımıyla ilgilenen ve yeni oluşmakta olan bir alandır. Uzayda mimari ürün, çevresel koşulların ekstremliği dolayısıyla kullanıcının ulaşılabilir bütün ortamını tanımlar. Uzay habitatları, yüksek riskli ve yüksek maliyetli projelerdir ve görece keşfedilmemiş konularla ilişkilidir. Bu nedenle, tasarımlarında sorgulanmamış ön kabullerden kaçınılması gerekir. Bu durum, insan – çevre etkileşimi üzerine kapsamlı araştırmalar gerektirir. Tasarım probleminin karmaşıklığı pek çok alanın katkısını zorunlu kılar. Bu katkının sağlanmasının interdisipliner tasarım yaklaşımlarına bağlı olduğu düşünülebilir. Şu ana kadar uygulanmış uzay habitatı tasarımlarının teknik ve maliyet nedenli kısıtlamalardan fazlaca etkilendiği ve mühendislik yaklaşımlarıyla çözüldüğü iddia edilebilir. Mimarın uzay aracı tasarımlarına dahil olması insanın çevresiyle ilişkisinin fiziksel ve ruhsal sağlığı için yeterli ölçüde sağlanabilmesi için olmuş; ancak alan ortaya çıkışından bu zamana araştırma alanları genişlemiştir. Bu tez, hem mimarlık hem uzay mimarlığı alanlarına potansiyel yansımaları arayışında, tasarım kriterleri ve tasarım süreçleri üzerinden bir uzay mimarlığı araştırmasıdır.

Anahtar Kelimeler: Ekstrem çevre tasarımı, interdisipliner tasarım, uzay mimarlığı, insan faktörleri ve yaşanılabilirlik.

to my brother

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INTRODUCTION

1.1. Premise

> Fifty thousand generations ago, Homo sapiens appeared. In just the last 1 per cent of our time on Earth, we began making architecture to tame harsh environments and express physical, psychological, sociological and aspirational needs. Now, in just the final hundredth of 1 per cent of our time, we have started pressing into places utterly alien to our origins and our being: the Arctic, air, undersea and Space.[1]

> The Earth is the cradle of humanity, but one cannot remain in the cradle forever.[2]

Modern humans have been on Earth for 200,000 years, protecting themselves from nature, creating and expanding their habitat by means of architecture since then. In *Global History of Architecture,* Ching et al. state that architecture, like civilization itself, was born in humans' prehistory, and the architectural products were by no means uniform, considering spatial organization, structural arrangement, material use, and design approach.[3] Since then, many changes and evolutions in human knowledge and understanding have occurred, affecting architecture.

In particular, after the 18th century, increasing development and resulting accumulation of knowledge unfolded two interrelated consequences. First, as Chris Welch states, it became impossible for one a single individual to comprehend "total

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[1] Brent Sherwood, "What next for Human Spaceflight?," *Architectural Design* 84, no. 6 (2014): 16–19.

[2] Tsiolkovsky, 1911. Source: "Konstantin E. Tsiolkovsky," accessed November 27, 2019, https://www.nasa.gov/audience/foreducators/rocketry/home/konstantin-tsiolkovsky.html.

[3] Francis D. K. Ching, Mark Jarzombeg, and Vikramaditya Prakash, *A Global History of Architecture*, 2nd ed. (Hoboken, New Jersey: John Wiley & Sons, Inc., 2011), 1.

knowledge," and individuals started to focus on subsets of it.[4] Second, communities and organizations were formed by individuals with common interests, with the aim of organizing, sharing, and developing the "subset of knowledge" of their focus.[5] This focus was turned more inwards than outwards, to Welch. Likewise, Jack Zunz claims that the knowledge base continued to widen within these communities, but not in harmony with, or for that matter communicating with the others.[6] These discipline-based communities, while increasing in number, narrowed in scope.[7] As one of the results of this discrimination, Antoine Picon argues that architecture has drifted away from science and technology after the 18th century.[8] The effects of disciplinary specialization also become apparent in more fundamental levels. Bryan Lawson's experiments, followed by many supporting studies, suggested that the disciplinary fields of individuals affect their cognitive style as well.[9]

Despite the separation that appeared between disciplines and their members, the requirements of architectural design and production remained the same,[10] and became distributed to multiple disciplines. While the meaning of "design" is read differently among the disciplines,[11] the resulting collaborative work might be interpreted as "multidisciplinary," rather than "interdisciplinary." In other words, the disciplines executed their definition of responsibilities in separate processes and could only be

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[4] Sandra Häuplik-Meusburger and Olga Bannova, Space Architecture Education for Engineers and Architects, Space and Society (Cham: Springer International Publishing, 2016), 6,

[5] Jack Zunz, "Foreword," in *The Collaborators: Interactions in the Architectural Design Process* (London: Routledge, 2013); Häuplik-Meusburger and Bannova, *Space Architecture Education for Engineers and Architects*, 6.

[6] Zunz, "Foreword."

[7] Britain the Institution of Civil Engineers was founded in 1818, including architects; and followed by Royal Institute of British Architects in 1834, The Institution of Mechanical Engineers in 1847, The Institution of Electrical Engineers in 1871... Zunz.

[8] Antoine Picon, "Architecture, Science and Technology," in *The Architecture of Science*, ed. Peter Galison and Emily Thompson (Cambridge, 1999).

[9] Bryan Lawson, *How Designers Think*, First edit (Architectural Press, 1980).

[10] These requirements can be interpreted both as "utilitas," "fermitas," "venustas;" and all activities from design-making to the realization of the project including the basis of knowledge. In this sense, throughout this thesis, "architecture" does not refer to the design process and design products of "architects," but rather more inclusive, without discriminating any disciplines that are/might become related to architecture.

[11] Lawson, *How Designers Think*; Nigel Cross, "Designerly Ways of Knowing," *Design Studies* 3, no. 4 (October 1982): 221–27, https://doi.org/10.1016/0142-694X(82)90040-0.

superficially integrated with each other. Such design approaches might be argued to prove Buckminster Fuller right on his view that specialization precludes comprehensive thinking.[12]

In addition, technological improvements led the increase in construction speeds, eventually leading to a decrease in the time allocated for the design process. Arguably, the increasing speed of architectural production, combined with the ineffective multidisciplinary collaborations, constitutes a reason for not rethinking already approved design assumptions and approaches, and rather progressing with long-unquestioned preconceptions regarding common practice in architecture.

In the present day, the accumulation of knowledge and the resulting technological advances are "reshaping [human] activity and its meaning,"[13] thus invalidating some of the rigid preconceptions. Furthermore, these advances are expected to increase with accelerating pace,[14] while continuously changing and expanding humans' understanding about themselves and their environment. There reveals a world that can be comprehended with neither narrow disciplinary, nor superficial multidisciplinary understandings and approaches.[15] From this point of view, the need for blurring the lines in between disciplines appears in order to explore, realize and enhance the hitherto and the future potentials. Zunz states that the "need for collaboration of all of the designers who create the world around us, and the integration of all the complex issues which go with our ever widening knowledge base, while obvious, still presents a formidable challenge."[16] This challenge is already accepted in architecture, with prominent examples from collaborations of architecture with computation, biology, and environmental sciences. Yet, its reflections on common practice might be argued to be insignificant if underlying potentials are to be considered. Being one of the

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[12] Richard Buckminster Fuller, "Operating Manual For Spaceship Earth," 1969.

[13] Langdon Winner, *The Whale and the Reactor: A Search for Limits in an Age of High Technology* (Chicago: The University of Chicago Press, 1989), 6.

[14] Ray Kurzweil, *The Singularity Is Near: When Humans Transcend Biology* (New York, NY: Penguin, 2005), chap. 2.

[15] Häuplik-Meusburger and Bannova, *Space Architecture Education for Engineers and Architects*, 7.

[16] Zunz, "Foreword."

architects in between disciplines, Rachel Armstrong says: “If we can unleash our imaginations, then we’ll begin to see the relationships and overlaps between different disciplines. We need audacious ideas that will give us optimism, so we can reclaim the 21st century as the age of impossible thinking.”[17] Welch emphasizes that interdisciplinarity should be transformational and change the disciplines, not only cross the borders between them while being in search of new ways of approaching problems and new forms of knowledge. He believes that “interdisciplinary disciplines” is the demonstration of such integration, one of which is the Space[18] architecture.[19]

1.2. Research Motivation

Space exploration has already affected the lives and understandings of humans on many levels. After the first photo of Earth taken from Space in 1946, it has been followed by many including Earthrise in 1968, the Blue Marble in 1972, the Pale Blue Dot in 1990 (Figure 1.1)... It is commonly believed that those photos have changed humans’ perception of their place in Space, while enhancing environmental awareness.[20] In 1969, Buckminster Fuller introduced Earth as a Spaceship, recognizing human beings as travelers on that Spaceship, accounted for their responsibilities to keep it functioning. The photo taken from more than 6,4 billion kilometers by Voyager 1 of Earth, inspired scientist Carl Sagan’s 1994 book *Pale Blue Dot: A Vision of the Human Future in Space*, emphasizing both the insignificance and significance of humankind “on a mote of dust suspended in a sunbeam.“[21] Likewise,

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[17] Rachel Armstrong, ed., *Star Ark* (Cham: Springer International Publishing, 2017), 447, https://doi.org/10.1007/978-3-319-31042-8.

[18] “Space,” being a synonymous word, is capitalized to distinguish its meaning. Capitalized version refers to what is commonly addressed as “outer space.”

[19] Häuplik-Meusburger and Bannova, *Space Architecture Education for Engineers and Architects*, 7.

[20] Andreas Vogler, “The Universal House – An Outlook to Space-Age Housing,” in *Concept House: Towards Customised Industrial Housing*, ed. Mick Eekhout, 2005, 77.

[21] “Voyager 1’s Pale Blue Dot,” n.d., https://solarsystem.nasa.gov/resources/536/voyager-1s-pale-blue-dot/; Carl Sagan, *Pale Blue Dot: A Vision of the Human Future in Space* (New York: Random House, 1994).

getting out of the boundaries of Earth, and even walking on the Moon have been appreciated without distinctions among people over the world. “The last man on the Moon” stated: “We went to explore the Moon, and in fact discovered the Earth.”[22] On the other hand, transfers in between Earth and Space technologies, which generally referred to as spin-in and spin-off, provided a considerable amount of practical applications, some of which are changing the everyday life on Earth. “Not only do certain technologies used on Earth owe their origins to developments in the space industry . . ., but also the whole of the space industry is ultimately conditioned by terrestrial concerns. Space, as such, becomes a mirror that reflects human concerns on Earth . . .”[23]

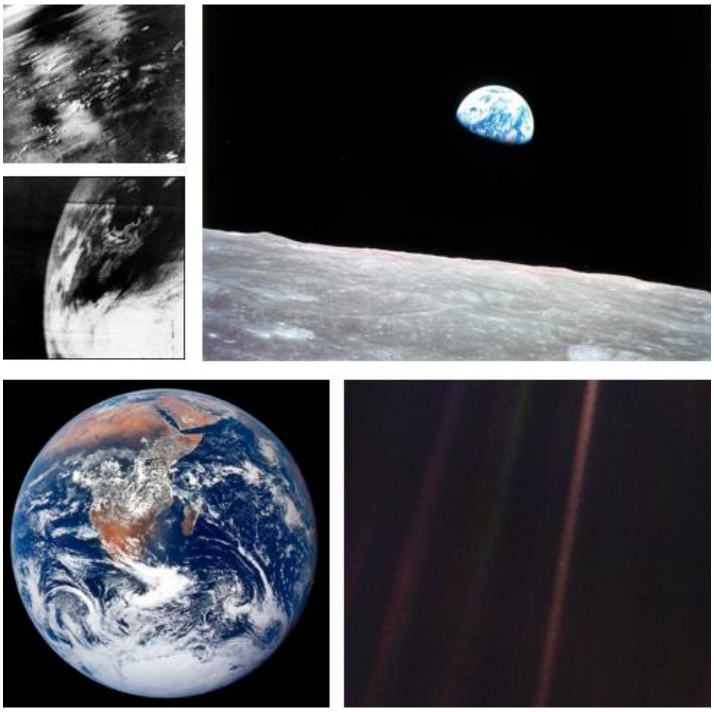

Figure 1.1. Photographs of Earth from Space: First photograph, first TV broadcast, Earthrise in 1968, the Blue Marble in 1972, the Pale Blue Dot in 1990.

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[22] Eugene Cernan, Apollo 17 Astronaut. *Spinoff*, 2009, https://spinoff.nasa.gov/Spinoff2009/pdf/spinoff2009.pdf.

[23] Neil Leach, “Space Architecture: The New Frontier for Design Research,” *Architectural Design* 84, no. 6 (November 12, 2014): 15, https://doi.org/10.1002/ad.1826.

This thesis takes its initial motivation from anticipated potential reflections of studies on Space habitation on architecture. Architecture, in this sense, refers to both terrestrial and Space applications. This motivation is driven by some key characteristics of designing for Space habitation, which might be argued to carry the potential of stimulating the questioning of human – environment interaction in the definition of the design problem, and the design methodologies for solving it. Space constructions, especially of habitat projects that are to keep humans alive in Space, are high-risk projects which require high amounts of investments. In Space, the induced environment becomes what human life depends on due to the extremity of the outer environment. The characteristics of this habitat, which are limited by the technical constraints, may become challenging on human psychology. Preconceived knowledge on human – environment interaction in such extreme conditions is limited, and assumptions on the issue cannot be relied on, as any misconception may lead to hazardous results. Likewise, the trial-error method becomes unfeasible. As a result, the need for comprehensive research examining all aspects of human needs and human – environment interaction appears for the design of Space habitats. On the other hand, high-risk, high-cost, and rather unexplored issues challenge the engineering aspects of the projects, requiring extensive research and evaluation on those aspects as well. Consequently, the period from the determination of the goal to the realization of the design generally extends over decades, while increasing the time allocated for the design process. The complexity of the design problem calls for interdisciplinary and research-based design approaches.

> Designing for Space, and specifically microgravity conditions, extends the area of design research outside of the common rules and consolidate methodologies that we use to consider and apply in a design process. Looking through the transformative lens of Space, we are freed from the conventional

> references and potentially advantaged by different points of view and new scenarios. . .[24]

Space architect Constance Adams, defines architecture as a field that involves the balancing of conflicting tendencies to effect harmony, and at its center, the human environment; and the job of the architect to track complex, nonrelated systems and directing them towards a unified goal.[25] Space architect Brent Sherwood specifies the essence of architecture as the act and product of grasping and manipulating a complex design problem characterized by thousands of parts, mutually conflicting requirements, diverse specialties, and the willful creation of order out of chaos.[26] The emphasis on human-centered design and the interdisciplinarity seems clear in the field. Furthermore, Ondrej Doule argues: "If we place architecture in an unfamiliar extreme environment, we will immediately see what system design aspects are key."[27]

The problem definition of Space habitat design is associated with many subjects, one of which is the human – environment interaction. To be able to solve the complex design problem of Space habitation, there is a need for contribution of many disciplines. This collaborative design process, arguably, can be best achieved by blurring the lines in between the disciplines to let a holistic understanding both for problem definition and for problem solving. This thesis, with the aim of gaining better understanding on human – environment interaction and exploring potential insights on methods and means of interdisciplinary collaboration, represents an inquiry on the field of Space architecture.

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[24] Annalisa Dominoni, Benedetto Quaquaro, and Susan Fairburn, "Space4Inspiration: Survival Lab. Designing Countermeasures for Natural Disasters," *The Design Journal* 20 (July 28, 2017), https://doi.org/10.1080/14606925.2017.1352710.

[25] Constance Adams, "Space Architecture: Building the Future," in *Washington University Lecture*, 1999.

[26] Scott A. Howe and Brent Sherwood, eds., *Out of This World: The New Field of Space Architecture* (American Institute of Aeronautics and Astronautics, 2009), 3.

[27] "Ground Control: Space Architecture as Defined by Variable Gravity," *Architectural Design* 84, no. 6 (2014): 90–95, https://doi.org/https://doi.org/10.1002/ad.1838.

1.3. Research Questions

This thesis addresses the main questions of:

- *What are the design approaches that can respond to the complex design problem of Space habitation?*

In order to respond to this main question, the sub-questions are constructed as:

- Which considerations appear in the definition of the design problem of Space habitats?
- What are the factors affecting the design process of Space architecture?
- What are the means and consequences of a holistic design approach in the designing of Space habitation?

1.4. Research Methodology

To be able to answer the above questions, the need appears to understand the design consideration and the design process of Space architecture. Thus, the thesis firstly takes an exploratory approach to examine the field. The thematic literature review orients to the specific aims of the thesis. The field is studied through the design considerations and design process. Design considerations are addressed as the issues that are directly related to the problem definition of Space habitation. Space habitat is taken as the interface of the interaction between human and environment, and the issues that are needed to be taken into consideration in the design of the habitat are evaluated in that context. Design process is addressed as means and methods used for the solving of the design problem, which eventually becoming a part of the design considerations in the field. The key issues affecting Space habitat designs regarding the process are presented. The findings are outlined and discussed as a result of this exploration. For this chapter, sources of information include:

- proceedings of the course "space4inspiraction,"[28]
- technical documents and reports,
- books written about the realized designs,
- oral histories of people with contribution to the designs,
- oral histories, logs, journals etc. of the users,
- biographies written by the users,
- existing interviews, online question-and-answer crowdsourced interviews with the users, explanatory videos presented by the users,
- books, articles, and research papers by Space architects, psychologists...

Following the exploration of the field through literature, holistic design approaches within the field are searched for. The intention is to find the means, methods, and potentials of designing for Space habitation with a holistic approach. In this context, the design considerations and design process of SEArch+ in their proposals for NASA 3D-Printed Habitat Challenge are examined by the case study method. Case study method can be used in order to gain insights from existing or new concepts and may allow retaining holistic and meaningful characteristics of them.[29] The method can be used in illuminating a set of decisions: "why they were taken, how they were implemented, and with what result."[32] Therefore, the case study method is regarded suitable for the purposes of this study. Further information about the research methodology of the case study can be gathered from Chapter 2. The data sources of this chapter are:

- competition rules, webinars, competition results; presentations of competitor teams that are reached through the websites of NASA and Bradley University,
- research papers on the proposals by SEArch+, Clouds AO, and Apis Cor,

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[28] by Annalisa Dominoni and Benedetto Quaquaro, 2018 Spring, Politecnico di Milano.

[29] Robert K. Yin, *Qualitative Research from Start to Finish*, 2nd ed. (New York: The Guilford Press, 2016); Robert K. Yin, *Case Study Research: Design and Methods*, 4th ed. (Los Angeles, California: SAGE Publications, 2009).

[32] Schramm, 1971, in: Yin, *Case Study Research: Design and Methods*, 37.

- presentations about the proposals given by the team members in various organizations,
- and semi-constructed interviews with:
    - Monsi Roman, NASA Centennial Challenges Program Manager,
    - Melodie Yashar, co-founder of SEArch+,
    - Lance LeBlanc, an engineer in collaboration with SEArch+ in the challenge.

1.5. Limitations

There are two possible limitations to this study. First, the literature review mostly relies on English sources, while a fair amount of literature on spacecraft design is known to exist in Russian, among other languages. Second, the case study has been selected from an unrealized concept, which is lighter on its constraints when compared to the realized or to be realized Space habitat designs. However, data from a large scope are available through the English sources (including translations), which are assumed to be enough for addressing the key issues in Space architecture for the courses of this study. On the other hand, the lightness on the constraints of the case study is especially sought for the process-based constraints. The case study is assumed to be a well-representative of the design studies that the thesis is in search of, due to its qualities that are explained in detail within Chapter 2.

1.6. Chapter Outline

Chapter 2 represents a thematic literature review as an exploration of the field. The chapter starts with a brief history of Space architecture. Afterward the considerations and the process of Space habitat design are evaluated with the focus of human – environment interaction. A discussion is carried out regarding the evaluation of design considerations of Space habitat design, current conditions in the aerospace industry, and obstacles to holistic approaches in Space architecture.

Chapter 3 is constructed as a case study, which is selected as a well-representative of the design approaches the thesis is in search of. In that manner, design considerations and design process of the selected case study is examined. A discussion is carried out in regard to the study.

Chapter 4 is the conclusion of the study, arrived from the juxtaposition of previous findings and discussions.

CHAPTER 2

SPACE ARCHITECTURE

2.1. Brief History and Definition of the Field

In the early 1960s, humans started to inhabit Space even for brief durations. As the plans included human presence in Space for longer durations, the need appeared to include living modules in the spacecrafts. Designs have been developed to respond to the apparent need: two red boxes have been drawn in the plans.[33] Sergei Korolev, who is often referred to as the father of the Soviet Space program, was unsatisfied by those "designs."[34] He sought for improvement for the interiors in the spacecrafts to host people, which led to architect Galina Balashova's inclusion to the design studies of spacecrafts, in 1963.[35] She has carried on her contributions for several decades.[36]

In the late 1960s and early 1970s, on another continent, the studies were ongoing with the enthusiasm of providing human habitation in Space for longer durations, with Skylab Space Station. The outer shell of the habitat has already been decided: one of the propellant tanks of the launch vehicle.[37] At the near end of the studies regarding the design, George Mueller, the director of the Skylab Program Office, restated his concerns regarding the habitability of the Space station. The concerns have been disregarded by the future residents of the Space station and making further modifications in the design of the station have been avoided by the contractors.[38] Eventually, industrial designer Raymond Loewy has been called to consult on the

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[33] Adeline Seidel, "Interview with Galina Balashova: Only the Watercolors Burned to Nothing," 2015, https://www.stylepark.com/en/news/only-the-watercolors-burned-to-nothing.

[34] Seidel.

[35] D. J. Pangburn, "The Soviet Architect Who Drafted the Space Race," 2015, https://www.vice.com/.

[36] Pangburn.

[37] Belew Leland F. and Stuhlinger Ernst, *Skylab a Guidebook* (National Aeronautics and Space Administration, 1973).

[38] Ben Evans, *At Home in Space: The Late Seventies into the Eighties* (Springer, 2012), 129.

interior design of the habitat. Some suggestions of Loewy have been received with strong objection mostly by the manufacturers of the hardware, amongst others.[39] Nonetheless, most of the proposals by Loewy's firm have been implemented in design by inner support, especially by Mueller.[40] During the time of its inhabitance, Skylab has served as a "house" of which the residents have been constantly in an interaction, thus frequently commented on its design. In a letter from Mueller to Loewy, it says: "I do not believe that it would have been possible for the Skylab crews to have lived in relative comfort, excellent spirits and outstanding efficiency had it not been for your creative design, based on a deep understanding of human needs."[41]

The field of Space architecture is recently emerging; it has only been six decades since humans have crossed the boundaries of Earth, a few years less since architects started to take place in the design of habitats that are used to accomplish that goal, and not even two decades since Space architecture has been defined as a separate disciplinary field. Hence, the field is considered not fully developed yet.[43] Following the first International Space Architecture Symposium held in World Space Congress in 2002, according to the "Millennium Charter,"[44] the definition of Space architecture has been acknowledged as "the theory and practice of designing and building inhabited environments in outer space" with the motivation of "responding to the deep human drive to explore and occupy new places," and the mission statement followed as:

> Architecture organizes and integrates the creation and enrichment of built environments. Designing for space requires specialized knowledge of orbital mechanics, propulsion, weightlessness, hard vacuum, psychology of hermetic

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[39] W. David Compton and Charles D. Benson, *Living and Working in Space: A History of Skylab* (United States Government Printing, 1983), 130.

[40] David Hitt, Owen Garriott, and Joe Kerwin, *Homesteading Space* (UNP - Nebraska, 2008), https://doi.org/10.2307/j.ctt1dgn4kv.

[41] "Raymond Loewy / Biography," accessed November 27, 2019, https://www.raymondloewy.com/about/biography/.

[43] Kriss J. Kennedy, "The Vernacular of Space Architecture," *AIAA Space Architecture Symposium*, 2002.

[44] AIAA Space Architecture Technical Committee, "The Millennium Charter," in *2nd World Space Congress* (Houston, Texas: AIAA Space Architecture Technical Committee, 2002).

> environments, and other topics. Space Architecture has complementary relationships with diverse fields such as aerospace engineering, terrestrial architecture, transportation design, medicine, human factors, space science, law, and art.[45]

2.2. Design Considerations

The design considerations for a spacecraft include a vast majority of technical constraints besides others and historically have been solved within science and engineering disciplines. The need for architectural considerations has appeared after the humans started to inhabit those crafts.[46] Space Architecture may refer to immense design considerations, also including considerations arising regarding the design process.

> Humans in future long-duration spaceflight and exploration endeavors will be assigned vital roles in the system. Therefore human needs and requirements must be addressed in overall mission architecture and spacecraft design. Human factors need to be taken into account at every stage of the design process – considering people to be more than an 'element' of the system but its modifier and innovator.[47]

Whereas the considerations are shaped by the extremity of the environmental features and the resulting consequences to an extent, Galina Balashova, the first Space architect, states that "architecture always depends on the same rules, and it doesn't matter whether it's about a house or a spaceship."[48] Similarly, Melodie Yashar

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[45] Jan Osburg, Constance Adams, and Brent Sherwood, "A Mission Statement for Space Architecture" (Houston, Texas: SAE International, 2003), https://doi.org/10.4271/2003-01-2431.

[46] Elizabeth Song Lockard, *Human Migration to Space*, Springer Theses (Cham: Springer International Publishing, 2014), 5, https://doi.org/10.1007/978-3-319-05930-3.

[47] Häuplik-Meusburger and Bannova, *Space Architecture Education for Engineers and Architects*, 10.

[48] Seidel, "Interview with Galina Balashova: Only the Watercolors Burned to Nothing."

emphasizes that the architectural considerations remain the same regarding the human aspect, apart from the environmental conditions.[49]

This section addresses design considerations that could directly be associated with the requirements of the final design product. In that manner, extreme environment characteristics and environmental factors are examined focusing on their relevance to the human aspect.

2.2.1. Space as an Extreme Environment

> Whereas there is no general agreement on how to define an extreme environment, the term is commonly used for any setting that exhibits life conditions detrimental or fatal to higher organisms with respect to its physicochemical properties.[52]

It is commonly emphasized that extreme is a relative world; therefore the definitions of extreme environment vary.[54] Generally, with an anthropocentric view, environments with features that are beyond the optimal range for human survival or development are defined as extreme. The reference features of the environment include:[56]

- Temperature
- Radiation
- Pressure
- Atmospheric composition

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[49] Melodie Yashar, "Personal Interview," 2019.

[52] Volker Thiel, "Extreme Environments," in *Encyclopedia of Geobiology, Encyclopedia of Earth Sciences Series*, 2011, 362–66, https://doi.org/10.1007/978-1-4020-9212-1_87.

[54] Jonas Jonsson, "Microsystems Technology for Underwater Vehicle Applications" (Uppsala University, 2012), 14; Olga Bannova, "Extreme Environments: Design and Human Factors Considerations" (Chalmers University of Technology, 2014).

[56] Thiel, "Extreme Environments"; Felipe Gómez, "Extreme Environment," in *Encyclopedia of Astrobiology* (Berlin, Heidelberg: Springer Berlin Heidelberg, 2011), 570–72, https://doi.org/10.1007/978-3-642-11274-4_566.

- Gravity

Extremity or anomaly in one or more than one of the above features can lead an environment to be difficult or impossible to maintain survival without protection. Consequently, human dwellings are rare in such places. However, an environment to be extreme does not always constitute reason to avoid those places, with many examples in Earth history and present. Sherwood claims that the reasons for the development of the dwellings are: control of coveted sources, strategic military advantage, and the intersection of trade routes.[57] On Earth examples to dwellings in unexpected environments may include deserts, swamps, inaccessible mountains, polar regions... Due to sharing similar characteristics, some of those environments are being studied as analogues of Space environments. Furtherly, analogies between the inhabitance of the Antarctic and Space are being made, as for both, the development of human habitation starts with a few explorers dealing with very harsh conditions, and while the number of the inhabitants raise, relatively comfortable living conditions can be provided.[58] In a similar way, there are expectations of Space habitats to evolve into settlements, and even cities.[59] It should be noted that in that scale, living conditions might be considered to be in their most extreme form during the exploration phase. The common characteristics of living in extreme environments include:

- Hardship of reach
- Autonomy
- Isolation and confinement
- Lack of external stimuli
- Social monotony
- Lack of resources
- Hardship of evacuation in case of emergency

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[57] Brent Sherwood, “Orbital Cities: Design Organizational Principles for Earth Orbital Architecture” (University of Applied Arts Vienna Institute of Architecture, 2009).

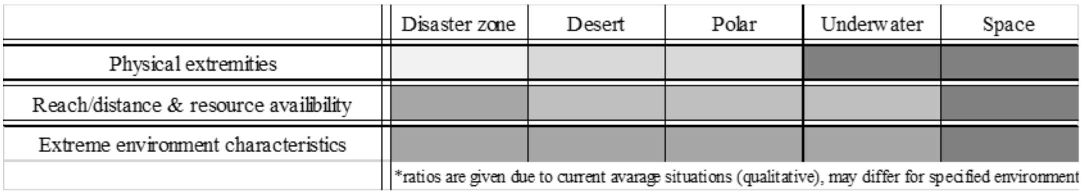
[58] Peter Suedfeld, “Mars: Anticipating the Next Great Exploration: Psychology, Culture and Camaraderie,” *Journal of Cosmology* 12, no. January 2010 (2010): 3723–40.

[59] Howe and Sherwood, *Out of This World: The New Field of Space Architecture*, chap. 13.

If the above-listed characteristics do not occur despite the physical extremities (e.g. cities in the desert), the environment might not be considered extreme. Likewise, if these characteristics are evident without the initial reasons, the environment might be classified as extreme; since in the field of architecture, the extremity of the environment does not solely refer to features affecting physiology but more inclusive. Bannova suggests that “an environment that poses special limitations and/or hardships for people to survive and maintain relative physical and psychological comfort” can be defined as extreme.[60] In that manner, in addition to Polar, desert, Space, underwater, subterranean etc. environments; war, disaster, and polluted environments may also be defined as extreme.[61]

Even though the definitions of extreme environment vary, design considerations regarding characteristics appear due to the environmental features that might be shared to a certain extent. This thesis will refer “extreme environments” as the environments in which human survival depends on protection by a habitat (i.e. “architecture”), and where it is either impossible or very challenging to survive in the exterior environment; making the architectural product the only possible environment of the user.

Table 2.1. *Comparison of different extreme environment examples*



	Disaster zone	Desert	Polar	Underwater	Space
Physical extremities	░	▒	▒	█	█
Reach/distance & resource availibility	▓	▒	▒	▒	█
Extreme environment characteristics	▓	▓	▓	▓	█
	*ratios are given due to current avarage situations (qualitative), may differ for specified environment				

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[60] Bannova, “Extreme Environments: Design and Human Factors Considerations.”

[61] Kürşad Özdemir, “Ekstrem Çevre Yapıları,” *Yapı* 08, no. 357 (2011).

"Space," may refer to various environments. The Earth surface may be included in the Space environments with a similar understanding to Fuller.[62] However, if Space is accepted to begin where the Earth atmosphere ends, it might be considered to pose characteristics of the extreme environment in the outlier (*Table 2.1*). Nevertheless, it still does not define a single location or one specific condition. Even if focused solely on the Space environments that might be reached by humans with the technology of the present day, environmental features, hardships and potentials vary drastically (*Table 2.2*). Sherwood describes the inner solar system as "truly a rich place, full of diverse types of destinations, conditions, and resources," and draws a conceptual map of the "human-accessible" solar system, illustrating site-specific challenges for possible locations (Figure 2.1).[63]

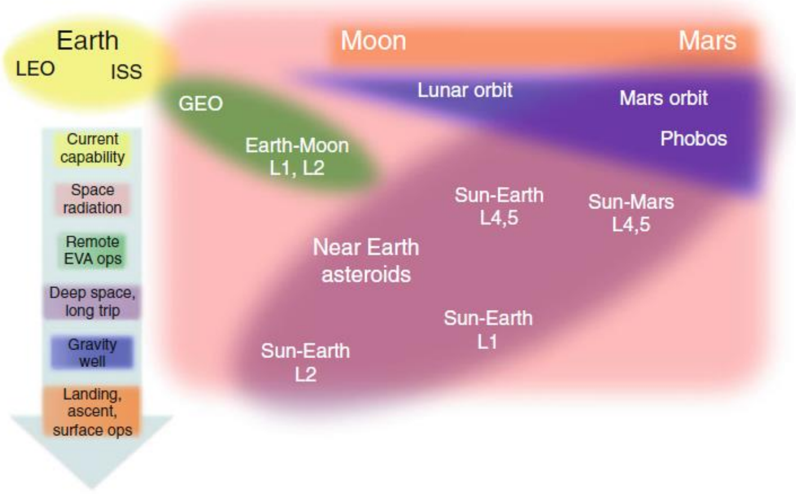

Figure 2.1. The conceptual map of the "human-accessible" solar system.[65]

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[62] Richard Buckminster Fuller, *Intuition* (New York: Doubleday, 1972).

[63] Häuplik-Meusburger and Bannova, *Space Architecture Education for Engineers and Architects*, chap. 2.6.

[65] Häuplik-Meusburger and Bannova, *Space Architecture Education for Engineers and Architects*, chap. 2.6.

The directions for Space Architecture might be considered to be closely related to the future plans of Space exploration. Global Exploration Roadmap (GER) is one of the most comprehensive roadmaps, with contributions of 14 agencies[67] participating in the International Space Exploration Coordination Group (ISECG).[68] The roadmap includes plans for Low Earth Orbit, Moon, Mars, and beyond.[69] It should be noted that GER is not a binding document,[71] and the discussions about Moon surface settlements are ongoing. Some argue that Moon, despite locally more harsh conditions there, given the relatively easy possibility of reach and advantages such as possible use as a jumping-off point for further missions by taking advantage of low gravity, should be used as a testbed before human Mars missions. One of the strongest advocates of moving forward towards Mars missions,[72] Apollo 11 astronaut Edwin "Buzz" Aldrin, has recently expressed that he had been persuaded by Stephen Hawking first to go back to Moon and colonize there, before human Mars missions.[73] On the other hand, others advocate that the limited funding should directly be directed to Mars missions, that even if in a perfect world it would be logical to first go to the Moon then to Mars, due to funding issues, it becomes more logical to focus all study and funding towards Mars missions.[74] As the roadmaps' direction, this thesis addresses LEO, beyond LEO (as the path to other celestial bodies), Moon and Mars surface.

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[67] ASI (Italy), CNES (France), CNSA (China), CSA (Canada), CSIRO (Australia), DLR (Germany), ESA (European Space Agency), ISRO (India), JAXA (Japan), KARI (Republic of Korea), NASA (United States of America), NSAU (Ukraine), Roscosmos (Russia), UAE Space Agency (United Arab Emirates), UKSA (United Kingdom).

[68] "The International Space Exploration Coordination Group," accessed November 27, 2019, https://www.globalspaceexploration.org/.

[69] ISECG, *The Global Exploration Roadmap*, 3rd ed. (Washington, DC: National Aeronautics and Space Administration, 2018).

[71] "The International Space Exploration Coordination Group."

[72] Buzz Aldrin and Leonard David, *Mission to Mars: My Vision for Space Exploration* (Washington, DC: National Geographic Society, 2013).

[73] Sarah Knapton, "Buzz Aldrin: Stephen Hawking Persuaded Me to Go Back to the Moon before Mars," 2019, https://www.telegraph.co.uk/science/2019/06/29/buzz-aldrin-stephen-hawking-persuaded-go-back-moon-mars/.

[74] Brian Cox and Robin Ince (Presenters), "The Infinite Monkey Cage" (UK: BBC Radio 4, 10.07.2017), podcast audio, https://www.bbc.co.uk/programmes/b08x8y1g.

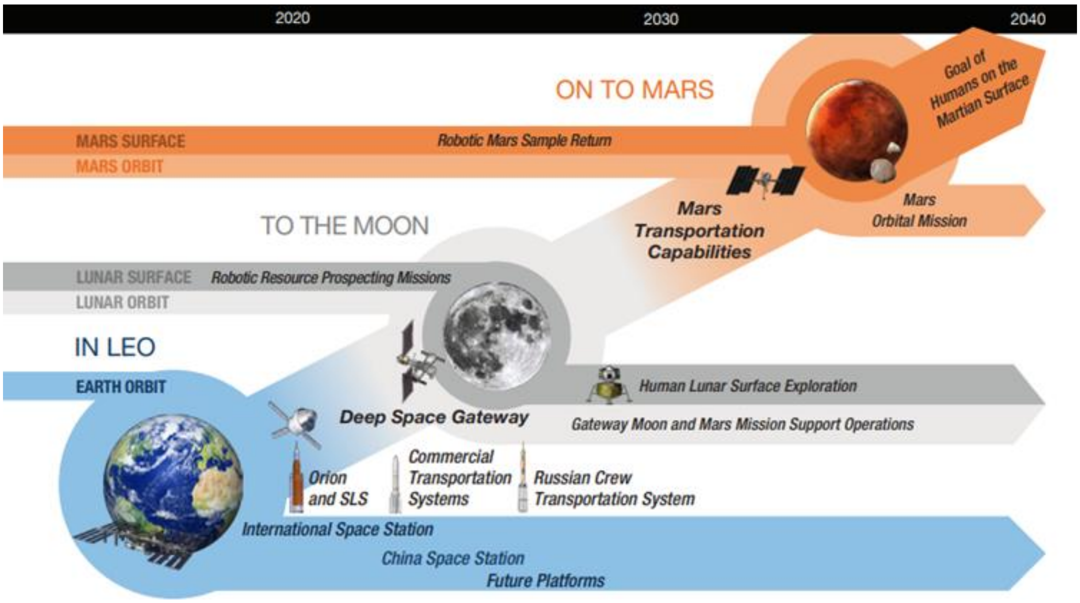

Figure 2.2. The Global Exploration Roadmap[75]

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[75] ISECG, *The Global Exploration Roadmap*.

Table 2.2. Selected Space environments' characteristics

	LEO	Beyond LEO (journey to Moon & Mars)
radiation	Exposure to Solar Particle Events and Galactic Cosmic Rays Protection by Earth's magnetic field, but exposure to trapped radiation	Exposure to Solar Particle Events and Galactic Cosmic Rays
temperature*	Max: 120 °C Min: -120 °C	Min: -270 °C
pressure	extremely low, practically vacuum	negligible, vacuum
atmospheric composition	-	-
gravity	microgravity	microgravity
possible threats	space debris & micrometeroids	micrometeroids
cycles	due to habitat orbit	-
reach/distance	200-2000 km to Earth surface	varies during journey
resources**	none resupply possible	none very limited or no resupply possible
autonomy**	Communication delay not apparent; Nearly continuous high-rate comminications with MCCs	Communication delay up to 20 minutes; Limited communications, drastic reduction of MCCs role
isolation & confinement**		
evacuation in case of emergency	return to Earth in 24 hours	depends on trajectory but unlikely
external stimuli	light cycle while orbiting Earth & visual stimuli (Earth gazing)	the view is mostly stable
social monotony**		
additional		

Table 2.2. Selected Space environments' characteristics (continued)

	Moon Surface	Mars Surface
radiation	Exposure to Solar Particle Events and Galactic Cosmic Rays Low protection by the mass, but exposure to secondary thermal b.	Exposure to Solar Particle Events and Galactic Cosmic Rays Half protection by the mass and the atmosphere
temperature*	Mean: -20 °C Max: 123 °C Min: -233 °C	Mean: -63 °C Max: 20 °C Min: -153 °C
pressure	extremely low, practically vacuum	0.004 to 009 atm (according to season)
atmospheric composition	Small amounts of He, Ar, and possibly Ne, NH3,CH4 and CO2	Major: CO2 - 95.32%; N2 - 2.7%; Ar - 1.6%; O2 - 0.13%; CO - 0.08% Minor (ppm): H2O - 210; NO - 100; Ne - 2.5; HDO - 0.85; Kr - 0.3; Xe - 0.08
gravity	1,62 m/s^2	3,69 m/s^2
possible threats	micrometeroids	micrometeroids
cycles	a day: 656 h a revolution around Earth: 28 Earth days a revolution around Sun: 365 Earth days	a day: 24 h 37 m a revolution around Sun: 687 Earth days
reach/distance	363 to 406 thousand km	54,6 to 401 million km
resources**	water, regolith limited or no resupply possible	water, regolith, atmospheric gases very limited or no resupply possible
autonomy**	Communication delay of a few seconds	Communication delays up to 20 minutes
isolation & confinement**		
evacuation in case of emergency	possible	abort mission almost impossible
external stimuli	light cycle while orbiting Earth & visual stimuli (Earth gazing)	light cycle, weather events
social monotony**		
additional		loss of visual connection to Earth

2.2.2. Human – Environment Interaction

> We live and become what we are only in and through our engagements with our many environments. All our perceptions, feelings, emotions, thoughts, valuations, and actions are thus consequent on our embodied transactions with our physical surroundings, our interpersonal relations, and our cultural institutions and practices. Our capacity to experience, make, and communicate (share) meaning is not just a result of the makeup of our brains and bodies, but depends equally on the ways our environments are structured.[89]

Inquiries on the interaction between human and environment regarding psychology (including social psychology) and physiology are being affected by their scope, approaches, and tools over time. Early studies on human that are still widely cited within the research of human – environment interaction include Gestalt theory on visual perception,[90] Maslow's pyramid on human needs,[91] Kurt Lewin's equation on human behavior[92]...

> No corpus of knowledge about human behavior and experience can be complete or fully meaningful without the inclusion of concepts and principles relevant to the influence of physical settings, regardless of how much or how little they contribute to the variance in such behavior and experience.[93]

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[89] Mark L. Johnson, "The Embodied Meaning of Architecture," in *Mind in Architecture: Neuroscience, Embodiment, and the Future of Design*, ed. Sarah Robinson and Juhani Pallasmaa, 2015, https://doi.org/10.7551/mitpress/10318.003.0004.

[90] founded by Wertheimer, Köhler and Koffka. Zeynep Mennan, "From Simple to Complex Configuration: Sustainability of Gestalt Principles of Visual Perception within the Complexity Paradigm," *Metu Journal of the Faculty of Architecture* 26, no. 2 (2009): 309–23.

[91] A. H. Maslow, "A Theory of Human Motivation," *Psychological Review* 50, no. 4 (1943): 370–96, https://doi.org/10.1037/h0054346.

[92] K. Lewin, "Defining the 'Field at a given Time.,'" *Psychological Review* 50, no. 3 (1943): 292–310, https://doi.org/10.1037/h0062738.

[93] Harold M. Proshansky, "Theoretical Issues in Environmental Psychology," *The School Review* 82, no. 4 (1974): 541–55.

As an “attempt to establish empirical and theoretical relationships between the behavior and experience of the person and the built environment,”[94] the interdisciplinary field of environmental psychology has been recognized primarily including psychology and architecture among other disciplines.[95] The scope of the field, which essentially addressed individuals’ experience with the environment during the first decades after its recognition,[96] has expanded to include contemporary subjects like sustainability, within a wider range of human surroundings like virtual environments.[97] However, according to Petrović et al. the strong collaboration between psychology and architecture, which had given rise to the field of environmental psychology has been faded in association with some studies challenging the architectural understandings of the time;[98] by either showing that stylistic differences were undistinguishable to the people outside of the profession,[99] or implying that people tend to retain their behavior regardless of the limitations imposed by space instead of changing their behavior to fit the space.[100]

On the other hand, Space psychologist Albert A. Harrison emphasizes that “[p]sychologists and architects are natural allies.”[101] Since the first human Space missions, studies focusing on human needs have been conducted to ensure human

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[94] Harold M. Proshansky, “Environmental Psychology and the Real World,” *American Psychologist* 31, no. 4 (1976): 303–10, https://doi.org/10.1037/0003-066X.31.4.303.

[95] Emina Petrović, Brenda Vale, and Bruno Marques, “On the Rise and Apparent Fall of Architectural Psychology in the 1960s, 1970s and Early 1980s,” in *Proceedings of the Society of Architectural Historians Australia and New Zealand*, ed. Hogben Paul and Judith O’Callaghan, vol. 32 (Sydney: Society of Architectural Historians, Australia and New Zeland, 2015), 480–87.

[96] Daniel Stokols, “The Paradox of Environmental Psychology,” *American Psychologist* 50, no. 10 (1995): 821–37.

[97] Stokols; “Journal of Environmental Psychology,” accessed November 27, 2019, https://www.journals.elsevier.com/journal-of-environmental-psychology.

[98] Petrović, Vale, and Marques, “On the Rise and Apparent Fall of Architectural Psychology in the 1960s, 1970s and Early 1980s.”

[99] Linda Groat, “Meaning in Post-Modern Architecture: An Examination Using the Multiple Sorting Task,” *Journal of Environmental Psychology*, 1982, https://doi.org/10.1016/S0272-4944(82)80002-9.

[100] Harold M. Proshansky, William H. Ittelson, and Leanne G. Rivlin, “Freedom of Choice and Behavior in a Physical Setting.,” in *Environment and the Social Sciences: Perspectives and Applications.* (Washington: American Psychological Association, n.d.), 29–43, https://doi.org/10.1037/10045-003.

[101] Albert A. Harrison, “Humanizing Outer Space: Architecture, Habitability, and Behavioral Health,” *Acta Astronautica* 66, no. 5–6 (2010): 890–96, https://doi.org/10.1016/j.actaastro.2009.09.008.

well-being. While most of the initial research focused solely on the impact of environmental factors such as noise stimulus, volume requirements or supplies such as food, the following research gave attention to interpersonal issues as well.[102] Further studies have included both the human-related issues and the environmental factors, and instead of examining those issues separately, developed an understanding to study the relationship in between.[103] It might be accepted that the research of environmental psychology and the research for Space habitation support each other. However, architect and researcher Elizabeth Song Lockard asserts that the research regarding spacecraft design has only recently started to address the issues that fall within the realm of environmental psychology.[104] Still, whether referred to as "environmental psychology" or "human factors" or "habitability," and whatsoever the extent of its scope, human – environment interaction can be claimed as one of the main research areas of Space architecture.

2.2.3. Human – Environment Interaction in Space

An extreme change of the environment is assumed to challenge and alter in the long term what human consists of together with the interventions to herself/himself and the environment she/he creates for her/his protection. The approach taken while making those interventions might be associated with objectives as Lockard addresses in four levels:[105]

- Level 1: Survival
- Level 2: Performance
- Level 3: Habitation
- Level 4: Adaptation

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[102] Marry M. Connors, Albert A. Harrison, and Faren R. Akins, *Living Aloft: Human Requirements for Extended Spaceflight* (Washington: NASA, 1985).

[103] Connors, Harrison, and Akins.

[104] Lockard, *Human Migration to Space*, 5.

[105] Lockard, *Human Migration to Space*.

If those levels are outlined briefly: survival refers to keeping human alive by supplying basic needs; performance refers to ensuring a level of comfort for human to let her/him operate more complex tasks; habitation refers to addressing human well-being with less immediate but equally indispensable aspects such as psychological issues; and adaptation refers to promoting evolutional adaptation to achieve engagement with the environment rather than only sheltering from it, and it exceeds lifespan of an individual.[106]

Survival and performance considerations are being studied and developed since the beginning of human Space missions, whereas adaptation level is long to come but started to be discussed even if limitedly.[107] Habitation is the question of today and where most studies of Space architecture, among many other human-centered disciplines like physiology and psychology, focus on. This focus is mostly addressed under the topics “human factors” and “habitability.” Human factors is generally defined to include all conditions that affect the performance of an individual.[108] The term ergonomics may be used as an equivalent of human factors;[109] however, NASA defines them separately:

> Human Factors relates to the consideration of the user in the design of equipment, operations, and systems with the goal of enhancing functional effectiveness while maintaining or enhancing human well-being (e.g. physical and mental health, safety, and satisfaction) in the process. Ergonomics focuses on the effect equipment, operations, and systems have on the user. This includes the physiological responses of the user to physically demanding tasks and environmental stressors such as vibration, heat, and noise.[110]

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[106] Lockard.

[107] See 2.2.4.

[108] Albert A. Harrison, *Spacefaring: The Human Dimension* (Berkeley; Los Angeles; London: University of California Press, 2001), https://doi.org/10.1525/j.ctt1ppdw2.

[109] Harrison, “Humanizing Outer Space: Architecture, Habitability, and Behavioral Health.”

[110] “International Space Station Flight Crew Integration Standard SSP 50005” (Houston, Texas, 2006).

The habitability concerns are mostly related to the induced environment, "habitat," and include conditions to affect human well-being within this environment.

> Habitability is defined as the quality of life in an environment. It is a general term which denotes a level of perceived environmental acceptability. The term includes quality standards to support the crew's health and well-being during the 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 condition. The extended level of habitability is introduced to take care of the long-term condition of the on-orbit stay time and supply not only the individuals' physical health but also the mental/psychological health.[111]

Both terms have been expanded in their scope since the beginning of human spaceflight. This expansion might be associated with the increasing mission durations and expansion of the activities or tasks that are expected to be performed in the spacecrafts. Whereas the "[e]arly spacecraft had been designed to be operated and not lived in,"[112] challenges increase with expanding objectives and resulting requirements. In spite of the widely acknowledged definitions of human factors and habitability in the present day, researchers commonly believe that the terms are still narrowly defined. Mohanty, Jørgensen, and Nyström state that these issues are addressed with an engineering bias, thus unlike the quantitative factors, qualitative factors do not get the attention they deserve.[113] They claim that the "gray zone" where those factors overlap should be recognized.[114] Following Philip R. Harris,[115] Harrison includes psychological, sociological, political, economic, and cultural variables to human

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[111] "International Space Station Flight Crew Integration Standard SSP 50005."

[112] Compton and Benson, *Living and Working in Space: A History of Skylab*, 130.

[113] Susmita Mohanty, Jesper Jørgensen, and Maria Nyström, "Psychological Factors Associated with Habitat Design for Planetary Mission Simulators," *American Institute of Aeronautics and Astronautics* 3, no. September (2006).

[114] Mohanty, Jørgensen, and Nyström.

[115] Philip R. Harris, *Living and Working in Space: Human Behavior, Culture, and Organization*, 2nd ed. (Chichester, UK: Wiley-Praxis, 1996).

factors considerations and defines the term by encompassing people's emotions, attitudes, personalities, and interpersonal behaviors.[116] In this sense, the research of human factors expands its focus from performance-related considerations to include aspects of life itself. Likewise, habitability concerns seem to include increasing qualitative requirements in addition to quantitative ones, to lead a more comprehensive understanding. Not only the concerns, but the research approaches diversify. For example, Peter Suedfeld suggests that the extremity of the environment depends on the individuals' perception.[117] In that manner, the experience, as the interpretation of humans of their interactions with their environment, rather than the environment itself should be studied:

> The relations between environmental features and behavior must be studied in terms of interaction, not main, effects. As several investigators have pointed out, the environment has no direct impact on human beings. Rather, it is filtered through their psychological and physiological information processing systems. In consequence, the crucial determinant of the response is not an environment, but an experience, this being defined as the environment and its meaning to the individual. Researchers should, therefore, adopt some new ways to gain an understanding of environmental impact on people. The most obvious one is to measure not only how individuals behave in the environment but also how they perceive it. [119]

There might appear many possible reflections of Suedfeld's understanding to architecture. One example might be given as researcher and architect Sandra Häuplik-Meusburger's book Architecture for Astronauts,[121] in which she develops an approach of examining habitability of spacecrafts by the activities of the users and the

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[116] Harrison, *Spacefaring: The Human Dimension*, chap. 2.

[117] Albert A. Harrison, Yvonne A. Clearwater, and Christopher P. McKay, eds., *From Antarctica to Outer Space: Life in Isolation and Confinement* (New York, NY: Springer-Verlag, 1991), 134–46.

[119] Harrison, Clearwater, and McKay, *From Antarctica to Outer Space: Life in Isolation and Confinement*, 134–46.

[121] Sandra Häuplik-Meusburger, *Architecture for Astronauts* (Vienna: Springer Vienna, 2011), https://doi.org/10.1007/978-3-7091-0667-9.

architectural layout. Notwithstanding, in a broader sense, defining spatial habitability criteria regarding the user's perception might be another approach. These criteria may include many aspects, some of which are discussed in further sections.

2.2.3.1. Environmental Factors That Might Affect Human

In order to illustrate the means of living and experiencing Space, some features of the environment that have/might have effects on human are being explored in the following topics. As indicated earlier, there are various approaches to investigate interrelations between human and environment, and the literature includes studies that suggest that the qualitative issues regarding human aspect might even overcome the issues regarding environmental conditions in the definition of human – environment interaction. However, understanding the conditions of the environment is still meaningful. Besides, classifying topics in regard to environmental conditions provides a premise for the case study, and allows the inclusion of the expected alterations in each feature of various environments that roadmaps indicate.

Gravity

Gravity is a consequence of the curvature of space-time, according to Einstein's Theory of General Relativity. What is experienced as gravity, on the other hand, is the gravitational acceleration.[122] On Earth surface, this acceleration is approximately 9,81 m^2/s and referred to as 1 G. In a spacecraft on orbit or on a journey towards another celestial body, eliminated by the trajectorial motion of the spacecraft; this acceleration is not experienced. This condition is referred as microgravity. On the other hand, on the surface of the celestial bodies other than Earth, this measure changes due to the mass and the radius of the body (distance from the center of the mass) and referred to

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[122] Theodore W. Hall, "Artificial Gravity and the Architecture of Orbital Habitats," *Journal of the British Interplanetary Society* 52, no. 7/8 (1999): 290–300.

as partial or reduced gravity (for smaller celestial bodies in respect to Earth). Whereas on Moon surface, this measure is approximately 0,16 G,[123] on the Mars surface, it is approximately 0,38 G.[124]

Almost all physical extremities of the Space environment, such as temperature, pressure, atmospheric composition, are eliminated for human habitation; but artificial gravity is a controversial subject, both in the topics of whether being essential or not, and its effects on human. To start with, as microgravity conditions cannot be simulated on Earth longer than 30 seconds (with parabolic flights), it has been a preferred condition for scientific purposes.[125] After the first human missions by which it is understood that humans can survive weightlessness, following missions proved that humans can stay for longer durations, and even "live" in weightless environments.[126] When added the cost requirements of a habitat with artificial gravity, there might appear enough reason to understand why an artificial gravity Space habitat concept has not been realized, in spite of the fact that being conceptualized long before the first human Space travel.[127] Therefore, gravity remains the most radical environmental change that is experienced in Space. It should be noted that for longer durations that are being planned, a considerable amount of studies claim that artificial gravity would be needed.[128]

On Earth, regardless of the time, place, and culture, gravity is experienced uniformly.[130] It is one of the main reasons of human body evolved the way it is. Among others, the musculoskeletal system, circulatory system, and vestibular system show

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[123] "Moon Facts," accessed November 27, 2019, https://www.esa.int/Science_Exploration/.

[124] "Mars Exploration Program," accessed November 27, 2019, https://mars.nasa.gov/.

[125] Marc M. Cohen, "Human Factors in Space Station Architecture 1: Space Station Program Implications for Human Factors Research," in *NASA Technical Memorandum 86702* (Washington, 1985).

[126] Hitt, Garriott, and Kerwin, *Homesteading Space*.

[127] Noordung Space Station concept in 1929 might be the earliest proposal of a Space habitat with artificial gravity. There had been many following concepts since then. Hermann Noordung, *The Problem of Space Travel: The Rocket Motor*, ed. Ernst Stuhlinger,]. D. Hunley, and Jennifer Garland (Washington, DC: NASA, 1995).

[128] Hall, "Artificial Gravity and the Architecture of Orbital Habitats."

[130] Häuplik-Meusburger and Bannova, *Space Architecture Education for Engineers and Architects*, chap. 4.5.

significant differences in weightless environments.[131] The alteration of gravity affects human on many levels, which are still being investigated.

Reduced gravity, such as on the Moon and Mars, has not yet experienced for long durations, whereas human reaction to microgravity up to year-long durations can be considered to be well observed (but not completely understood). The research within NASA suggests that:

> Microgravity significantly changes some human body lengths, circumferences, and the posture. Although it is not certain, this is likely to also be true in reduced gravity.[132]

Not being pulled together by gravity, the body elongates in differing measures up to individuals. Bones lose density over 1% per month by losing minerals, and without the constant need to respond to gravity, muscle mass, strength, and endurance decrease.[133] The circulatory system shows deconditioning. To provide a level of prevention to those, proper nutrition and exercise are being seen essential.[134] As a result, Space habitants of the present day spare a considerable amount of time for exercising, an average of a few hours a day.[135] In addition, the circulatory system, being evolved to pump blood stronger from feet to upper parts of the body, pumps more blood to upper body and face, causing a level of bloating towards the head and shrinking towards feet during weightlessness. One of the most visible effects may be having a "puffy face."[136] Having more blood pressure around kidneys may cause the feeling of thirst to be reduced; thus, to prevent dehydration, the fluid consummation needs to be tracked. Fluids shifting upwards to head may also cause vision problems by putting pressure on eyes. Similarly, nasal congestion is experienced, altering the

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[131] Annalisa Dominoni, *Industrial Design for Space* (Milano: Silvana Editoriale, 2002).

[132] "NASA-STD-3001 Volume 2" (Washington, DC, 2015), 18.

[133] *Human Integration Design Handbook* (Washington, DC: National Aeronautics and Space Administration, 2014).

[134] *Human Integration Design Handbook*.

[135] "Daily Life," accessed November 27, 2019, http://www.esa.int/Science_Exploration/.

[136] Dominoni, *Industrial Design for Space*.

sense of smell and taste.[137] There are also research indicating alteration on visual perception.[138]

As an immediate response to weightlessness, the body gains a relaxed characteristic neutral body posture, “the Vitruvian man of space” as Brand Griffin calls (Figure 2.3). Additionally, the sense of spatial orientation and balance is highly effected. Normally, in terrestrial conditions, those senses are maintained by overlapping multi-sensory information that is continually updated and cross-referenced.[139] The inputs are sensed through visual, vestibular, auditory, haptic (relevant to touch), and proprioceptive (perceiving the movement or position of the body) senses.[140] Vestibular system processing the input data depending on the position of the fluid in the inner ear, cannot normally perform in weightless conditions. Consequently, the sense of orientation and balance depend on the remaining senses. Space motion sickness, which may last a few days, is commonly observed in Space travelers both after arrival and in return.[141]

Some Earth-normal postures, such as sitting or bending down, is observed to be very uncomfortable due to putting pressure on stomach muscles.[142] All chairs that have been designed for Skylab had been demounted by the users, as being designed with the dimensions of a regular chair.[143] In the present day, inhabitants of ISS mostly maintain the desired position by handholds and restraints.

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[137] D. Williams et al., “Acclimation during Space Flight: Effects on Human Physiology,” *Canadian Medical Association Journal* 180, no. 13 (June 23, 2009): 1317–23, https://doi.org/10.1503/cmaj.090628.

[138] Nick Kanas and Dietrich Menzey, *Space Psychology and Psychiatry* (Dordrecht: Springer, 2008).

[139] Ben D. Lawson, Angus H. Rupert, and Braden J. McGrath, “The Neurovestibular Challenges of Astronauts and Balance Patients: Some Past Countermeasures and Two Alternative Approaches to Elicitation, Assessment and Mitigation,” *Frontiers in Systems Neuroscience* 10 (November 22, 2016), https://doi.org/10.3389/fnsys.2016.00096.

[140] *Human Integration Design Handbook*, chap. 5.3.

[141] Martina Heer and William H. Paloski, “Space Motion Sickness: Incidence, Etiology, and Countermeasures,” *Autonomic Neuroscience* 129, no. 1–2 (October 2006): 77–79, https://doi.org/10.1016/j.autneu.2006.07.014.

[142] Compton and Benson, *Living and Working in Space: A History of Skylab*, 307–10.

[143] Hitt, Garriott, and Kerwin, *Homesteading Space*, 124.

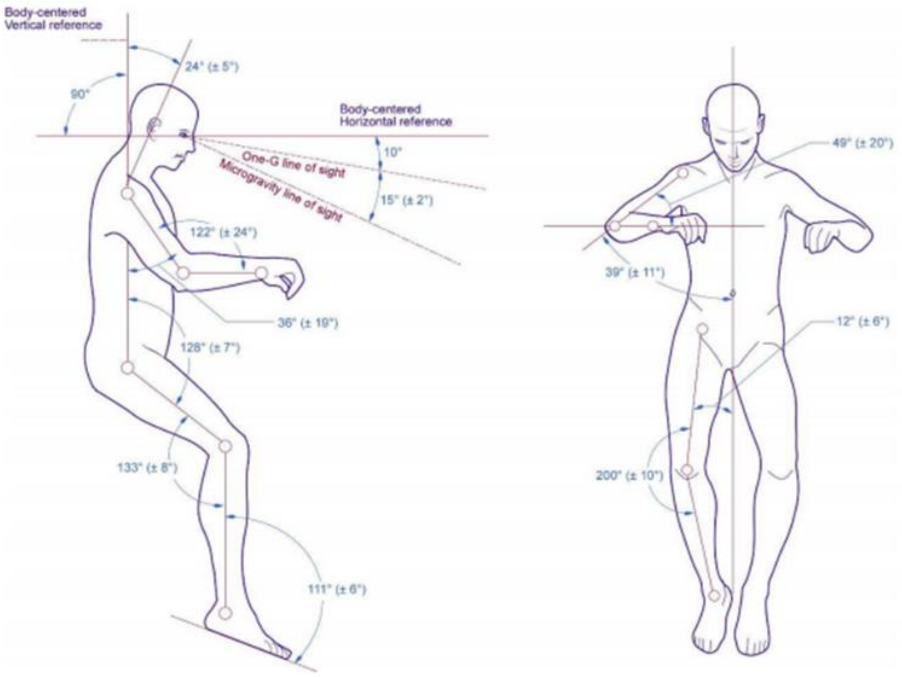

Figure 2.3. Neutral Body Posture (NBP)[144]

The gestures and movements of the users also eventually adapt to the weightless conditions. "Walking" becomes floating from one handhold to other, and "standing" or "sitting" becomes restraint attachment. The effects even become physically visible on the human body, for example, feet getting soft on the bottom and raw on top.[145] Even though the adaptation, or "gracefulness" of the movement as astronaut Jerry Linenger describes,[146] is achieved after differing durations for individuals; in the beginning, moving might pose a challenge for the Space visitors. Due to the lack of reference points and the lack of resistance by gravity, accurate estimation of necessary physical effort for certain operations might be difficult for the first days.[147]

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[144] *Human Integration Design Handbook*, 59.

[145] Chris Hadfield, "The Five Senses in Space: Touch" (Canadian Space Agency, 2013), https://youtu.be/MaYxZEara0I; Scott Kelly, "I Am Astronaut Scott Kelly, Currently Spending a Year in Space. AMA!," 2016, https://www.reddit.com/r/IAmA/.

[146] Jerry M. Linenger, *Letters From Mir* (New York: McGraw Hill, 2004).

[147] Dominoni, *Industrial Design for Space*, 48.

The body is almost always relaxed with the lack of the constant force to fight with. The situation, in addition to physiological response of the body (e.g. loss of bone and muscle mass), may also cause loss of perception of activity during the day. Scott Kelly mentions this condition making sleeping harder, as there is little or no difference in body position from work to sleep.[148] On the other hand, sleeping in microgravity is described differently by individuals. There are many Space visitors who mentioned sleeping weightless as extremely comfortable.

Additional issues occur related to microgravity. For example, as there is not an "up" for warm air to rise, the exhaled carbon dioxide can easily form a blob around the face.[149] To prevent this, especially during sleep and exercise, air movement near the body becomes necessary. In addition, as objects do not fall onto a surface but may float around, losing something becomes highly probable. Especially smaller objects are stated as hard to detect, as eyes tend to focus on a surface in the background, instead of focusing on an unknown point in the whole volume. Keeping track of everything becomes important due to the risk of harming equipment. Velcro is used to be able to have a level of control over the items, but wider use of it is avoided as it cannot be recycled, and tiny particles scattered out are lost.[150] As a consequence, housekeeping becomes one of the main issues.

After varying durations of adaptation process, Space habitants are able to adapt and engage with their habitat in weightless conditions. Chris Hadfield, during an interview while he was on ISS, says:

> I completely feel adapted. I feel like a Spaceling. It might sound weird; it is not a common word. But I do not feel like an Earthling. I can fly and float and turn upside-down. I do not need to touch the floor. It is a whole new way to be.

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[148] Jim Hoskinson, "The Late Show with Stephen Colbert" (USA, 2017), https://youtu.be/UwUxvzb8qm4.

[149] "NASA-STD-3001 Volume 2."

[150] Yvonne Clearwater, "A Human Place in Outer Space" (Standford University, 2010), https://youtu.be/nmVrQPjnX9c.

> At first it feels very strange . . . but then you become graceful and elegant. . . It is a wonderful way to be. . . and it is just the physical side of things.[151]

In fact, this adaptation becomes so perpetual that after adapting to microgravity, Space habitants need time to re-adapt gravity on return, not just on physical level but also perceptual and behavioral. Confusion may occur regarding their position relative to the ground in the lack of visual cues. Astronauts even report "forgetting" the existence of gravity on their return, making them leave objects on air, with an expectation of finding the fallen item hanging in the air. In videos of astronauts on their return, the change in their gestures can be seen clearly.

During Apollo missions, astronauts have experienced reduced gravity. The stepping rate had been less than Earth, and the walking or running observed to be 40% slower.[153] Additionally, the ability to change direction, stopping, or turning is stated to be reduced. [154] There may not be enough data to predict the effects of reduced gravity for longer terms. However, based on current data from astronauts that have been to the Moon surface and the data from users of Space stations might provide insight about longer exposure to reduced gravity. In that manner, it might be assumed that habitants of the Moon or Mars would be able to adjust their movements and gestures to their current conditions. Jerry Linenger, after spending months in Mir Space Station, writes: "The adaptability of the human being is remarkable."[155]

Radiation

Radiation, which can be described as energy in transit in the form of electromagnetic waves and high-speed particles, is categorized as non-ionizing and ionizing

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[151] Chris Hadfield, "Canadians Converse About Life in Space" (NASA, 2013), https://youtu.be/usRYa_dpPFU.

[153] Häuplik-Meusburger and Bannova, *Space Architecture Education for Engineers and Architects*, chap. 4.3.

[154] Häuplik-Meusburger and Bannova, chap. 4.3.

[155] Linenger, *Letters From Mir*.

radiation.[156] The first type is common in daily life, including visible light, microwaves, radio and television waves, whereas the latter is hazardous and what Space radiation primarily consists of.[157] NASA describes three naturally occurring sources of Space radiation: trapped radiation, galactic cosmic radiation (GCR), and solar particle events (SPEs).[158]

On Earth, atmosphere and magnetosphere provide efficient natural protection from ionizing radiation. And LEO is still in the cocoon of the magnetosphere, providing a level of protection. While additional shielding is implemented for protection from radiation on and in orbiting spacecrafts in LEO, the need for protection is expected to increase with longer duration missions to further distances. Thus, it becomes one of the main design considerations. Especially during increased SPE, additional temporary precautions might be needed. This kind of precaution could be addressed directly regarding the layout of the habitat by providing a volume with more shielding or by different approaches such as the PERSEO project by ESA, in which a protective vest is proposed.[159]

Research on how and how much the human body gets affected by radiation are ongoing, while the need for protection from ionizing radiation is agreed to be necessary. One of the immediate effects of ionizing radiation is seeing “flashes” even with eyes closed, as most space visitors mention. The amount of flashes and resulting discomfort (especially before sleeping) differs. Scott Kelly additionally mentions psychological discomfort caused by the realization of radiation passing through his body.[160]

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[156] “What Is Space Radiation,” accessed November 27, 2019, https://srag.jsc.nasa.gov/.
[157] “What Is Space Radiation.”
[158] “What Is Space Radiation.”
[159] Marco Vuolo et al., “PERSEO: Personal Radiation Shielding For Interplanetary Missions,” 2015.
[160] Hoskinson, “The Late Show with Stephen Colbert.”

Atmospheric Composition and Density

Space is considered as a perfect vacuum with only a few particles in a cubic meter. Whereas the Moon lacks an atmosphere, Mars contains an atmosphere consisting mainly of carbon dioxide and more than a hundred times less dense than Earth's. Evidently, a habitable volume's one of the essential criteria is creating a similar atmospheric composition and pressure. On Earth, atmospheric composition is approximately 21% oxygen and 78% nitrogen, and pressure is 1 atm at sea level, 0,33 atm on the highest land altitude (Mount Everest), whereas the highest human settlements are not under 0,53 atm. Space habitats until today have been pressurized for lowest 0,35 atm (Skylab),[162] and highest 1 atm (ISS).[163]

As the speed of sound is dependent on the density of the medium and smells spread within the air, the air pressure (therefore density) alters those features. In addition, as too much pressure inside an EVA suit makes movement harder (because of the ballooning effect inside the suit without adequate pressure to compensate from outside), the pressure and the atmospheric composition becomes different than the habitat.[164] The amount of difference determines the time pre-breathing time before wearing those suits (6 hours in ISS),[165] therefore, the minimum time to be spent to get out of the habitat.

Temperature

In Space, temperatures of objects vary due to how much radiant energy received. In LEO, this variance may become hundreds of degrees depending on whether the object faces the Sun, the Earth, each other, or deep Space.[166] On celestial bodies, atmosphere, distance to Sun, location on the body determines the temperature. Due to the lack of

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[162] Belew Leland F., ed., *Skylab, Our First Space Station* (NASA, n.d.).
[163] Alan Bartos, "Ask the Expert," accessed November 27, 2019, https://spaceflight.nasa.gov/.
[164] Emilio Della Sala, "Extravehicular Activities" (Politecnico di Milano, 2018).
[165] Sala.
[166] Howe and Sherwood, *Out of This World: The New Field of Space Architecture*, 26.

atmosphere, it is not possible to specify a temperature for the Moon surface. However, Mars is estimated to have -63 °C on average, with the lowest -140 °C and highest 30 °C.[167] These values are indicated as an average 14 °C for Earth, with the lowest -88 °C and highest 58 °C.[168] It should be noted that diurnal temperature variances on the Mars surface are greater compared to Earth.[169]

Light

Visible light (or light) refers to the part of the electromagnetic spectrum that can be perceived by the human eye, which is the wavelength range between 380 and 780 nm.[170] On Earth, Sun illuminates the sky by scattering through the atmosphere. The different amounts of atmosphere it passes through (angle) determine the color temperature (with some additional factors such as atmospheric conditions). As a result, color temperature provides a sense of time during the day (Figure 2.4.)

Figure 2.4. Sun as observed on Earth.[171]

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[167] "Mars Exploration Program."

[168] "Mars Exploration Program."

[169] James E. Tillman, "Mars: Temperature Overview," 1995, https://www-k12.atmos.washington.edu/k12/resources/mars_data-information/temperature_overview.html.

[170] *The Lighting Handbook*, 6th ed. (Zumtobel Lighting GmbH, n.d.).

[171] *The Lighting Handbook*, 6th ed. (Zumtobel Lighting GmbH, n.d.).

If Sun is not observed through an atmosphere, it lacks such properties and perceived just as a close star. Without light scattering through an atmosphere, the color temperature is almost always observed the same, while unfiltered Sunlight is 40% brighter in Earth orbit, and may cause glares (1389 W/m^2 solar spectrum, including ultraviolet wavelengths).[172] The distance from the Sun is one of the main determiners of the light received, in addition to atmospheric composition and density. In Figure 2.5, it can be seen a few examples of how Sunlight is observed from different locations within the Solar System. The daily cycle of Mars is 40 minutes longer compared to Earth.[173]

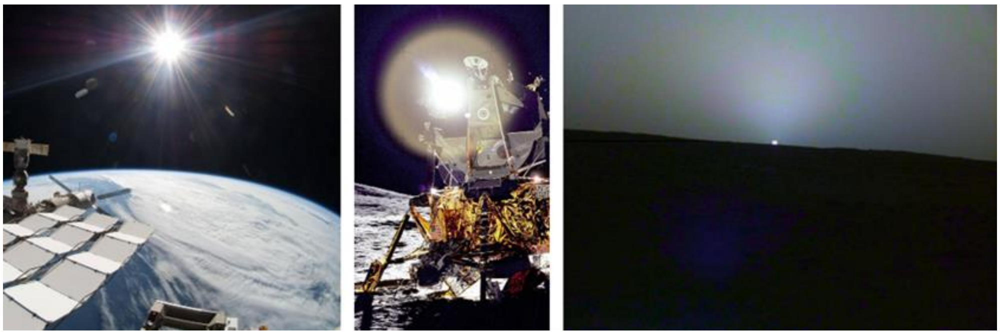

Figure 2.5. Sun as observed in LEO, on the Moon and on Mars.[174]

Even though earlier it was thought that humans are insensitive to light and more sensitive to social cues on their circadian rhythms, the latter studies proved otherwise, revealing that the human biological clock is affected by the timing, intensity, duration, and wavelength of light.[175] Without a natural light cycle fitting human routine and

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[172] Howe and Sherwood, *Out of This World: The New Field of Space Architecture*, 26.
[173] “Mars Exploration Program.”
[174] “Image Galleries,” accessed November 27, 2019, https://www.nasa.gov/multimedia/imagegallery/; “Resources,” accessed November 27, 2019, https://solarsystem.nasa.gov/resources/.
[175] Jeanne F. Duffy and Charles A. Czeisler, “Effect of Light on Human Circadian Physiology,” *Sleep Medicine Clinics* 4, no. 2 (2009): 165–77, https://doi.org/10.1016/j.jsmc.2009.01.004.

biology, lighting gains importance not only for creating a functional and pleasing environment but to support human both physiologically and psychologically.

Magnetic Fields

The magnetic field is a vector field in which magnetic forces are observable and may be produced by magnets, electric currents, or changing electric fields.[176] Most of the Earth's magnetic field is thought to be produced by the conductive movement of liquid iron in its outer core.[177] Other sources include fields caused by currents flowing in the ionized upper atmosphere and within the crust of Earth.[178] Neither Moon nor Mars presently has a global magnetic field due to lack of active cores, but both have crustal magnetic fields.[179]

It is known that a considerable amount of species, from bacteria to mammals, are able to sense geomagnetic field, whereas there are studies going back to decades asking the question if humans have any response to the magnetic field too.[180] A recent study by Wang et al., in which the changes of human brain waves are examined during exposure to magnetic fields pointed at different directions, presents one of the strongest evidence that humans are subconsciously sensitive to changes in the magnetic field.[181] The results of the study also indicate that the human brain may become insensitive to changes that are far from the expected geomagnetic field.[182] Still, it is not yet known if the information sensed by the brain is used or disregarded, and the study is not replicated yet.

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[176] "Magnetic Field," in *Encyclopedia Brittannica*, n.d., https://www.britannica.com/science/magnetic-field.

[177] "Further Understanding of Geomagnetism," accessed November 27, 2019, https://www.ngdc.noaa.gov/geomag/.

[178] "Further Understanding of Geomagnetism."

[179] R. A. Carley et al., "Magnetization of the Lunar Crust," *Journal of Geophysical Research: Planets* 117, no. E8 (August 2012): n/a-n/a, https://doi.org/10.1029/2011JE003944.

[180] Connie X. Wang et al., "Transduction of the Geomagnetic Field as Evidenced from Alpha-Band Activity in the Human Brain" 6, no. April (2019).

[181] Wang et al.

[182] Wang et al.

2.2.3.2. Factors That Might Affect Human – Environment Interaction

The environmental conditions cannot be assumed to define the interaction between human and environment directly. On the contrary, there are many factors affecting this interaction. To start with, the users themselves, as being the other side of the equation, might be considered equally effective; or as being the interpreter, they might even be considered more effective in the definition of their interaction with their environment.[183] Topics in relation to environmental conditions cover most physiological issues while touching some psychological ones, however human interaction with the environment does not solely depend on those conditions.

> Living in a confined environment as a space habitat is a strain on normal human life. Astronauts have to adapt to an environment characterized by restricted sensory stimulation and the lack of "key points" in normal human life: seasons, weather change, smell of nature, visual, audible and other normal sensory inputs which give us a fixation in time and place. Living in a confined environment with minimal external stimuli available, gives a strong pressure on group and individuals . . . Therefore designing a space habitat must take into consideration the importance of design, not only in its functional role, but also as a combination of functionality, mental representation and its symbolic meaning, seen as a function of its anthropological meaning.[185]

The psychology of human in Space is widely related to a more extensive definition of living conditions in Space. These definitions can be interpreted as addressing not the environment itself, but the protective environment: the Space habitat. Some psychological considerations in Space, which architecture addresses/might address, are adapted from various sources as follows:[187]

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[183] Harrison, Clearwater, and McKay, *From Antarctica to Outer Space: Life in Isolation and Confinement*, 134–46.

[185] Andreas Vogler and Jesper Jørgensen, "Windows to the World, Doors to Space: The Psychology of Space Architecture," *Leonardo* 38, no. 5 (October 2005): 390–99.

[187] Harrison, Clearwater, and McKay, *From Antarctica to Outer Space: Life in Isolation and Confinement*; Kanas and Menzey, *Space Psychology and Psychiatry*; Clearwater, "A Human Place in

- Physical confinement,
- Social isolation,
- Lack of privacy,
- Feeling of crowdedness,
- Under stimulation,
- Over stimulation,
- Limitations of interdependence,
- Dependence to artificial environment,
- Continuous perception of risk.

The user's physical and psychological condition might be shaped by the combination of many factors, including their profession, training, age, gender, culture, nationality...[191] Thus, a considerable proportion of research focusing on Space missions have been dedicated to crew selection. Until today, the types of the user stayed for long duration have almost all been highly trained, motivated, and mission-oriented professionals.[192] In his autobiography, Linenger frequently describes himself in various situations as continuously aware of his psychological condition and acting in order to achieve the tasks that are needed to be done.[193] While first visitors of Space have all been military-based, during the following years, the variety of user type has expanded to include non-military scientists, doctors, engineers too. Even if in extremely limited amounts, there have also been Space tourists. Still, almost all Space visitors of today are being selected with strict requirements and are trained for years for the missions, for the equipment they might need to use, for the place they are going to live in. This type of user, however, is expected to be varied in the near future,

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Outer Space"; Harrison, "Humanizing Outer Space: Architecture, Habitability, and Behavioral Health"; Douglas A. Vakoch, ed., *Psychology of Space Exploration* (Washington, DC: National Aeronautics and Space Administration, 2011); Jack Stuster, "Behavioral Issues Associated with Long- Duration Space Expeditions : Review and Analysis of Astronaut Journals Experiment 01-E104 (Journals): Phase 2 Final Report," *National Aeronautics and Space Administration* (Houston, TX, 2016).

[191] Kanas and Menzey, *Space Psychology and Psychiatry*, chap. 1.4.

[192] Clearwater, "A Human Place in Outer Space."

[193] Jerry M. Linenger, *Off the Planet: Surviving Five Perilous Months Aboard the Space Station Mir* (McGraw-Hill Education, 2000).

starting with the increase of initiatives about Space tourism. Preiser points out that the upcoming visitors of Space might be less amenable to endure hardships, inconveniences, and sensory deprivation caused by features of environmental design.[194]

Additionally, habitability considerations increase with mission duration.[195] As classified by Kennedy, short duration missions last up to a few weeks, medium duration missions last up to six months, and long duration missions are years long.[196] For short durations, it might be enough to ensure the physical health of human; for increased durations, a level of comfort is needed to let the person perform tasks. For medium durations, the conditions should become sufficient to provide living of habitants, meaning the inclusion of more qualitative considerations. As the durations become longer, it can be expected to have more weight of extended qualitative considerations, among others.

> For brief periods, 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.[197]

The more the continuous durations of stay in Space increase, the more knowledge is being gained about the human capacities of living in Space. For example, Skylab mission authorities could not be sure about the effects of weightlessness on human before the missions. At the time, even if it had been observed that humans can survive and function for limited periods, in their return, medical values showed significant

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[194] Harrison, Clearwater, and McKay, *From Antarctica to Outer Space: Life in Isolation and Confinement*, 155.

[195] Tommaso Sgobba and Irene Lia Schlacht, “Habitability and Habitat Design,” in *Space Safety and Human Performance* (Elsevier, 2018), 653–719.

[196] Howe and Sherwood, *Out of This World: The New Field of Space Architecture*, 12.

[197] Connors, Harrison, and Akins, *Living Aloft: Human Requirements for Extended Spaceflight*.

changes.[198] It was unknown if the changes would continue or be stabilized at a point.[199] The only way to answer this question was "to do it" according to Mueller.[200] Similarly, in the present day, there are concerns about some issues that could not be predicted with confidence. For example, for Mars missions, visual connection to the home planet will be lost for longer durations than ever; and the communication with Earth will have a delay of approximately 20 minutes.[201] Furtherly, in case of an emergency return will not be practical most of the time. The longest duration of a single stay until today has been about a year, in a few occasions. The current missions for a crew of ISS generally last six months. The roadmaps show increasing durations for missions, requiring further inquiries on habitability.

In the present time, out of a few touristic visits, Space is always visited as a mission with specific objectives. Time aboard being very expensive, detailed schedules have been designed to accomplish those objectives, with alterations in their approach and level of tightness. Apart from the work to be done, the schedules address the time needed for basic human needs and activities such as sleep, hygiene, food, leisure, and exercise (as classified in Architecture for Astronauts).[204] The schedules might be claimed to become more flexible as the mission durations increase. Astronaut Sandra Magnus, who states that she sees herself as a resident of space due to living in ISS, explains the relation in between the duration of stay and the activities during the stay as:

> A shuttle mission is very much like a sprint. It is very choreographed. Every 15 minutes you have got something to do. Inevitably you are getting behind. There are contingency plans on top of contingency plans when things go

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[198] S. Fred Singer, ed., *Manned Laboratories in Space*, vol. 16, Astrophysics and Space Science Library (Dordrecht: Springer Netherlands, 1969), https://doi.org/10.1007/978-94-010-3420-3.

[199] Singer.

[200] Summer Chick Bergen, "NASA Johnson Space Center Oral History Project: George E. Mueller," 1998, https://historycollection.jsc.nasa.gov/.

[201] Franco Fenoglio, "Human Spaceflight & Exploration from ISS to Deep Space" (Milano: Politecnico di Milano within the course Space for Inspiraction by Dominoni and Quaquaro, 2018).

[204] Häuplik-Meusburger, *Architecture for Astronauts*.

> wrong. Because you are only there for a very short period of time and you have a lot to get done. When you live on the Space Station and you are there for months and months, it is a marathon. You cannot work in a sprint pace for months. You got to have a normal lifestyle. Living in the Space Station really is moving to Space. You adapt to home in another level. Your days start to flow in a similar rhythm you have on ground, you get up, go to work, you go to home – which happens to be the same place, you do not have to go far. You develop this sort of rhythm of life, you are just doing it in microgravity with this beautiful view out the window.[205]

Upcoming missions with the increase in the duration and the distance require a change in the schedule design. The crew will need to be more autonomous. In addition, new initiatives such as Space tourism introduce the necessity of new functions in the habitats by introducing a new type of user with a different motivation of being there.

Additional issues influencing the psychology of the users are also considered as the relationships in between habitants (crew heterogeneity),[206] and the relationship with ground-control.[207] Communication with personal relationships are also regarded as crucial. Furtherly, communication with Earth through social media is also acknowledged to be important recently.[208]

> The issues of distance from rescue, proximity to the unknown, reliance on a limited contained environment, difficulties in communication, microsociety formation, increasing autonomy, and diminishing resources will be the greatest challenges that designers face for extreme environments, especially for a Mars mission.[209]

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[205] Cox and Ince, "The Infinite Monkey Cage: Astronaut Special."

[206] Kanas and Menzey, *Space Psychology and Psychiatry*, chap. 1.4.

[207] Kanas and Menzey, chap. 4.

[208] Clearwater, "A Human Place in Outer Space."

[209] Marilyn Dudley-Rowley et al., "Design Implications of Latent Challenges to the Long-Duration Space Mission," in *AIAA Space 2003 Conference & Exposition* (Reston, Virigina: American Institute of Aeronautics and Astronautics, 2003), https://doi.org/10.2514/6.2003-6239.

It is safe to assume that the knowledge to be gained with upcoming missions with wider variety in aspects of the user, duration, and aim will provide more data. Nevertheless, while entering the next phase of Space exploration, current knowledge based on previous missions holds valuable insight about life in Space and to define Space habitat design criteria to an extent.

2.2.4. The Expanding Notions of Human and Environment

The extremity of the environment induces some approaches that might be considered intrusive. Additionally, the plans with the direction of longer duration missions lead to speculative discussions that include evolutionary changes in human.[210] The term "cyborg" was firstly presented by Clynes and Kline in 1960, as a blend of the terms "cybernetics" and "organism."[211] The idea of integration of humans and machines might be traced back to the fictional character Nyctalope by Jean de La Hire, also the first seen superhero in popular culture,[212] with adventures in Space.[213] Indeed, the article that presents the term "cyborg" for the first time, discusses the future presence of humans in Space, and proposes that humans should attempt partial adaptation to environmental conditions of there, instead of carrying their whole environment along with them.[214]

> Altering [humans'] bodily functions to meet the requirements of extraterrestrial environments would be more logical than providing an earthly environment for [them] in space.[215]

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[210] Armstrong, *Star Ark*; Lockard, *Human Migration to Space*.

[211] Manfred E. Clynes and Nathan S. Kline, "Cyborgs and Space," *Astronautics*, no. September (1960): 26–27, 74–76.

[212] Paul E. Zehr, *Inventing Iron Man: The Possibility of a Human Machine* (Johns Hopkins University Press, 2011).

[213] Le Mystère des XV was later translated as The Nyctalope on Mars.

[214] Clynes and Kline, "Cyborgs and Space."

[215] Clynes and Kline.

The technology of the time when Clynes and Kleine's article was published might be insufficient for most of the suggestions. In the present, despite the existence of ethical and existential discussions, the advancements in technology seem to offer a potential to realize the suggestions. In addition to advancements in the field of genetic engineering, and restorative technologies like replacing missing organs by bioprinting,[216] replacing missing limbs by sensible synthetics,[217] and replacing missing senses by sensory substitution;[218] other technologies with the aim of extending human capacity to perform and perceive, such as creating new physical capabilities through exoskeletons[219] and creating new senses[220] are amongst the realities of present day.

On the other hand, the environment of human might be examined as "place" in "space" that she/he exists in.[222] Understanding of space as a realm has not been stable, with effects seen both in art and architecture. After the 19th century, with scientific discoveries and new mathematical theorems, different conceptions of space and alternative systematizations of geometric space have been recognized as opposed to an absolute and a priori space.[223] Influences of the new understandings, such as the introduction of higher dimensions, led to movements like Cubism, Dadaism,

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[216] Željka Kačarević et al., "An Introduction to 3D Bioprinting: Possibilities, Challenges and Future Aspects," *Materials* 11, no. 11 (November 6, 2018): 2199, https://doi.org/10.3390/ma11112199; Udayabhanu Jammalamadaka and Karthik Tappa, "Recent Advances in Biomaterials for 3D Printing and Tissue Engineering," *Journal of Functional Biomaterials* 9, no. 1 (March 1, 2018): 22, https://doi.org/10.3390/jfb9010022.

[217] Jose M Carmena et al., "Learning to Control a Brain–Machine Interface for Reaching and Grasping by Primates," ed. Idan Segev, *PLoS Biology* 1, no. 2 (October 13, 2003): e42; Luke Osborn et al., "Biologically Inspired Multi-Layered Synthetic Skin for Tactile Feedback in Prosthetic Limbs," in *2016 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)* (IEEE, 2016), 4622–25, https://doi.org/10.1109/EMBC.2016.7591757.

[218] Scott D. Novich and David M. Eagleman, "Using Space and Time to Encode Vibrotactile Information: Toward an Estimate of the Skin's Achievable Throughput," *Experimental Brain Research* 233, no. 10 (October 17, 2015): 2777–88, https://doi.org/10.1007/s00221-015-4346-1.

[219] Neil Bowdler, "Rise of the Human Exoskeletons," *BBC News*, 2014, https://www.bbc.com/news/technology-26418358.

[220] Novich and Eagleman, "Using Space and Time to Encode Vibrotactile Information: Toward an Estimate of the Skin's Achievable Throughput."

[222] Yahuda E. Kalay and John Marx, "Architecture and the Internet: Designing Places in Cyberspace," *First Monday*, no. 5 (2005).

[223] Gökhan Kınayoğlu, "A Reconsideration of the Concept of Architectural Space in the Virtual Realm" (Middle East Technical University, 2007).

Constructivism, and Futurism.[224] Although space, as humans perceive and experience, has not changed, and Euclidean geometry remained the fittest even if not true, according to Cache.[225]

The notion of space is considered to extend beyond the material world with the introduction of cyberspace.[226] Even though earlier examples of “imaginary spatial fields,” as described by Kınayoğlu,[227] had been present, “cyberspace” as a term first appeared in 1984 novel by William Gibson, Neuromancer, with the definition:

> A consensual hallucination experienced daily by millions of legitimate operators, in every nation, by children being taught mathematical concepts… A graphic representation of data abstracted from the banks of every computer on the human system. Unthinkable complexity. Lines of light ranged in the nonspace of the mind, clusters and constellations of data.[228]

Technologies as extensions of cyberspace, starting from the World Wide Web, include Virtual Environments (VEs), Virtual Reality (VR), Augmented Reality (AR), amongst others, and offers opportunities that are not possible in physical space.[229] Despite the controversies on whether the cyberspace already is (or ever to be) a “place” for humans, it is accepted that cyberspace expanded the human environment that can be perceived and experienced, while “becoming an extension of [human’s] physical and temporal existence.”[230]

In this context, apart from the technologies with direct interferences to genetics or morphology of the body, the use of mobile devices with internet access is considered enough to be cyborgs to researcher Amber Case, as the use of those devices presents

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[224] Kınayoğlu.
[225] Bernard Cache, “Plea for Euclid,” n.d.
[226] Kalay and Marx, “Architecture and the Internet: Designing Places in Cyberspace.”
[227] Kınayoğlu, “A Reconsideration of the Concept of Architectural Space in the Virtual Realm.”
[228] William Gibson, *Neuromancer*, 1984.
[229] Lockard, *Human Migration to Space*, chap. 4.
[230] Kalay and Marx, “Architecture and the Internet: Designing Places in Cyberspace.”

an extension to the mental self.[231] Similarly, Elon Musk states that humans have already become cyborgs by having digital versions of themselves online.[232] On the other end, it is commonly argued that the machines humans create and control, and receive data from, such as robotic devices exploring spaces that might be considered out of the range of physical human presence in the present day, become another extension of human senses. Adapting the original definition as "The cyborg deliberately incorporates exogenous components extending the self-regulatory control function of the organism in order to adapt it to new environments,"[233] architect and researcher Elizabeth Song Lockard concludes that humans have always been cyborgs in a degree, considering even the earliest and simplest technologies were extensions and supplementations of them.[234] To Lockard, the only differences are the amount of the options of the technologies, the invention rate, and the extent of modifications that are promised by these technologies.[235]

The intensive debates in the field of architecture devoted to the expansion of the notions of human and her/his environment fall beyond the scope of this thesis, as well as further semantic discussions. However, it is important to note that, especially to provide living in the restricted and confined environments of Space habitats with the plans suggesting longer durations to be spent in those habitats, the subject might become closely relevant to the definition of the design considerations. There are already numerous speculative studies regarding human-environment interaction with an evolutionary approach within the field.[236]

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[231] Amber Case, *An Illustrated Dictionary of Cyborg Anthropology* (CreateSpace Independent Publishing Platform, 2014).

[232] Elon Musk, "We Are Already Cyborgs," in *Code Conference* (Los Angeles, California: Recode, 2016), https://youtu.be/ZrGPuUQsDjo.

[233] Clynes and Kline, "Cyborgs and Space."

[234] Lockard, *Human Migration to Space*, chap. 6.

[235] Lockard, chap. 6.

[236] Lockard, *Human Migration to Space*; Armstrong, *Star Ark*.

2.2.5. Space Habitat Design Issues

If the Space habitat is recognized as an interface of human – environment interaction, then it should respond to the requirements regarding both ends of this interaction. In that manner, design considerations include quantitative and qualitative issues, some of which might be identified as in Figure 2.6. It might be important to note that the figure illustrates the design issues in an oversimplified manner. There are many interrelated considerations. For instance, human physiology and psychology are not distinct from each other at all. On the other hand, design issues such as mass, material, structure, volume, and form might also affect each other drastically. The examples might be multiplied as many of the specified assets are interrelated. Design problem might always be considered as complex and ill-defined. The figure only attempts to illustrate some of the intersections in the factors that should be responded by the design of the Space habitat.

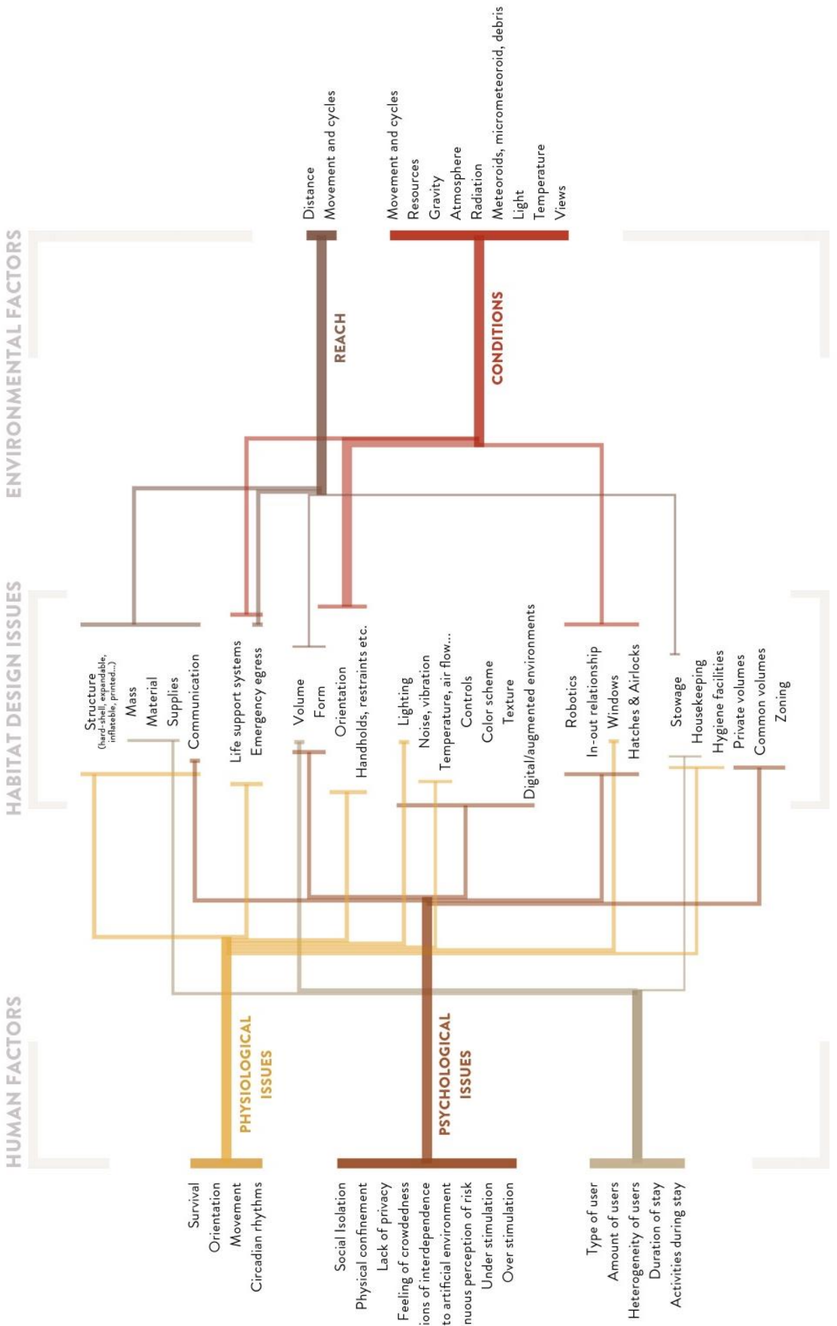

Figure 2.6. Space habitat design issues (by author)

First of all, mass, volume, and form of the habitat are mostly dependent on the rocket vehicle capacity. Additionally, the capability of the reach is limited to launch windows. Even for LEO launch windows might not be considered short, it might be for Mars as the relevant position of the planets determine the possibilities, amongst other factors. That leads to extreme limitations of re-supplies or frequent visits from Earth. Most of the resources need to be recycled, and limited building materials could be provided from Earth. That might require in-situ resource utilization (ISRU). On the other hand, any return which is not planned (in case of an emergency) might become impractical for the most phases of the journey and from the surface of the planet. The distance of the environment also causes delays on communication, which might become more than 20 minutes for a Mars mission, preventing any real-time conversation with Earth. The habitats need to become more autonomous as the distances increase.

As the environmental conditions are hazardous to human life on many levels, the habitat's first objective might be recognized as providing a level of protection for human survival. Ionizing radiation and micrometeoroid shielding might become primary concerns for the protective shell in that manner, addressing the structural properties, mass, and material choices regarding habitat design, among others. Providing conditions that support human life inside this shell is apt to mechanical systems for today (ECLSS), while the research on supporting these systems with biological processes continue. Space habitats might be considered as one of the most developed examples of artificial closed systems supporting human survival needs.

Due to the challenges posed by the environment and reach capacities, and the dependence to an artificial environment, considerations regarding human physiological and psychological well-being increase in the design of a Space habitat. This induces research on the effects of spatial features of habitat on human.

Volume

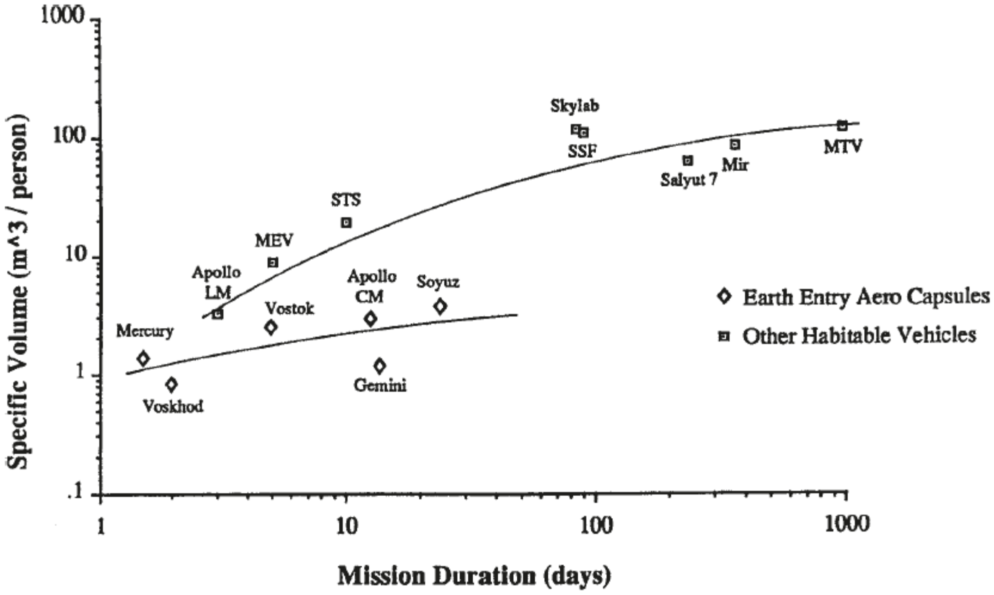

Figure 2.7. Historical Spacecraft Total Pressurized Volume Data[241]

Historically, the volume of the Space habitats increased with the mission duration (Figure 2.7). One of the most cited studies while determining the required volume is the "Celentano Curve," which is a 1963 study offering three curves indicating "tolerable, performance, optimal" volumes per crew member for increasing durations of a Space mission. This study has been followed by many others, one of which is included in NASA standards (Figure 2.8).

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[241] Howe and Sherwood, *Out of This World: The New Field of Space Architecture*, 124.

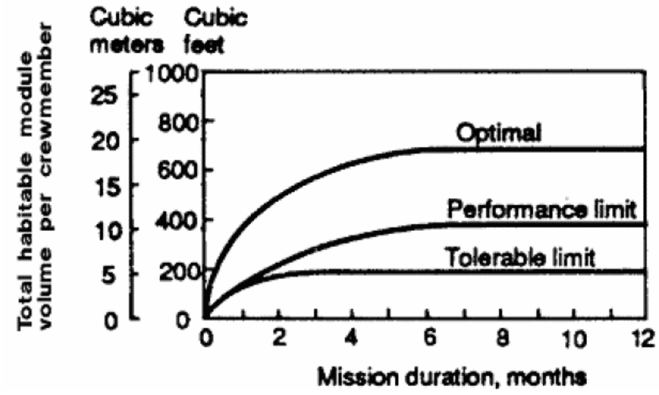

Figure 2.8. Guideline for Determination of Total Habitable Volume per Person in the Space Module[242]

However, Space architect Marc M. Cohen draws attention to the fact that "spacecraft volume met crew needs only insofar as none of them became sick, performed inadequately, or died from the cause of insufficient volume. What the historical record affords is a metric to analyze how pressurized volume varies with mission duration."[243] Regarding his survey, he concludes that "there is no single or simplistic answer for predicting pressurized spacecraft volume as a function of mission duration," but the mission duration directly affects the volume while crew size and functional operations may have secondary effects.[244] One of the important findings of the survey is the curve keeps rising "out about 1000 days, a nominal length of a Mars mission."[245]

As the actual volume is restricted by many factors, there is a strong focus on how to make the user perceive more volume: "the feeling of spaciousness can be achieved

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[242] "NASA STD 3000 Volume 1" (Washington, DC, n.d.), chap. 8.
[243] Marc M. Cohen, "Testing the Celentano Curve: An Empirical Survey of Predictions for Human Spacecraft Pressurized Volume," *SAE International Journal of Aerospace* 1, no. 1 (June 29, 2008): 2008-01–2027, https://doi.org/10.4271/2008-01-2027.
[244] Cohen.
[245] Cohen.

visually through the arrangement, color, and design of the walls and position of the space module.”[246]

Form

Exterior shell forms of the hitherto realized Space habitats’ are being defined by the launch vehicles, which are shaped due to physical considerations like friction while leaving the atmosphere. Inside the cylindrical shell, the spatial arrangement of equipment and stowage mostly define the perceived interior boundaries. “Irregular shaped rooms are perceived to have more volume than compact or regular shaped rooms of equal volume.”[247] However, irregular/amorph spatial arrangements are not yet realized in previous habitats. Figure 2.9 shows examples of the interior layouts of realized Space habitats. Upcoming missions may provide larger variety in the forms of the habitats, especially when considered the potentials arising due to the challenges posed by new frontiers, one of which is the exploration of new construction techniques.

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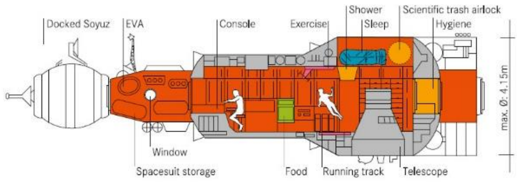
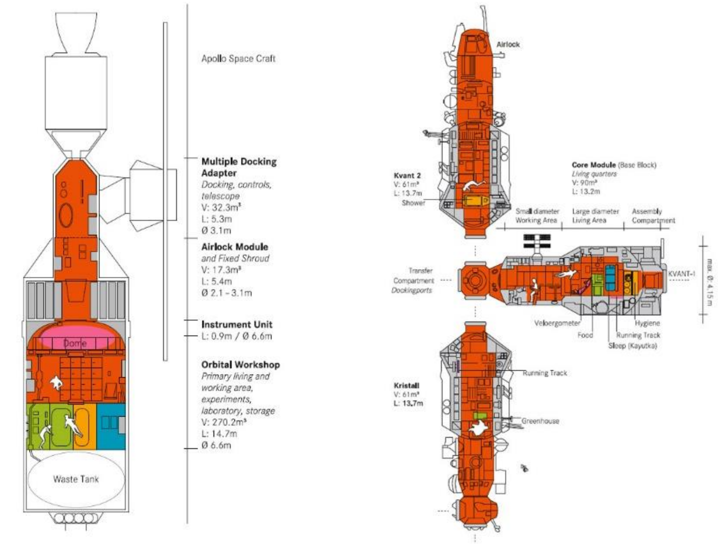
[246] “NASA STD 3000 Volume 1,” chap. 8.

[247] “NASA STD 3000 Volume 1,” chap. 8.

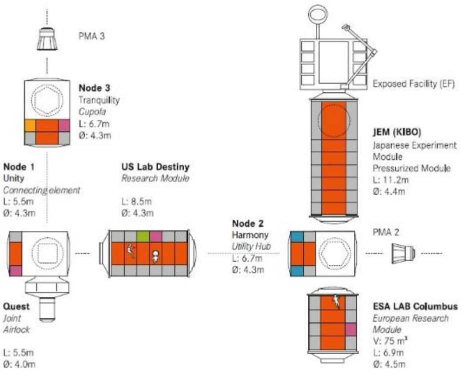


Salyut Space Station.



Skylab Space Station.

Mir Space Station.



International Space Station.

Figure 2.9. Layouts of realized Space stations[249]

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[249] Häuplik-Meusburger, *Architecture for Astronauts*.

Windows

Windows, creating many technical challenges, has been a controversial element to include in the designs of Space habitats. For example, the Skylab window, while being “unthinkable not to have” for industrial designer Raymond Loewy, was not essential for the mission success according to the centers responsible for building it.[251] The issue led many discussions because of its hardship of application until its acceptance.[252] However, the latter research emphasizing the importance of windows has been supported by the users of the realized Space habitats.[253] Similar to the previous and following mission crews, Skylab astronauts have reported looking out of the window as the most favored off-duty activity (Figure 2.10).[254] Haines later introduces several psychological issues related to windows, some of which are providing variety and sensory stimulation and reducing feelings of isolation and confinement.[255]

Windows might also become important for physiological well-being. It is known that Space habitants might experience myopia because of the limited environment which prevents focusing on distant objects.[256] In that manner, providing windows that might occasionally be seen (not only during specific times but while working, for example) might be meaningful physiologically in addition to its potential psychological advantages. However, it should be noted that such an arrangement would pose specific challenges to radiation and micrometeoroid protection.

One importance of having windows is having a direct visual connection to the outer of the habitat while performing a task in relation to the exterior of the habitat. Also, it

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[251] Compton and Benson, *Living and Working in Space: A History of Skylab*.
[252] Hitt, Garriott, and Kerwin, *Homesteading Space*.
[253] Clearwater, “A Human Place in Outer Space.”
[254] Caldwell C. Johnson, *Skylab Experiment M487 Habitability/Crew Quarters* (National Aeronautics and Space Administration, 1975).
[255] Harrison, Clearwater, and McKay, *From Antarctica to Outer Space: Life in Isolation and Confinement*, 349–58.
[256] Irene Lia Schlacht and Henrik Birke, “Space Design,” *Personal and Ubiquitous Computing* 15, no. 5 (June 28, 2011): 497–509, https://doi.org/10.1007/s00779-010-0326-4.

has been included in the NASA standards that the windows can be used for natural lighting. It is undeniable that both the lighting capabilities and the views seen through the window vary significantly for different Space environments. Some might argue that during the long journeys presenting almost unchanging views, windows might lose the importance. Such an argument would contradict with a considerable amount of findings suggesting the importance of the windows is not only with respect to the presented views through it. Kanas and Menzey emphasize that:

> . . . in a confined environment like a space habitat, windows not only represent a "nice-to-have" feature of the habitat architecture, but they must be regarded as an indispensable element of exceptional psychological significance.[257]

Figure 2.10. ISS Cupola

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[257] Kanas and Menzey, *Space Psychology and Psychiatry*, 166.

Lighting

> Lighting determines how we see surrounding objects and therefore how we perceive them, generating sensations and thoughts which vary depending on the individual . . . Humans have common values with respect to light: performing a given activity with inadequate lighting creates discomfort or inconvenience, and artificial light or light changes alter our circadian rhythms influencing our alertness, performance, and sleep patterns.[258]

In addition to regulations about lighting (adequate illumination, emergency lighting...), natural and artificial lighting also taken into consideration regarding the role of light on the circadian rhythms.[259] Furtherly, studies suggest that the lighting might help to provide a sense of local vertical for microgravity environments as "up" is associated with the source of light.[260] On the other hand, the arrangement of lighting may offer spatial qualities by defining separate or semi-separate volumes that can easily be "built."

Colors

Compatible with the design decisions of architect Galina Balashova and industrial designer Raymond Loewy on the interior color scheme of the spacecraft designs that they have been involved, the latter research on color suggested avoiding monochromatic illumination, and limiting the use of bright colors to small surfaces or objects.[261] However, the same research also emphasized that neither it would be sufficient to trust on a designer's choice solely, nor directly applying personal

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[258] Carolina Caballero-Arce, Adolfo Vigil de Insausti, and Javier Benlloch Marco, "Lighting of Space Habitats: Influence of Color Temperature on a Crew's Physical and Mental Health," in *42nd International Conference on Environmental Systems* (Reston, Virigina: American Institute of Aeronautics and Astronautics, 2012), https://doi.org/10.2514/6.2012-3615.

[259] "NASA-STD-3001 Volume 2," chap. 8.

[260] Clearwater, "A Human Place in Outer Space."

[261] Barbara K. Wise and James A. Wise, "The Human Factors of Color in Environmental Design: A Critical Review" (Washington, DC, 1988).

preferences of the inhabitant. Rather, the colors should be specified regarding their "performance criteria," and then both the designer's contribution, and allowing a level of personal choice for the inhabitant becomes meaningful.[262] One of the most important findings of this report was indicating "no hard-wired linkages between environmental colors and particular judgmental or emotional states."[263]

> Although there appear to be some basic emotional or semantic connotations of color dimensions [hue, chroma, value] - particularly chroma and value - that are maintained in a perceptually rich setting, much environmental color meaning and acceptability seems to rely on cognitive appraisals between what is viewed and some ideal prototype or exemplar.[264]

Framed Views

Durao and Favata emphasize the stated desire by the Space visitors for a variance of the environment.[265] This desire might address spatial features such as light, color, and texture, as well as pictures, simulated windows, screens... Balashova has included watercolor paintings in the very early Space habitat interiors.

> . . . I sat down one night and painted pictures for the space capsules. Usually watercolors depicting Russian countryside. They all burned to nothing on re-entry.[266]

Psychologists Clearwater and Coss suggest the use of pictures support the well-being of the users in the confined environment.[267] Their research, which was conducted on

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[262] Wise and Wise.

[263] Wise and Wise, 110.

[264] Wise and Wise, 99.

[265] Maria Durao and Paola Favata, "Color Considerations for the Design of Space Habitats," in *AIAA Space 2003 Conference & Exposition* (Reston, Virigina: American Institute of Aeronautics and Astronautics, 2003), https://doi.org/10.2514/6.2003-6350.

[266] Seidel, "Interview with Galina Balashova: Only the Watercolors Burned to Nothing."

[267] Harrison, Clearwater, and McKay, *From Antarctica to Outer Space: Life in Isolation and Confinement*, 331–48.

the Antarctic Stations by providing five different themes of pictures to the crew,[268] implied that spacious landscape themed pictures are being preferred by habitants.[269] They also emphasize the possible change of these results for Space habitat interiors.[270] Nevertheless, the study suggests the use of "pictures to simulate a view to the outside of the spacecraft" in the confined environment of Space habitat because:

> . . . esthetically pleasing pictures would periodically catch the viewer's attention, momentarily enlarging the contextual framework of the viewer to include the properties of other settings, they could increase the diversity of cognitive activity.[272]

Additional Stimulus

There might be many suggestions for the elements that could be implemented in a Space habitat for human well-being. The most obvious suggestions might be the inclusion of plants and water as a part of the architectural design of the habitat. The literature of environmental psychology includes numerous studies on the effects of "green" on humans. Similarly, there are studies exploring the effects of "blue." The studies suggest that even might be through the poorly understood mechanisms, the interaction with plants and water has recognizable effects on human health and well-being.[273] Moreover, both water and plants are considered almost mandatory for a

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[268] 1) Relatively dry landscape photographs, 2) glittery landscape photographs with contrasting highlights, 3) action-oriented photographs of people, 4) photographs of wild animals in natural settings, and 5) photographs of landscape paintings.

[269] Harrison, Clearwater, and McKay, *From Antarctica to Outer Space: Life in Isolation and Confinement*, 331–48.

[270] Harrison, Clearwater, and McKay, 331–48.

[272] Harrison, Clearwater, and McKay, *From Antarctica to Outer Space: Life in Isolation and Confinement*, 333.

[273] Catharine Ward Thompson et al., "More Green Space Is Linked to Less Stress in Deprived Communities: Evidence from Salivary Cortisol Patterns," *Landscape and Urban Planning* 105, no. 3 (April 2012): 221–29, https://doi.org/10.1016/j.landurbplan.2011.12.015; Mathew White et al., "Blue Space: The Importance of Water for Preference, Affect, and Restorativeness Ratings of Natural and Built Scenes," *Journal of Environmental Psychology* 30, no. 4 (December 2010): 482–93, https://doi.org/10.1016/j.jenvp.2010.04.004.

closed system that could support human life. For the longer and more distant missions, the autonomy of the habitat needs to increase. Thus, the studies, including supporting mechanical systems with biological systems, are ongoing.

Arrangements for Orientation and Movement

Prior to ISS, Space stations have been designed with significant “up” and “down” suggestions (local verticals). ISS, making use of every surface, lacks that kind of distinct visual cues (Figure 2.11). Raymond Loewy states that the design of Skylab with orientation suggestion has been a design decision that required some effort to establish:

> I felt that a semblance of gravity was essential. The astronauts and scientists all argued against this – they were prepared to sleep floating in Space and to eat that way.[275]

Figure 2.11. Interior of Mir Space Station (from mission simulator) and ISS

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[275] Susan Heller Anderson, “The Pioneer of the Streamlining,” 1979, https://www.nytimes.com/1979/11/04/archives/design-the-pioneer-of-streamlining-design.html.

Skylab was built to have local verticals in the modules, but one module was left without a specific suggestion of up and down as a design experiment, to see if the astronauts would be comfortable in such volume.[276] The observations indicated that the modules having consistent local verticals were easier to use.[277] Based on this experience, it is included in the NASA standards that:

> Each crew station shall have a local vertical (a consistent arrangement of vertical cues within a given visual field) so that the vertical orientation within a specific work station or activity center remains consistent.[278]

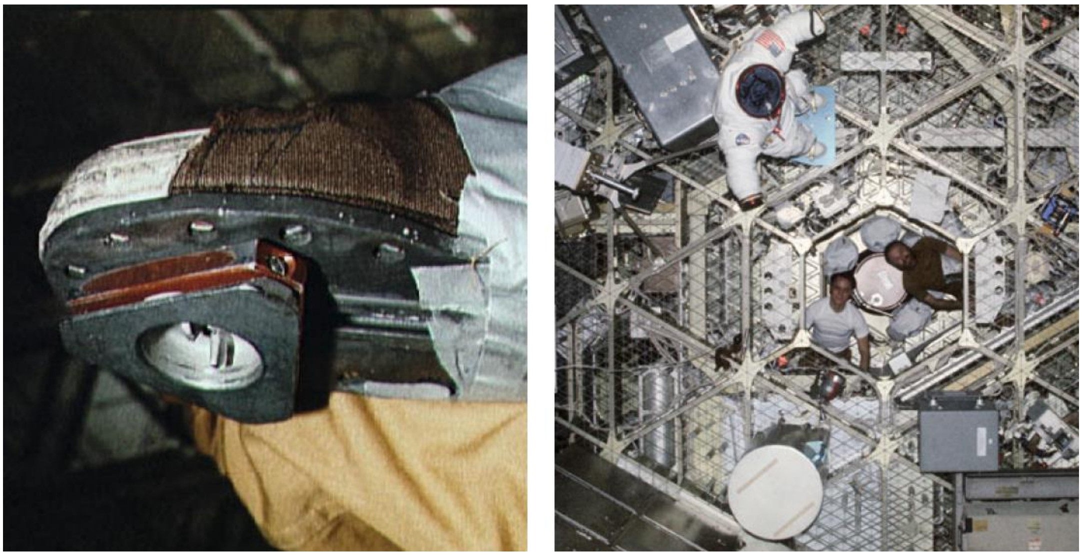

Figure 2.12. Skylab shoes and the perforated surface[279]

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[276] Evans, *At Home in Space: The Late Seventies into the Eighties*.
[277] "NASA STD 3000 Volume 1," chap. 8.
[278] "NASA-STD-3001 Volume 2," chap. 8.
[279] Häuplik-Meusburger, *Architecture for Astronauts*, 56.

Figure 2.13. “Space acrobatics”[280]

Additionally, due to the changes altered gravity causes on the movement of the Space habitants, specific additions to the habitat are needed to support the movement. These additions are usually provided as handholds and restraints. In Skylab, additionally, shoes with cleats compatible with the perforated surface of the interior have also been provided (Figure 2.12). As indicated earlier, many Space habitants mention their ability to move in weightlessness improves during their stay. In Skylab, some of the implementations to ease moving had been removed by the crews in time and using the potentials the larger volumes provide; they had regularly performed “Space acrobatics” (Figure 2.13).[281] As not only microgravity but reduced gravity is known to affect the movement capabilities of humans, design might require similar arrangements.

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[280] Emily Carney, “Ed Gibson’s Dances With The Sun: Skylab 4, 1973 – 1974,” National Space Society, accessed November 27, 2019, https://space.nss.org/.
[281] Hitt, Garriott, and Kerwin, *Homesteading Space*.

Crew restraints shall be provided to assist in the maintaining of body position and location in reduced gravity conditions or during high accelerations.[282]

Zoning, Private and Common Volumes

The zoning and functional layout of the space might become associated with many factors. An approach, which is included in NASA standards, might be allocating space regarding the noised levels and privacy needs (Figure 2.14).

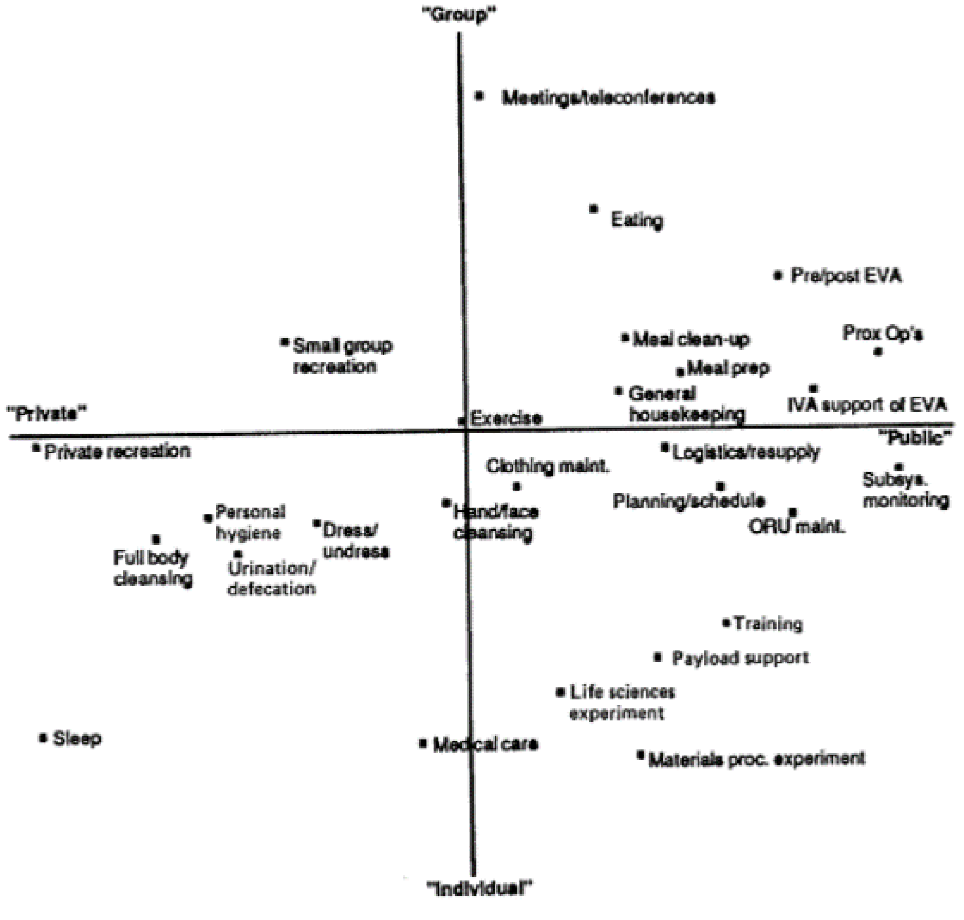

Figure 2.14. "Consideration for the Relative Locations of Space Module Functions Based on the Results of Functional Relationships Analysis"[283]

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[282] "NASA-STD-3001 Volume 2," chap. 8.

[283] "NASA STD 3000 Volume 1," chap. 8.

Adams and McCurdy emphasize the importance of including social, public-access, and private areas to the habitat in a balance.[284] Adams also states that "the establishment of private space for each individual crew member, as well as a range of semiprivate work and rest areas represents a significant departure from established norms in space habitat design."[285] However, it might be claimed that the value of including separately defined volumes for personal and common use and also the "in-between" volumes is being acknowledged regarding previous research and experience. Even if not realized with "ideal" conditions yet, the issues started to reflect on the standards.

> For missions greater than 30 days, individual private quarters shall be provided to support crew health and performance. For individual private quarters, the system shall provide the crew control of lighting, noise, ventilation, and temperature.[286]

After Loewy insisted on including personal volumes for each crew member in Skylab, "crew quarters" started to be acknowledged as a necessity (Figure 2.15). The decision of Loewy to individualize crew quarters of Skylab by differentiating the floor plans is interpreted as a "statement" by Cohen.[287] Later experience and research supported the need for a private volume providing visual and acoustic shielding from the rest of the habitat and the need for personal storage. Allowing personalization (by décor, individual environmental control etc.) of personal space is also considered important.[288] Having the controls of lighting, temperature, odor, noise levels etc. within the personal space and having respectively less control on these features for the rest of the habitat might be argued to create a perception of "in" and "out" for the user.

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[284] Constance M. Adams and Matthew Riegel McCurdy, "Habitability as a Tier One Criterion in Advanced Space Vehicle Design: Part One-Habitability," in *29th International Conference on Environmental Systems* (Denver: SAE International, 1999), https://doi.org/10.4271/1999-01-2137.

[285] Constance Adams, "Four Legs in the Morning: Issues in Crew-Quarter Design for Long-Duration Space Facilities," 1998, https://doi.org/10.4271/981794.

[286] "NASA-STD-3001 Volume 2," chap. 7.

[287] Marc M. Cohen, "Space Station Design" (Southern California Institute of Architecture, 1985), https://youtu.be/k3ybvFl1ZAc.

[288] Kanas and Menzey, *Space Psychology and Psychiatry*, chap. 6.

Furtherly, the constant changes in the features of the habitat independent from the user (e.g. to support circadian rhythm) might also be used for providing external stimuli.

Figure 2.15. Crew quarters (1) Skylab; (2), (3), (4) ISS

> In addition to private crew quarters, the design of the habitat should provide opportunities for common meetings and leisure activities of the entire crew. . . The minimum equipment should include a table with enough room for all crewmembers.[289]

Loewy has designed a wardroom table for the crews of Skylab to let them eat and talk together.[290] Similarly, in collaboration with psychologist Clearwater, Cohen has offered a table to provide group gatherings in ISS.[291] The latter design was not implemented. However, it can be claimed that since the early Space stations, modules, even if not implemented with the primary purpose of a wardroom, might be used with such function by habitants (Figure 2.16).

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[289] Kanas and Menzey, 165.

[290] Compton and Benson, *Living and Working in Space: A History of Skylab*.

[291] Clearwater, “A Human Place in Outer Space.”

Figure 2.16. Examples to various uses of the modules in ISS

Even it is considered as important to define volumes that are “personal” or “common,” designers might also need to take into consideration that the perception of privacy or commonality is not only dependent on the physically defined volumes. For example, it is pointed out that looking out of the window even if in the presence of other people in the room, might define a private moment as well. Likewise, working in solitude while listening to the music of personal choice might be perceived as a private activity, as reported by Skylab astronauts. Therefore, the design might need to allow “in-between” spaces as much as private and common volumes.

Emergency Egress

Providing clear translation paths, and specifically highlighting those paths for emergency situations is needed.[292] Adams also emphasizes that the design of the habitat should impart the crew's understanding of its emergency provisions without special training for optimal habitability.[293]

Housekeeping

Space habitats, both as closed systems and being in hard-to-reach locations, might become cluttered in time. The issue is emphasized by many disciplines involved in the design of Space habitats, as well as almost every habitant of Space.

Human – Machine Interaction

It might be claimed that a Space habitat in fact is "a machine for living in." Thus, any interaction of humans with the habitat might be classified as interaction with a machine. However, the focus of the topic is specific to the situations in which the machine becomes an extension of the capabilities or perception of the habitant. The literature involves speculative proposals envisaging intrusive interferences to the body of Space habitant. However, despite a few individuals who are open to the idea of intruding to the physical integrity of their body, this acceptance cannot be argued to be common. As a matter of fact, Clearwater draws attention to the subject that since the beginning of human Space missions, women tend to keep long hair despite the

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[292] "NASA STD 3000 Volume 1," chap. 8; Sara (ESA) Pastor, "Gateway: When the Architecture Meets the Design Constraints" (Milano: Politecnico di Milano within the course Space for Inspiraction by Dominoni and Quaquaro, 2018).

[293] Adams and McCurdy, "Habitability as a Tier One Criterion in Advanced Space Vehicle Design: Part One-Habitability."

hardship it could cause.[294] Thus, at least for near-future plans, the limits of this topic might stay in the boundaries in which human body integrity is preserved.

One end of human – machine interaction in that manner might be the robotic extensions that the habitant is in control of. For example, as the environment poses many hardships to let the habitant out and perform activities there, Canadarm has been implemented to the exterior of one of the modules of ISS. The robotic arm not only provides control of exterior operational tasks from the interior of the habitat, but also used for carrying humans to specified locations when they are outside (Figure 2.17).

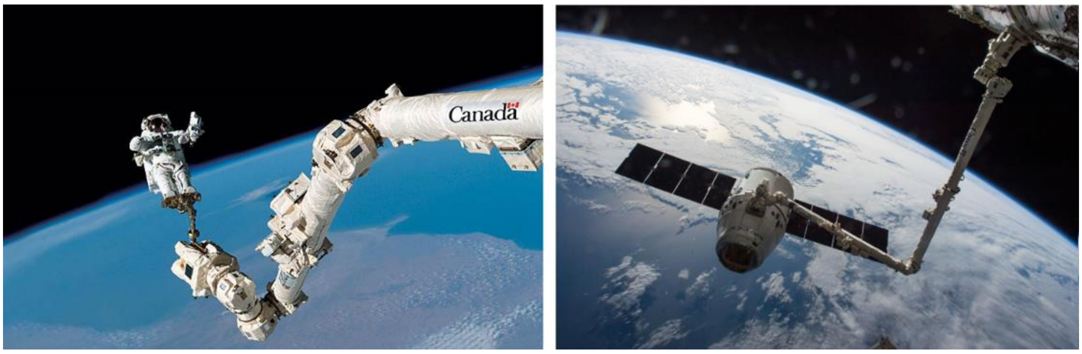

Figure 2.17. Canadarm and Canadarm2

Another end of human – machine interaction might be specified as the use of augmented or virtual reality technologies, which might be argued to extend the environment of the user in a digital manner.[295] The concurrent evaluation of both ends might offer many possibilities and enlarge the extent that architecture touches. The examples with such understanding may include speculative projects such as Intelligent Spacecraft Module (ISM)[296] and Spherical Environment Exploration Device

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[294] Clearwater, "A Human Place in Outer Space."

[295] See 2.2.4

[296] Konstantinos-Alketas Oungrinis et al., "Intelligent Spacecraft Modules: Employing User-Centered Architecture with Adaptable Technology for the Design of Habitable Interiors in Long-Term Missions," in *64rd International Astronautical Congress* (Beijing, China, 2013).

(SEED).[297] ISM team offers an add-on layer to any habitat, as a combination of low-tech and high-tech techniques to create a “sesponsive” (sense-responsive) environment for the user (Figure 2.18).[298] The offered system alters both the spatial (volume, surface) and ambient (audio, visual, olfactory, haptic) factors of the environment, to “induce a desirable spatial and/or psychological condition.” [299] Therefore, they attempt to use the limited volume to create different perceptions in the user by diversifying the sensory stimuli through digital and mechanical support. On the other hand, SEED is a proposal of a mobile habitat for Mars surface missions.[300] The authors offer a double shell sphere reflecting real-time visual information of the outside environment to the protected inside through an OLED surface while supporting free walking movement of the human within the system (Figure 2.19). Thus, they aim to provide a level of integration of the user to her/his environment.[301]

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[297] Kürşad Özdemir and Süheyla Müge Halıcı, “Roll SEED Roll: An Architectural Assessment of a Spherical Mobile Habitat for Mars,” in *46th International Conference on Environmental Systems* (Vienna, 2016).

[298] Oungrinis et al., “Intelligent Spacecraft Modules: Employing User-Centered Architecture with Adaptable Technology for the Design of Habitable Interiors in Long-Term Missions.”

[299] Oungrinis et al.

[300] Özdemir and Halıcı, “Roll SEED Roll: An Architectural Assessment of a Spherical Mobile Habitat for Mars.”

[301] Özdemir and Halıcı.

Figure 2.18. ISM project[302]

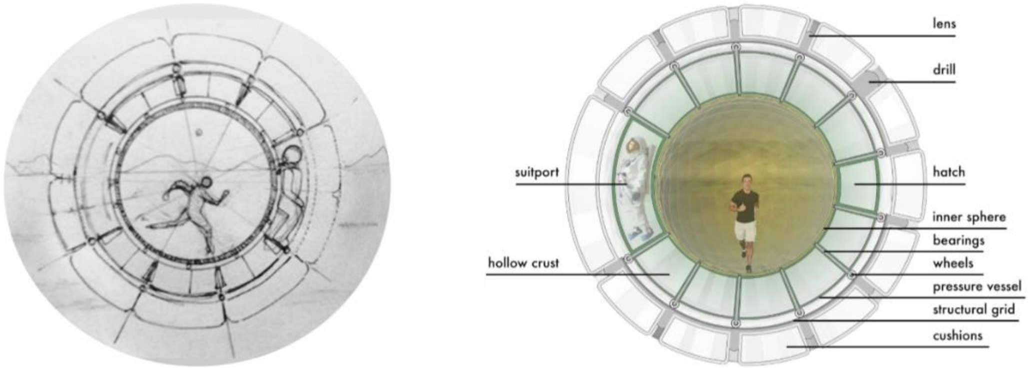

Figure 2.19. SEED project[303]

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[302] Oungrinis et al., "Intelligent Spacecraft Modules: Employing User-Centered Architecture with Adaptable Technology for the Design of Habitable Interiors in Long-Term Missions."

[303] Özdemir and Halıcı, "Roll SEED Roll: An Architectural Assessment of a Spherical Mobile Habitat for Mars."

2.3. Design Process

The term design might be understood both as an artificial product that has been created to respond to needs and considerations, and as the efforts for the creation of it. This topic intends to address the latter.

2.3.1. Interdisciplinarity and the Role of the Architect

Through his well-known experiments that have been supported by many following studies, Lawson concludes that the thinking processes of architects and scientists differ.[305] In "Designerly Ways of Knowing," in respect to Lawson's experiments, Cross concludes that: "scientists problem-solve by analysis, whereas designers problem-solve by synthesis."[306] The different approaches and "mind-settings" of engineers and architects are often emphasized in the field of Space architecture. Hauplik and Bannova state that even the meaning of "design" differs among disciplines.[307] At that point, it is important to repeat that "architecture" does not necessarily refer to the studies of architects in the thesis, rather implies the definition and solution of the design problem of human habitation through this thesis. Likewise, it might be argued that architectural thinking does not have to be in particular to architects.

As mentioned earlier, historically, Space habitat designs had not been regarded as an architectural design problem and solved within engineering disciplines. The inclusion of designers and architects to Space habitat designs had been needed regarding the concerns about human psychology in the initial designs of the interiors of early Space

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[305] Lawson, *How Designers Think*.

[306] Cross, "Designerly Ways of Knowing."

[307] Häuplik-Meusburger and Bannova, *Space Architecture Education for Engineers and Architects*, 12.

habitats, which did not seem “homely”[308] or even habitable[309] to mission authorities. Raymond Loewy describes their experience in the designing of Skylab as “educated intuition rather than anything else.”[310] The lack of experience in the environment poses many challenges and induces comprehensive research upon many subjects, some of which are being discussed in the previous sections. The required knowledge base on the diverse fields results the interdisciplinary collaboration of researchers, scientists, engineers, medical doctors, psychologists, industrial designers, architects, and artists, among others. The role and the effects of the contributing disciplines in different phases of the design are schematized by Hauplik and Bannova as in Figure 2.20.[311] However, it might be argued that the estimated weights of the disciplines are interchangeable and not stable. The roles of the many design actors might be defined regarding a specific project and might change for another. As it cannot be claimed a “conventional approach” has already appeared for the field of Space architecture, architects’ role might alter during the search of possible design approaches.

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[308] Balashova mentions she was called to design interiors because Feoktistov did not find the proposals made by engineers homely. Seidel, “Interview with Galina Balashova: Only the Watercolors Burned to Nothing.”

[309] Skylab mission director Mueller states that he asked Loewy to consult on the interiors of Skylab, because he thought no one can stay in the space proposed in the original design. Bergen, “NASA Johnson Space Center Oral History Project: George E. Mueller.”

[310] “Intetview with Raymond Loewy,” n.d., https://youtu.be/fwKu1u7yhpM.

[311] Häuplik-Meusburger and Bannova, *Space Architecture Education for Engineers and Architects*, 17.

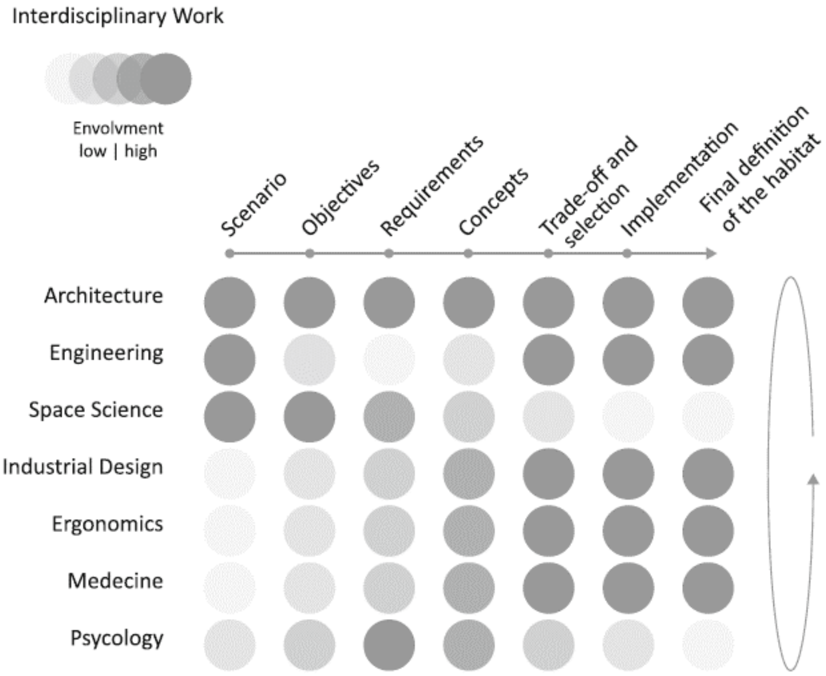

Figure 2.20. Involvement of disciplines in different design phases according to Hauplik and Bannova[312]

As being dominated by the engineering-based approaches and design methods, it remains questionable how much of acceptance for architects there is in the current aerospace industry. Kriss Kennedy describes being an architect in NASA as a struggle due to “being an architect in an engineering environment.” From his point of view, in NASA, engineers are the ones doing architecture, and architects are doing interior design. Griffin arrays some of the areas of contribution of practicing Space architects to human spaceflight as mission planning, vehicle integration, habitat design and human factors, and mostly design integration and concept development.[317]

> I feel a little out of place in the field of Space architecture. Among the aerospace engineers, architects come in like artists adding window dressings.

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[312] Häuplik-Meusburger and Bannova, 17.

[317] Brand N. Griffin, “Space Architecture: The Role, Work and Aptitude,” *AIAA SPACE 2014 Conference and Exposition*, no. August (2014): 1–14, https://doi.org/10.2514/6.2014-4404.

> After all, builders build without architects and engineers have sent humans into space, without too much substantial input from designers - so far. . . [318]

The above statement of Christina Ciardullo might draw attention to the issues of communication and mutual understanding between the fields in the aerospace industry, especially regarding architecture and engineering. The statement also implies an expectance of the acknowledgement of the relevance of architecture and architects to Space habitat designs within the industry. Brand Griffin, one of the first Space architects, draws attention to his current title being Senior Engineer (in NASA).[319] Griffin also argues that:

> . . . architects "get" engineers but the reverse is not true. Engineers think architects make things prettier, difficult to build and more expensive [sic]. Some can, but space architects are different. They analyze like an engineer and synthesize like an architect. [320]

Such an emphasis is not rare among the practitioners and researchers of Space architecture. The field is sometimes described as holding a gap between engineering and architecture. Griffin states that Space architects have to "sneak under the engineering tent masquerading" and have job titles including system architect, space system architect, configurator, subject matter expert, and systems engineer.[321] This masquerade can also be observed in the language of Space architecture. Marc Cohen describes his early experience in NASA while emphasizing the communication issues: "I had to learn how to talk to the engineering world, because I was always one architect in a sea of engineers. That meant working to understand their language and what's important to them and how to communicate what I thought was important."[322] He suggests not mentioning the "looks" of a design, as it would possibly create a suspicion

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[318] Christina Ciardullo, "Architecture with Space Applications" (Delft: BouT Symposium, 2018), https://youtu.be/ky1fsSMNx3Q.

[319] Ondrej Doule, "Interview: Brand Griffin," *The Orbit*, no. 1 (2016): 5–16.

[320] Griffin, "Space Architecture: The Role, Work and Aptitude."

[321] Griffin.

[322] "Interview with a Space Architect (Marc Cohen)," Boston Society of Architects, 2010, https://www.architects.org/news/interview-space-architect.

in the engineers, even if the choice has not made solely in respect to appearance. He suggests:[323]

> . . . talk about the function, the structure, the mass, the cost, the viability, the safety and crew productivity. . . validate what you're doing empirically, if not quantitatively. . . [324]

This approach is common in the field of Space architecture, as much as it is in Space psychology. For instance, due to the need for quantification of the design decisions, the need for human well-being is generally supported by evidence of potential hazards (psychological and psychiatric issues that could lead to mission failure) if human well-being is not provided. Furthermore, the choice of a human-centered design approach might be seen to be rationalized as: ". . . it is extremely complex and expensive to take a human being off the planet, and second, being there they have to optimally use the short time to fulfill the assigned tasks 100%. Therefore, this 'up-valuation' is not a question of comfort, but rather one of high mission priority."[326] Many examples might be provided with this approach or this language. On the other hand, the same Space architects might be come across with an approach which might seem opposing at first glance, asking questions from another perspective, questioning the choice of providing minimum requirements, while supporting their articles with figures including artworks.[327]

It is not unusual to see the same architect's contribution to Space design all on technical issues, human-centered design, design methodology, and philosophical discussions. This variety in the understanding and questioning capability of the architects might be argued to put them in a position in which they may be able to manage and see a diversity of considerations of design at the same time. This role might resemble the traditional role of the architect as mostly referred to as an

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[323] "Interview with a Space Architect (Marc Cohen)."
[324] Ibid.
[326] Häuplik-Meusburger, *Architecture for Astronauts*, xi.
[327] Marc M. Cohen and Sandra Häuplik-Meusburger, "What Do We Give Up and Leave Behind?," in *45th International Conference on Environmental Systems* (Washington, DC, 2015).

orchestrator. The main difference within the field of Space architecture is observed to be the requirement of the knowledge base to accomplish such a role. Practitioners and researchers of the field commonly emphasize the relevance of architects to the field and suggest potentials that might be offered to the field by architectural thinking.

> Architecture is using structural elements to define spaces, organize them and create a ‘place’. The education of the architect is deeply based on an understanding of space. Space in its functions, its technology, but also in its psychology, sociology and meaning. It is also the profession, who is organizing all the consultants and specialist by the design, at least on Earth. In the design of space habitats, this is so far poorly recognized. Whereas the engineers, who are designing habitats are often confused by the contradicting theories of e.g. psychologists and the multitude of options and ‘soft requirements’, the architect is by its profession very used to that. The Architect has, next to the technical expertise, a deep understanding of the elements ‘vagueness’, the ‘blurred’ and the multiple meanings of inhabited spaces. [329]

> On Earth, architects are the professionals who orchestrate the disciplines necessary to create coherent, built solutions that meet the needs of human use. Thus, to establish practical and noble habitable environments, space architects must master many subjects, and this will challenge historical traditions within both the architecture and space industries.[330]

> . . . architectural thinking is comprehensive. Architects are equally comfortable with large scale planning as with detailing a cabinet joint. Within the space community, it is assumed that one person or a small group of people cannot do it all. Much is lost in organizational handoffs and distributed responsibilities. I

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[329] Vogler and Jørgensen, “Windows to the World, Doors to Space: The Psychology of Space Architecture.”

[330] Howe and Sherwood, *Out of This World: The New Field of Space Architecture*, 4.

> have often thought that an architectural approach would benefit spacecraft design.[332]

To summarize, while the Space habitat design undeniably requires contributions by many disciplinary fields, architecture is not widely acknowledged as one of those fields in the aerospace industry. Even the long practicing Space architects with many contributions on the realized Space habitats might still be observed to spend some effort in discussing the relevance of the field of architecture to the aerospace industry, to tell the potential provisions of architecture, which are believed to be more than consulting on habitat designs. On the other hand, the attempt (or need) for rationalizing the design considerations is seen commonly. This attempt might be associated with the "struggle" of communication with the fields that are mostly able to quantitate their considerations.

2.3.2. Technology

The effects of technology on the design process might be examined in two facets: First one being the technology that is used during design-making, and the second one being the technology required for the realization of design.

> The advent of electronic communication devices and information processing machines such as computers has generated a new perspective on human thought.[333]
>
> We are only just beginning to explore the possible ways in which networks of computers can support collaborative work. The roles designers play could very easily be redefined in such a world. It is quite possible that the effect of

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[332] Doule, "Interview: Brand Griffin."

[333] Lawson, *How Designers Think*, 134.

> networks will ultimately have much more of an impact on the design process than has the single humble computer.[334]

The first effect of technology is commonly discussed in the field of architecture. The discussions focus on the perception and the cognitive activities of the designer on one level and the collaborative opportunities on the other. There are various studies suggesting that the methods and tools used for design-making affect the designer's perception and decision-making, therefore the design product.[335] On the other hand, the potentials arising by various software to let the architect be more in communication with the actors of design are also widely studied. The second effect, which might be outlined as the influence on new technologies on the products, is argued to be visible through many buildings and typologies that emerged after the introduction of many different technologies. The field of Space architecture is surely influenced by both categories. Howbeit, the literature of Space architecture includes the studies regarding the latter category. The design of Space habitats relates to technology closely, and design approaches address present and expected technological advancements.

Technology that is available or possible at the time of design can be considered as a strong input to frame the possibilities for the design product. There appears a need for designers and planners to understand the compatibility and reliability of possible technologies that can be used.[336] Considering that the design process for Space habitats stretches to several decades, the need for understanding technologies during this process for the time of application might be recognized as essential. The concept of Technology Readiness Levels (TRLs) is originally developed through NASA studies with the aim of reducing uncertainty in "the three major challenges of any project: performance, schedule and budget."[337] Mankins introduces the definition of the concept as "a systematic metric/measurement system that supports assessments of the

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[334] Bryan Lawson, *What Designers Know* (Architectural Press, 2004), 83.

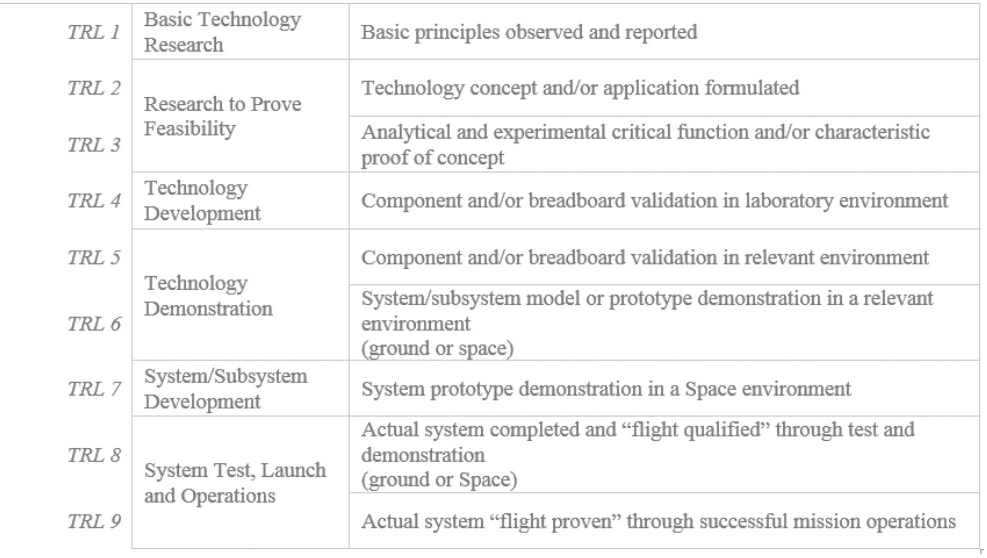
[335] Alberto Pérez-Gómez, "Phenomenology and Virtual Space: Alternative Tactics for Architectural Practice," *OASE*, no. 58 (2001): 35–58.

[336] Häuplik-Meusburger and Bannova, *Space Architecture Education for Engineers and Architects*, 66.

[337] John C Mankins, "Technology Readiness Levels," 1995. For more detailed definitions of TRLs as currently in use: https://www.nasa.gov/pdf/458490main_TRL_Definitions.pdf

maturity of a particular technology and the consistent comparison of maturity between different types of technology," and specifies nine levels for technologies regarding their "maturity" as addressed in *Table 2.3*.[338] Since its introduction, TRL is used and developed by numerous agencies and industries, as being accepted as an effective concept to understand the reliability of technologies.[339] Among many assessment models mapped to TRLs, the concept of Habitation Readiness Levels (HRLs) is also introduced, addressing habitability requirements and design considerations as being acknowledged widely among different agencies, as summarized in *Table 2.4*.[340]

Table 2.3. *Technology Readiness Levels Summary*[341]



TRL 1	Basic Technology Research	Basic principles observed and reported
TRL 2	Research to Prove Feasibility	Technology concept and/or application formulated
TRL 3		Analytical and experimental critical function and/or characteristic proof of concept
TRL 4	Technology Development	Component and/or breadboard validation in laboratory environment
TRL 5	Technology Demonstration	Component and/or breadboard validation in relevant environment
TRL 6		System/subsystem model or prototype demonstration in a relevant environment (ground or space)
TRL 7	System/Subsystem Development	System prototype demonstration in a Space environment
TRL 8	System Test, Launch and Operations	Actual system completed and "flight qualified" through test and demonstration (ground or Space)
TRL 9		Actual system "flight proven" through successful mission operations

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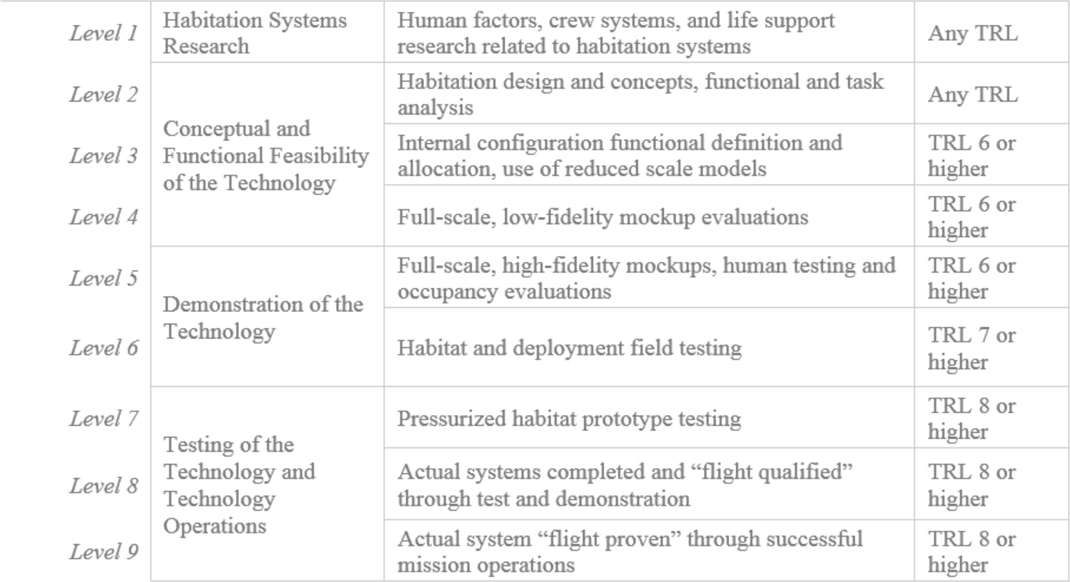
[338] Mankins.

[339] Häuplik-Meusburger and Bannova, *Space Architecture Education for Engineers and Architects*, 66.

[340] Jan Connolly et al., "Definition and Development of Habitation Readiness Level (HRLs) for Planetary Surface Habitats," in *Earth and Space 2006 - Proceedings of the 10th Biennial International Conference on Engineering, Construction, and Operations in Challenging Environments*, 2006, 81, https://doi.org/10.1061/40830(188)81.

[341] Adapted from: Mankins, "Technology Readiness Levels"; Connolly et al., "Definition and Development of Habitation Readiness Level (HRLs) for Planetary Surface Habitats."

Table 2.4. *Habitation Readiness Levels Summary*[342]



Level 1	Habitation Systems Research	Human factors, crew systems, and life support research related to habitation systems	Any TRL
Level 2	Conceptual and Functional Feasibility of the Technology	Habitation design and concepts, functional and task analysis	Any TRL
Level 3		Internal configuration functional definition and allocation, use of reduced scale models	TRL 6 or higher
Level 4		Full-scale, low-fidelity mockup evaluations	TRL 6 or higher
Level 5	Demonstration of the Technology	Full-scale, high-fidelity mockups, human testing and occupancy evaluations	TRL 6 or higher
Level 6		Habitat and deployment field testing	TRL 7 or higher
Level 7	Testing of the Technology and Technology Operations	Pressurized habitat prototype testing	TRL 8 or higher
Level 8		Actual systems completed and "flight qualified" through test and demonstration	TRL 8 or higher
Level 9		Actual system "flight proven" through successful mission operations	TRL 8 or higher

As the dependence on technology in Space architecture is prominent, in the field, one of the widely accepted classifications of habitats is regarding habitats' use of technology. According to this approach, habitats are classified as in *Table 2.5* in "The Vernacular of Space Architecture."[343] Kennedy hypothesizes that while the level of habitats' technology increases in time (from Class I to Class III), infrastructure volume would also increase. The broad studies on expandable and inflatable habitat structures, including one example that is being experimented in ISS,[344] seems to suggest that this claim is accurate. However, ongoing studies on Deep Space Gateway, which are

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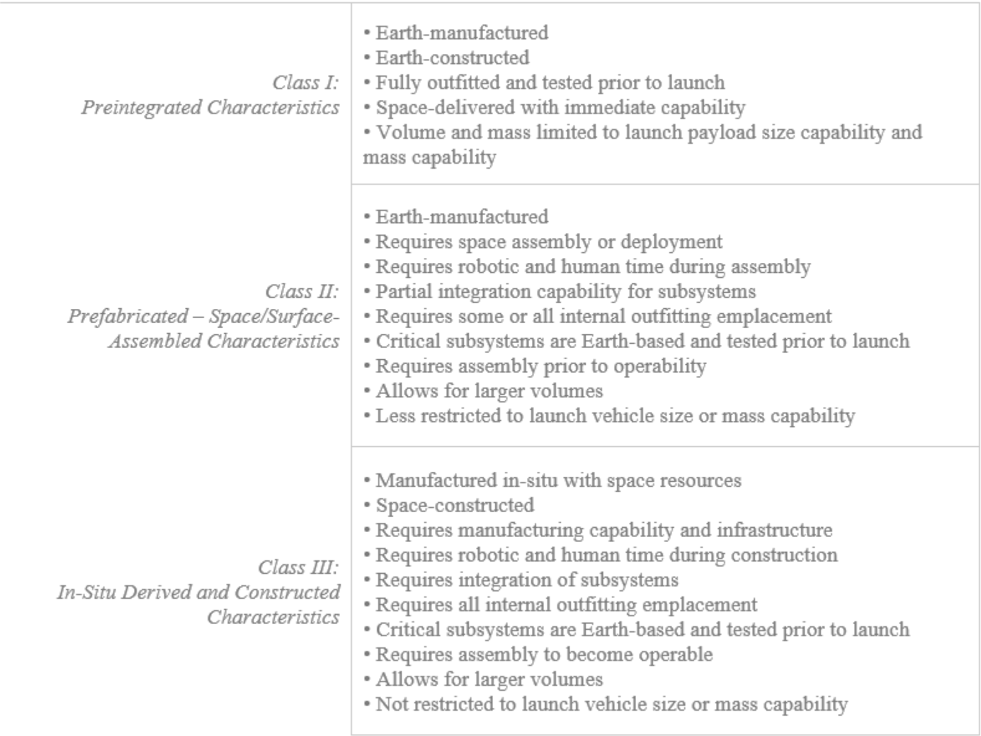
[342] Adapted from: Connolly et al., "Definition and Development of Habitation Readiness Level (HRLs) for Planetary Surface Habitats."

[343] Kennedy, "The Vernacular of Space Architecture."

[344] Kriss J. Kennedy and Constance M. Adams, "ISS TransHab: An Inflatable Habitat," in *Space 2000* (Reston, VA: American Society of Civil Engineers, 2000), 89–100, https://doi.org/10.1061/40479(204)8. BEAM, as an experiment module for TransHab project that has been proposed for Mars Journey, is on orbit attached to ISS since 2016. More information can be gathered from: https://www.nasa.gov/content/bigelow-expandable-activity-module

focusing more on human-environment interaction through technologies like VR as the volume is very restricted, might be suggesting otherwise.

Table 2.5. *Habitat classifications regarding technology*[345]



Class I: *Preintegrated Characteristics*	• Earth-manufactured • Earth-constructed • Fully outfitted and tested prior to launch • Space-delivered with immediate capability • Volume and mass limited to launch payload size capability and mass capability
Class II: *Prefabricated – Space/Surface-Assembled Characteristics*	• Earth-manufactured • Requires space assembly or deployment • Requires robotic and human time during assembly • Partial integration capability for subsystems • Requires some or all internal outfitting emplacement • Critical subsystems are Earth-based and tested prior to launch • Requires assembly prior to operability • Allows for larger volumes • Less restricted to launch vehicle size or mass capability
Class III: *In-Situ Derived and Constructed Characteristics*	• Manufactured in-situ with space resources • Space-constructed • Requires manufacturing capability and infrastructure • Requires robotic and human time during construction • Requires integration of subsystems • Requires all internal outfitting emplacement • Critical subsystems are Earth-based and tested prior to launch • Requires assembly to become operable • Allows for larger volumes • Not restricted to launch vehicle size or mass capability

In addition, the harder it becomes to resupply the habitats, the more the need of self-reliability appears. Cesare claims that regarding atmospheric controls and fire suppression, conducting environmental control operations has been mastered.[346] Even though current technologies provide a level of self-reliability, studies on the subject are ongoing.

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[345] Adapted from: Kennedy, "The Vernacular of Space Architecture."

[346] Häuplik-Meusburger and Bannova, *Space Architecture Education for Engineers and Architects*, 223.

To sum up, advances in some of the following technologies seem promising for Space habitats: Material technologies, 3d printing, robotics, artificial intelligence, virtual and immersive environments, biotechnologies... On the other hand, advances of some technologies might lead to alterations in the design process, hopefully making interdisciplinarity more feasible. It seems safe to assume that upcoming technological developments in that area will affect the overall design of habitats. However, for longer timespans, "forecasting" technologies that are to be available for use, and their implications might not be possible, as Lockard emphasizes that the increased rate of technologies is expected to accelerate.[347] It might be argued that, while the technology, as an extension of human being, alters both the notions of human and her/his environment, the human – environment interaction remains as one of the fundamental questions regarding both the design-making and the design of the human environment.

2.3.3. Funding

The amount of money invested in Space studies is highly effective in research, design, and application of Space habitats. Impacts might be observed at two levels. First, the long-term goals and roadmaps are developed considering the expected budget. In particular, human Mars mission is considered as a funding issue more than it is technical, by many.[348] Second, as the projects spread over decades, highly probable changes of the budget during that time span might redirect design decisions, affecting the final product. ISS lacking the "habitation module," or Skylab being designed with Apollo components that are available at the time, can be given examples for the visible effects of the budget on the projects. Space architects and psychologists mostly emphasize the fact that the "soft" requirements regarding human well-being are the first to get cut-out in case of a budget shortage.

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[347] Lockard, *Human Migration to Space*, chap. 4.1.

[348] Cox and Ince, "The Infinite Monkey Cage: Astronaut Special"; Lluc (ESA) Diaz, "Space and Down to Earth" (Milano: Politecnico di Milano within the course Space for Inspiraction by Dominoni and Quaquaro, 2018).

The source of invested money is primarily effective on the purpose of the designs, which becomes the main determiner of function and user of habitat in addition to the duration of habitation. For example, public funding with the purpose of "putting a man on the Moon,"[349] led to a habitat design which is capable of keeping the crews alive and functional for roughly ten days, whereas "sending humans to Mars"[350] requires designs are apt to sustain and provide crews' living and working both physiologically and psychologically likely for about three years. On the other hand, private investments with purposes like Space tourism bring out necessities like hosting users with totally different profiles compared to mission crews and might also introduce new functions into habitats while emphasizing some existing ones like window gazing. Besides, the source of the investment may also become the determiner of the timespan to achieve the purpose, which can be considered as an important factor affecting design process. It should be noted that such a direct effect of the source of investment is more likely to be seen in missions funded by a single organization.

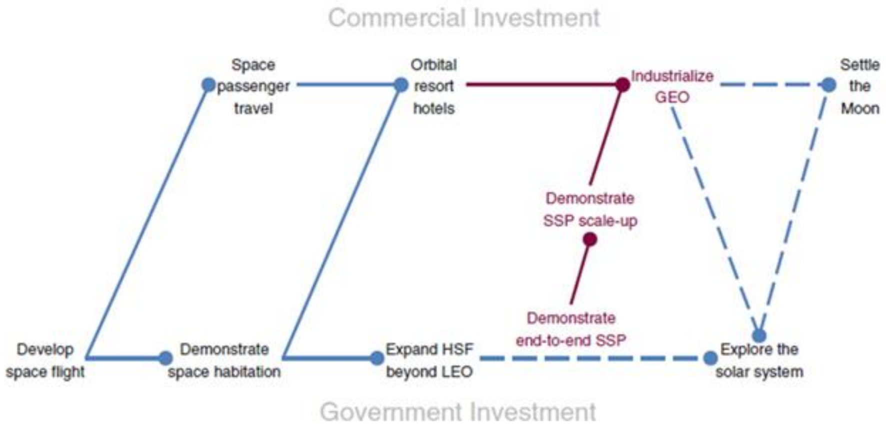

Figure 2.21. Brent Sherwood's suggestion as roadmap of exploration with consideration of funding requirements[351]

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[349] "John F. Kennedy Moon Speech - Rice Stadium," 1962, https://er.jsc.nasa.gov/seh/ricetalk.htm.

[350] Barack Obama, "America Will Take the Giant Leap to Mars," CNN, 2016, https://edition.cnn.com/2016/10/11/opinions/america-will-take-giant-leap-to-mars-barack-obama/.

[351] Häuplik-Meusburger and Bannova, *Space Architecture Education for Engineers and Architects*, chap. 2.6.

It is commonly claimed that goals like human Mars missions require an amount of investment that could not be provided by any public or private organization solely.[352] For such goals, collaborations between multiple public agencies and private entrepreneurs is seen as essential.[353] Sherwood suggests an alternative path to the Space agency model of exploration by including the need for attracting private capital (Figure 2.21). In addition, increased public awareness and interest in the projects are thought to be helpful in promoting this collaboration.[354] Videos that are presenting a view of Mars colonization or terraforming of Mars, architecture or engineering competitions on human spacecraft or terrestrial habitats, movies with the theme of Space exploration etc., which are targeting public attention, can be considered as efforts in contribution to such aim. Furtherly, the importance of spin-in and spin-off technologies is evident regarding fund search. Especially for goals that need an extreme amount of investment (e.g. Moon Village, colonization of Mars etc.) the involvement of the non-Space industry becomes requisite.[355] To ensure that involvement, especially spin-off Space technologies and commercialization provided by those technologies are sought. Space agencies support and produce studies and projects that are focusing on the issue (e.g. ESA: Technology Transfer Program,[356] NASA: Innovative Partnerships Program[357]). Lluc Diaz, from Technology Transfer and Business Incubation Office of ESA, emphasizes that designs for Space should be made with consideration of the issues regarding the commercialization of at least some of the technologies that are to be produced.[358]

In that manner, the interaction between funding and purpose might become converse, as the purpose is not defined by investors, but investors are brought together to achieve

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[352] Häuplik-Meusburger and Bannova, chap. 2.6; Diaz, “Space and Down to Earth.”

[353] Diaz, “Space and Down to Earth.”

[354] Diaz.

[355] Diaz.

[356] “Technology Transfer,” ESA, accessed November 27, 2019, https://www.esa.int/Applications/Telecommunications_Integrated_Applications/Technology_Transfer.

[357] “Innovative Partnerships Program,” NASA, n.d., https://spinoff.nasa.gov/Spinoff2009/ippn_1.html.

[358] Diaz, “Space and Down to Earth.”

the purpose. In that case, the design process might get altered; as in order to provide adequate funding, the design might need to be made with consideration of on-Earth utilizations as much as the primary use of design.

2.3.4. Analogues and Simulations

It might not be possible to replicate the environmental conditions of Space, and the small amount of historical precedents of Space habitation limits the experience-based knowledge. Thus, regarding some intersecting aspects, some habitations are studied as analogues of Space habitation. The intersecting aspects might be outlined as characteristics of extreme environment habitations such as isolation and confinement, limited resources, limited communication...[359] Bishop states that: "The use of extreme environments with characteristics relevant to those inherent in space travel and habitation will play a crucial role in preparing humans for egress from planet Earth."[360] This category of analogues may include submarines, polar stations, previous expeditions (Figure 2.22)... On the other hand, simulations and analogues might be designed with the purpose of investigating a specific condition, such as imitating weightlessness or studying many facets of terrestrial Mars habitation. Examples of the latter category may include Mir training modules, NASA Neutral Buoyancy Laboratory (NBL), Mars500, NASA Extreme Environment Mission Operations (NEEMO), Hawaii Space Exploration Analog and Simulation (HI-SEAS) (Figure 2.23)...

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[359] See 2.2.1

[360] Vakoch, *Psychology of Space Exploration*, 57.

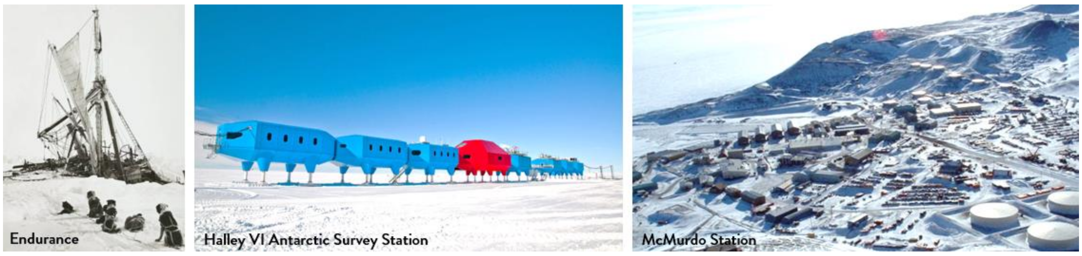

Figure 2.22. Analogues that share some extreme environment characteristics of Space: Endurance (Antarctic expedition ship from early 20th century), Halley VI Antarctic Survey Station, McMurdo Station

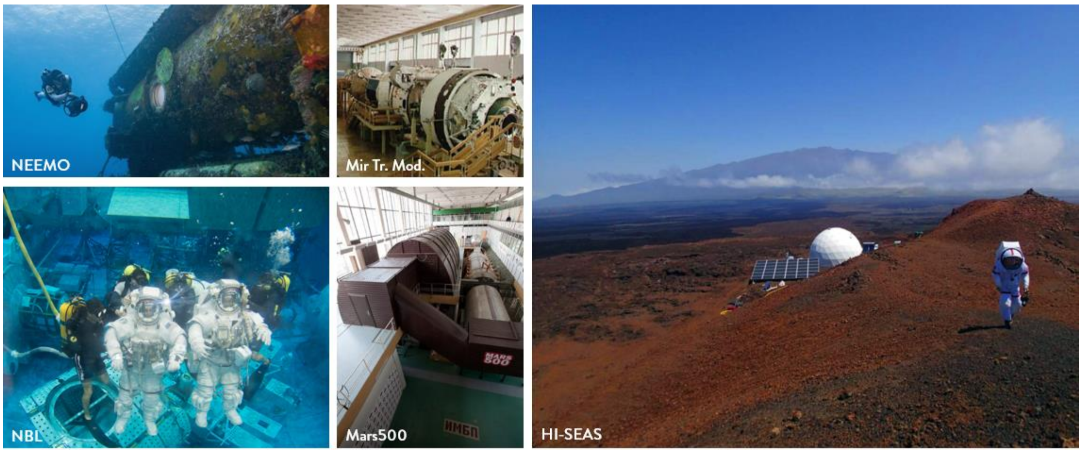

Figure 2.23. Designed habitat simulations: NEEMO, NBL, Mir training modules, Mars500, HI-SEAS

Analogues, simulations, mock-ups, and experiments are valued regarding Space missions and benefit many disciplines, including psychologists, architects, and engineers. As much as the mock-ups and simulations are used for the verification and the presentation of the design, they are used for the training of the crew, and also to support solving some problems after launch. The analogues and simulations are also valued by the researchers studying human behavior. In that manner, habitations on extreme environments on Earth are widely studied. It should be noted that, once an extreme environment is inhabited, then the habitation of that environment might be investigated as an analogue for further challenges. For example, the ISS can be considered as the analogue of the planned missions to Moon orbit, amongst further missions.

The effects of the simulations and analogues might be argued to be confirmed by the experience during the design process of previous habitats. To start with, the early mock-up of Skylab resulted the mission authorities' acknowledgement of the need for improvement in the living conditions through the design. Creator and director of the responsible office of Skylab design, George Mueller later states that "Nobody could have lived in that thing for more than two months, they'd have gone stir-crazy." regarding the mock-up.[361] In addition, the habitat had initially planned to be furnished by astronauts in microgravity.[362] However, causing many challenges, the initial plans with such direction had been changed during the process.[363] Mueller states that the decision to launch the station fully furnished has been made after his own experience of using the neutral buoyancy facility, during which he realized the hardship of performing in weightlessness.[364] A different example might be in regard to a major design decision of Salyut Space Station. Balashova, the architect of the station, states that the decision of designing the habitats with the definition of a local vertical has been made because of the practicality of experimenting that design on Earth prior to launch:[365]

> Back then I drew up two proposals. In the one, we gave the space a floor and a ceiling. . . . That was the case in the Soyuz space capsules, for example. The other idea was not to distinguish clearly between top and bottom but to structure the capsule by means of different volumes. . . . Before our cosmonauts flew into space they trained in identical, true-to-scale models. Here on Earth .

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[361] Compton and Benson, *Living and Working in Space: A History of Skylab*, 133.
[362] Leland F. and Ernst, *Skylab a Guidebook*, chap. 2.
[363] Philip Baker, *The Story of Manned Space Stations* (Springer, 2007).
[364] Bergen, "NASA Johnson Space Center Oral History Project: George E. Mueller."
[365] Seidel, "Interview with Galina Balashova: Only the Watercolors Burned to Nothing."

> . . we all found it easier to work in rooms that had a clearly defined top and bottom.[367]

Throughout the literature, the emphasis on the increasing acknowledgement regarding the importance of the designed environment (i.e. architecture) is evident. It is commonly accepted that the environment which humans interact with affects them on many levels; thus human needs and behavior should be studied with respect to their environment. In that manner, it might be expected the architectural design would be included in the research areas of designed analogues and simulations. However, architects state that the designs of analogs or mock-ups hardly focus on architectural design issues.[368]

2.3.5. Space Habitat Designing Issues

As indicated by the research, the design of a Space habitat is not only shaped by the requirements of the product but depends on many "designing" issues addressing the design-making process and concerns regarding the capacities and capabilities of realization of the design. To summarize, communication capabilities with many disciplines that are involved in design-making becomes an issue; first, while addressing the requirements of the design, and then to satisfy the addressed requirements in the realized design. Technologies that are planned to be used in the realization of the design need to be proved. Furtherly, the high costs that are needed for the realization of the design lead the designer to address not only the requirements of the product but the values that could be used to support funding. The hardship and the uniqueness of the environmental conditions added with the impracticality of the trial-error method, substitutes the need for experimenting the design in Earth

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[367] Seidel, "Interview with Galina Balashova: Only the Watercolors Burned to Nothing."

[368] Cohen, "Space Station Design"; Marc M. Cohen, "Mockups 101: Code and Standard Research for Space Habitat Analogues," in *AIAA SPACE 2012 Conference & Exposition* (Reston, Virigina: American Institute of Aeronautics and Astronautics, 2012); Olga Bannova, "Space Architecture Manual for a Multi-Planetary Future" (Minnesota: University of Minnesota College of Design, 2017).

conditions. Thus, the design should not only be responding to the constraints of the aimed environment but should be experimented in Earth conditions to an extent. The issues and challenges of the design process, therefore, add design considerations. The problem definition extends its scope.

In that manner, the design of the Space habitat does not solely depend on the requirements regarding the final product that is to be realized, but shaped by many factors. The weight of these additional considerations might overcome the requirements and become more effective in the definition of the design.

2.4. Chapter Summary and Discussion

The study illustrates that the design considerations of Space architecture include many factors from various directions, some of which directly related to the requirements of the final product, and some of which process-related. Extreme environment characteristics of Space, even if the Space environments are diverse, might be considered to be shared to an extent for many different kinds of Space habitation. The hardship of reach, hazardous conditions, and limited supplies might be included in the shared challenges.

Inquiries on human – environment interaction might become insufficient with an isolated view focusing solely on human or environment; therefore, the interaction itself might need to become the area of inquiry. Such inquiry requires the inclusion of many qualitative research angles amongst the quantitative issues. The scope of human factors and habitability research for Space habitat design seems to continuously increase in the field, while the acknowledgment of the influence of the architectural design of the habitat to human well-being widens.

Hitherto observations and studies on humans who have lived in the Space environment demonstrate that humans are able to adapt to their environments physiologically and psychologically to an extent, even if the conditions are unfamiliar to their nature.

Nevertheless, some human needs appear commonly in previous examples, and within those needs, the following might be considered as directly related to the spatial arrangement of the habitat: direct visual connection to the outer environment, privacy, socialization, resemblance to familiar conditions (e.g. orientation suggestion in microgravity environments), variety of spatial experience, personalization of the volumes that are lived in...

The realized and planned to be realized Space habitat designs are not only shaped by the considerations regarding the requirements of the final product, but the influence of the design process is evident. The complexity and the uniqueness of the problem call for a design process involving comprehensive research on diverse subjects, with contributions of actors from various disciplinary fields. There is a continuous search including the issues that might be outlined as designing the use, the user, and the production methods of the habitats. Nonetheless, the constraints of Space habitat design might also become limiting: high-risk conditions of human Space missions commonly leading the use of already proven concepts, high costs of production making the use of already existing products and production methods preferable, and the partially fragmented design and production processes... The designs of hitherto realized Space habitats can be argued be to be under the pressure of excessive constraints. Thus, interdisciplinary collaborations and the role of the architect might be limited during the design process, which can become fragmented. As a result, the potentials of Space architecture might be argued to not yet fully reflect on the realized projects. The next chapter, with the intention of examining holistic design approaches within the field, moves on to seek for a design process which is not limited by the conventionalized methods in the aerospace industry, while still taking account of adequately realistic constraints

CHAPTER 3

CASE STUDY

3.1. Research Methodology

The thesis is in search of means and methods of addressing the complex design problem of Space habitation. However, as discussed previously, it can be observed that the product-related design considerations of realized Space habitats are suppressed to a degree under the weight of process-based considerations. Historical examples are not enough to cover the issues regarding the intention of the thesis. As a result, contemporary design approaches within the field are also included in the research.

According to Yin's definition, "[a] case study is an empirical inquiry that investigates a contemporary phenomenon in depth and within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident."[370] This method can be applied when the researcher has little or no control over the examined process.[371] The intent of examining the designs is observing the characteristics and thus gaining insight about their means and consequences. As being fit to the purposes and qualities of the research, the case study method is selected.

The explanatory evaluation of the reasons to be given in the following section, the case is selected as the design proposals and design process of SEArch+ for the NASA 3D-Printed Habitat Challenge. To gain information on the case, the challenge and the proposals are examined. As a result, design considerations and the challenge process have been observed. The sources for this part are the online informational data about the case by the organizational parties, and the research papers and presentations

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[370] Yin, *Case Study Research: Design and Methods*.

[371] Yin.

prepared in relation to the proposals by the design team. However, as the thesis intends to gain insight about the design process as much as the design considerations, more data was needed about the process of the team. To gather such information, semi-constructed interviews with Melodie Yashar, Lance LeBlanc and Monsi Roman are conducted. Melodie Yashar is cofounder of the SEArch+, whereas Lance LeBlanc is a mechanical engineer who has collaborated with SEArch+ for the competition proposals. Monsi Roman is the program manager of the NASA Centennial Challenges. Further information about the interviewees and the interviews can be found in *Table 3.1*.

Table 3.1. *Interviewees*

interviewee 1	**Melodie Yashar** / MHCI, M. Arch, B.A. Industrial Design Co-founder of SEArch+ Team member and team leader for the case proposals	45 minutes / Video call
interviewee 2	**Lance LeBlanc** / Mechanical Engineer Consultant engineer for two of the case proposals	30 minutes / Voice call
interviewee 3	**Monserrate (Monsi) Román** NASA Centennial Challenges Program Manager Marshall Space Flight Center	15 minutes / Voice call

The interviews are semi-constructed. An outline of the questions that have been asked are as follows:

to Melodie Yashar:

- *A considerable amount of researchers define steps of design process as analysis, synthesis, and evaluation. According to the relationship between those steps, design models might be categorized under two general approaches: waterfall (linear) and cyclical. Where would you place your design process in between those two extremes?*

- *You have a relatively large design team, including the consultants. Through the design process, I could assume that their contribution differed during different phases of design. Could you define those differences? Which actors were more involved in different phases of design?*
- *How was the understanding of actors from different backgrounds of different fields?*
- *How was the communication between team members achieved?*
- *How did merging and optimizing various ideas achieved? Has there been appearances of one or more team leaders during different phases of design?*
- *It can be observed that there had been some trade-offs during the transitions from one challenge proposal to other. Even if not reflected to the final proposals, I believe similar trade-offs have been made during the design processes of each proposal. Is it possible to define weights among design considerations? How those trade-offs have been made?*
- *What was the role of architects during the whole design process in your opinion?*
- *You have also worked on Mars Ice Home in collaboration with NASA after the first phase of the challenge. How was the process different from designing the competition entries?*

to Lance LeBlanc:

- *Have the contributions of different actors differed during different phases of design?*
- *How was the understanding of actors from different backgrounds of different fields?*
- *How was the communication between team members achieved?*
- *How did merging and optimizing various ideas achieved? Has there been appearances of one or more team leaders during different phases of design?*
- *Is it possible to define weights among design considerations? How the trade-offs have been made?*

- *What was the role of architects during the whole design process in your opinion?*

to Monsi Roman:

- *How would be the differences regarding process and considerations of the actual Mars habitations?*
- *What did you observed to be different about 3D-Printed Habitat Challenge out of the Centennial Challenges regarding the approaches of the actors during the definition and solving of the design problem?*
- *I assume that the weights of design considerations differed, and not judged strictly by definitions that were made. How were the weight of considerations decided?*
- *What was the role of architects during the whole design process in your opinion?*

3.2. Case Selection: NASA 3D-Printed Habitat Challenge and SEArch+

Realized Space habitats are very few. The International Space Station constitutes one of the newest,[376] and the only currently inhabited example. For the ISS, even if there are still being implementations to the modules, the design of the main shell and system – when considered as finalized before the first launch – has been completed more than twenty years ago. Additionally, as discussed earlier, the realized and to be realized Space habitats' design approaches can be argued to be following conventionalized methods within the aerospace industry. The thesis intends to explore the potentials of alternative design approaches within the field. Thus, the research focus of the study is directed to the habitat designs without the requirement of being already realized. Designs which still take into consideration adequately realistic constraints, while not being limited by the conventionalized methods in the aerospace industry are sought

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[376] Later, Tiangong-1 and Tiangong-2 have been launched but not long-inhabited, and both have de-orbitted.

for. Neil Leach argues: “Just as science fiction often informs developments in science itself, so the realm of ‘design fictions’ can also inform design.”[377] There might be observed increasing interest among architects in Space design. There are increasing architectural competitions resulting generation of a variety of speculative designs for the Moon, Mars or non-terrestrial locations. In that manner, many design competitions might have been examined. Nevertheless, while the value of “design fictions” is recognized, the intent of the study necessitates the examination of “realistic” designs. Consequently, realistic considerations and judging criteria appreciating the complexity of the design problem are sought in the competitions.

Since 2005, as a program of Space Technology Mission Directorate (STMD), NASA organizes Centennial Challenges “to generate revolutionary solutions” to the problems related to Space innovations through “diverse and non-traditional sources.”[378] Previous challenges include CO_2 Conversion Challenge, Vascular Tissue Challenge, Space Robotics Challenge, and Cube Quest Challenge.[379] As declared by NASA, the competitors are not receiving government funding, and “awards are only made to successful teams when the challenges are met.”[381]

> The goal of the program is to stimulate innovation in basic and applied research, technology development, and prototype demonstration that have the potential for application to the performance of the space and aeronautical activities of the administration.[382]

Within Centennial Challenges, as an extension of current roadmaps and plans, NASA partnering with Bradley University[383] have announced a design challenge in 2015 for Mars habitats. The main objective of the challenge was defined as follows:

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[377] Leach, “Space Architecture: The New Frontier for Design Research,” 15.

[378] “Space Technology Mission Directorate,” accessed November 27, 2019, https://www.nasa.gov/directorates/spacetech/home/.

[379] “Space Technology Mission Directorate.”

[381] Ibid.

[382] Ibid.

[383] Allied partner: Bradley University, Sponsor: Caterpillar, Sub-sponsors: Bechter, Brick and Mortar Ventures, American Concrete Institute

> The 3D-Printed Habitat Challenge is a NASA's Centennial Challenges program competition to build a 3D-printed habitat for deep space exploration, including the agency's journey to the Moon, Mars or beyond. The multi-phase challenge is designed to advance the construction technology needed to create sustainable housing solutions for Earth and beyond.[384]

The challenge consisted of three phases distributed within approximately four years (2015-2019). The phases were divided into levels with various objectives and judging criteria (*Table 3.2*). Level 1 and Level 2 of Phase 1, and Level 1 and Level 4 of Phase 3 mostly focused on architectural design of habitats, whereas the other levels gave more weight on construction methods and fabrication technologies. Neither the disciplinary fields of eligible competitors nor the number of members of a team was limited. Therefore, it can be interpreted that the challenge has not focused on specific disciplines; rather the focus has been on the requirements of the design product. In fact, the program manager of centennial challenges, Monsi Roman, puts emphasis on the matter that the challenge was not initially targeting architects: "We were not targeting architects for this competition. We are very glad that they joined, and they had so much to contribute. However, the competition was not geared towards architects. We knew they could participate as well as the people from other disciplines."[385] The judging criteria of the proposals have been defined detailly. Yet, in the webinars, it was stated that the evaluation of proposals in architectural design phases had not been according to a "checklist," but rather the subjectivity of the jury had been supported.[386] Regarding the signified qualities, it can be concluded that the design competition was in search of a solution for a complex design problem within the aerospace industry, while not being suppressed by the conventionalized design methods in the industry. Thus, the challenge is selected for further study.

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[384] "NASA's Centennial Challenges: 3D-Printed Habitat Challenge," NASA, accessed November 27, 2019, https://www.nasa.gov/directorates/spacetech/centennial_challenges/3DPHab/.

[385] Monsi Roman, "Personal Interview," 2019.

[386] "NASA's 3D-Printed Habitat Challenge," Bradley University, accessed November 27, 2019, https://www.bradley.edu/sites/challenge/webinar/.

In Spring 2019, the challenge was finalized. The winners of all levels can be followed in *Table 3.3*. The winner proposals of the levels that have more weight on the architectural design concept and their submitted visualizations of the projects can also be followed through Figure 3.1. As observed, Space Exploration Architecture (SEArch+), partnering with Clouds Architectural Office[387] in Phase 1, and partnering with Apis Cor[388] in Phase 2 and Phase 3, shows a continuum of participance and nomination through the architectural design levels. The team has developed three different proposals for human Mars habitation for the challenge. Regarding the continuum through the challenge and the large interdisciplinary team (), design proposals and process of SEArch+ and the collaborators are selected as the case study.

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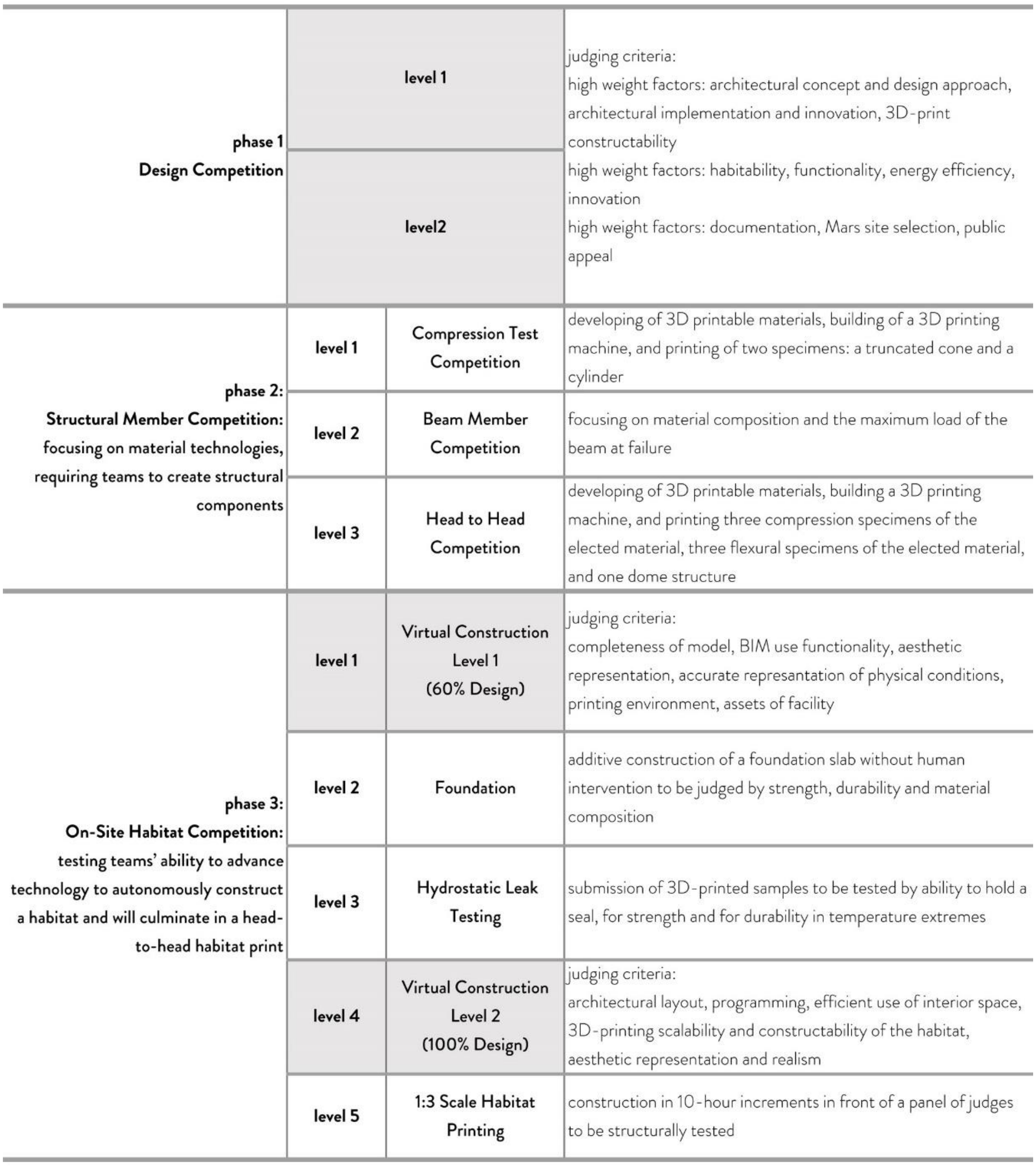
[387] "Clouds AO," accessed November 27, 2019, https://cloudsao.com/.

[388] Apis Cor is a company developing equipment for 3D printing in the construction industry. "Apis Cor: We Print Buildings," accessed November 27, 2019, https://www.apis-cor.com/.

Table 3.2. *The 3D-Printed Habitat Challenge phases overview*[389]



phase 1 **Design Competition**	**level 1**		judging criteria: high weight factors: architectural concept and design approach, architectural implementation and innovation, 3D-print constructability
	level2		high weight factors: habitability, functionality, energy efficiency, innovation high weight factors: documentation, Mars site selection, public appeal
phase 2: **Structural Member Competition: focusing on material technologies, requiring teams to create structural components**	**level 1**	Compression Test Competition	developing of 3D printable materials, building of a 3D printing machine, and printing of two specimens: a truncated cone and a cylinder
	level 2	Beam Member Competition	focusing on material composition and the maximum load of the beam at failure
	level 3	Head to Head Competition	developing of 3D printable materials, building a 3D printing machine, and printing three compression specimens of the elected material, three flexural specimens of the elected material, and one dome structure
phase 3: **On-Site Habitat Competition: testing teams' ability to advance technology to autonomously construct a habitat and will culminate in a head-to-head habitat print**	**level 1**	Virtual Construction Level 1 (60% Design)	judging criteria: completeness of model, BIM use functionality, aesthetic representation, accurate represantation of physical conditions, printing environment, assets of facility
	level 2	Foundation	additive construction of a foundation slab without human intervention to be judged by strength, durability and material composition
	level 3	Hydrostatic Leak Testing	submission of 3D-printed samples to be tested by ability to hold a seal, for strength and for durability in temperature extremes
	level 4	Virtual Construction Level 2 (100% Design)	judging criteria: architectural layout, programming, efficient use of interior space, 3D-printing scalability and constructability of the habitat, aesthetic representation and realism
	level 5	1:3 Scale Habitat Printing	construction in 10-hour increments in front of a panel of judges to be structurally tested

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[389] Data from: "NASA's Centennial Challenges: 3D-Printed Habitat Challenge"; "NASA's 3D-Printed Habitat Challenge - Phase 2," Bradley University, accessed November 27, 2019, https://www.bradley.edu/sites/challenge-phase2/; "NASA's 3D-Printed Habitat Challenge - Phase 3," Bradley University, accessed November 27, 2019, https://www.bradley.edu/challenge; "Structural Member Competition Rules" (NASA & Bradley University, 2017); Tracie J. Prater et al., "NASA's Centennial Challenge for 3D-Printed Habitat: Phase II Outcomes and Phase III Competition Overview," 2018.

Table 3.3. *The 3D-Printed Habitat Challenge nominations*[390]

phase 1	**level 1**	10.9.2015	Tomasz Dzieduszynski, Hybrid Composites, Mars Terrain Intelligence Collaborative, MP1-S7, Team Staye, N.E.S.T., A.R.C.H., Red House, Team Neiro, Rustem Baishev, **SEArch+ and Clouds AO**, SICSA, LeeLabs, Martian Domes, RedWorks, Digital Structures, CTLGroup Mars, MOA Architecture, GAMMA, SPACE IS MORE, PARALLAX, WSU 3D Printing Research Team, MASS, NBVS, LavaHive, Tridom, Mars Hab N1, 3D Fabrication Technology (3DFABTECH), ImMoDe, IRONLIGHT
	level2	27.9.2015	1. **SEArch+ and Clouds AO** 2. Team Gamma 3. Team LavaHive
phase 2	**level 1**	4.5.2017	1. Foster + Partners | Branch Technology 2. University of Alaska
	level 2	6.7.2017	1. Moon X Construction 2. Form Forge 3. Foster + Partners | Branch Technology 4. University of Alaska 5. CTL Group Mars 6. ROBOCON
	level 3	28.8.2017	1. Foster + Partners | Branch Technology 2. Penn State Den@Mars
phase 3	**level 1**	28.6.2018	ALPHA Team, Colorado School of Mines and ICON, Hassell & EOC, Kahn-Yates, Mars Incubator, AI. SpaceFactory, Northwestern University, **SEArch+/Apis Cor**, Zopherus, X-Arc
		23.7.2019	1. Zopherus 2. AI. SpaceFactory 3. Kahn-Yates 4. **SEArch+/Apis Cor** 5. Northwestern University
	level 2	22.8.2018	1. **SEArch+/Apis Cor** 2. Pennsylvania State University 3. FormForge|Austin Industries|WPM
	level 3	1.2.2019	1. **SEArch+/Apis Cor** 2. AI. SpaceFactory 3. Pennsylvania State University 4. Colorado School of Mines and ICON
	level 4	27.3.2019	1. **SEArch+/Apis Cor** 2. Zopherus 3. Mars Incubator
	level 5	5.5.2019	1. AI. SpaceFactory 2. Pennsylvania State University

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[390] Data from: “NASA’s Centennial Challenges: 3D-Printed Habitat Challenge”; “NASA’s 3D-Printed Habitat Challenge - Phase 2”; “NASA’s 3D-Printed Habitat Challenge - Phase 3”; “Structural Member Competition Rules”; Prater et al., “NASA’s Centennial Challenge for 3D-Printed Habitat: Phase II Outcomes and Phase III Competition Overview.”

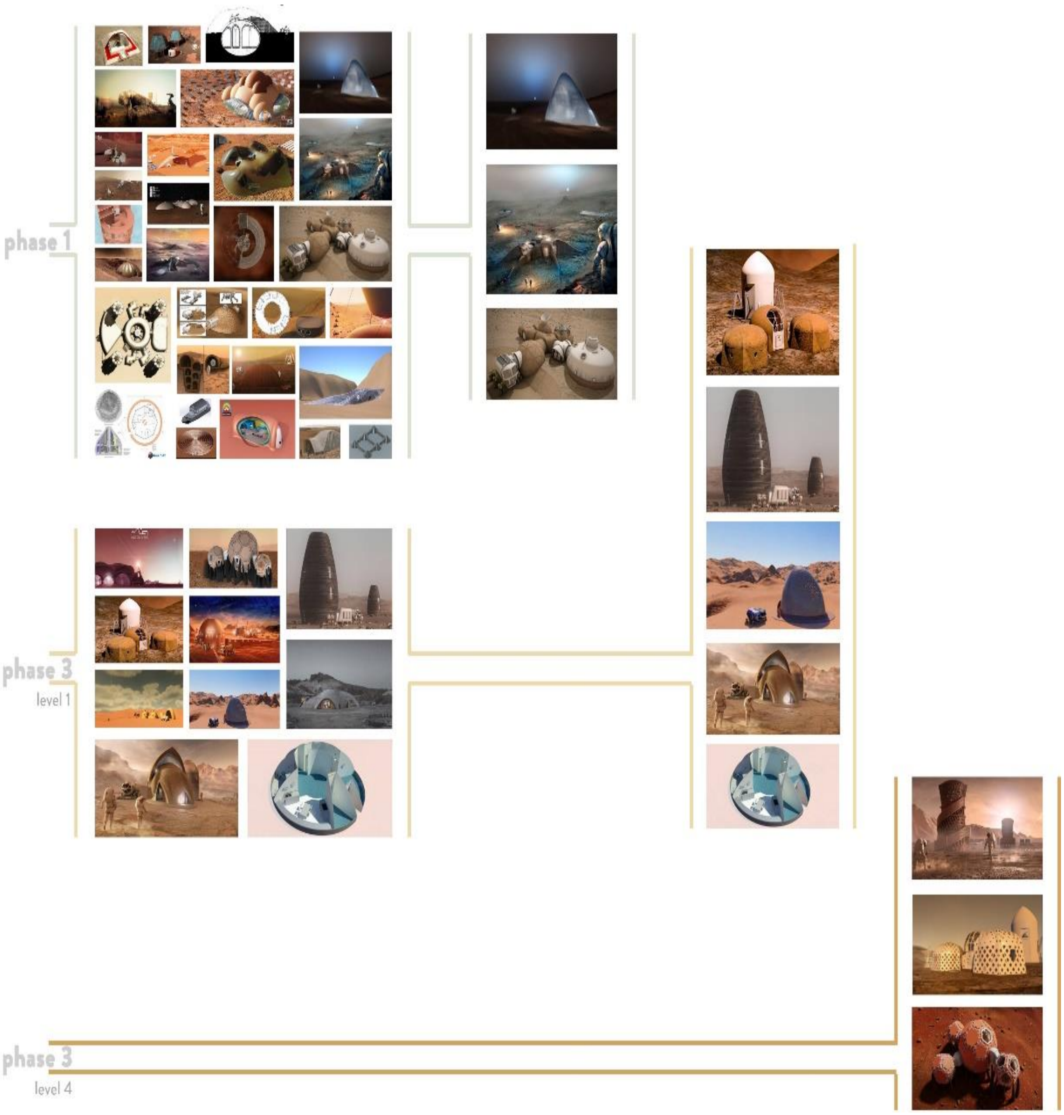

Figure 3.1. Nominations in architectural design levels of the 3D-Printed Habitat Challenge

Table 3.4. *SEArch+ team members and the collaborators for the challenge*[391]

Mars Ice House	**Mars X House V.1**	**Mars X House V.2**
Project Team	**Project Team**	**Project Team**
- Christina Ciardullo; SEArch - Kelsey Lents; SEArch - Jeffrey Montes; SEArch - Michael Morris; SEArch **- Melodie Yashar; SEArch** - Ostap Rudakevych; CloudsAO - Masayuki Sono; CloudsAO - Yuko Sono; CloudsAO	- Christina Ciardullo, SEArch+ - Nikita Cheniuntai, Apis Cor - Michael Morris, SEArch+ - Sergey Nefedov, Apis Cor - Rebeccah Pailes-Friedman SEArch+ - Melodie Yashar, SEArch+ / team leader	Principal: - Christina Ciardullo, SEArch+ - Nikita Cheniuntai, Apis Cor - Michael Morris, SEArch+ - Sergey Nefedov, Apis Cor - Rebeccah Pailes-Friedman SEArch+ **- Melodie Yashar, SEArch+ / team leader** Associate: - Geoffrey Bell - Layla van Ellen - Nihat Mert Ogut - Tianhui Shen - Reece Tucker
Research consultants		**Consultants**
- Jared W. G. Atkinson; Planetary Geophysics, MIT - Maria Banks PhD; Geology and Planetary Scientist, Planetary Sciences Institute - Kim Binstead PhD; Associate Professor, ICS Depatment, University of Hawaii - Eric Barnett PhD; Research Associate, Department of Mechanical Engineering, Laval University - Casey J. Handmer PhD; Applied Mathematics, California Institute of Technology - Stefan Harsan Farr; Engineer and Software Architect - Jeffrey H. Hoffman PhD; Professor of Practice of Aerospace Engineery, MIT Department of Aeronautics and Astronautics - Norbert Koemle PhD; Geophysics, Austrian Academy of Sciences, Space Research Institute - Petr Novikov; Co-Founder of Asmbld Construction Robotics - Yaz Khoury, Electrical Engineer at Asmbld Construction Robotics - Javier Roa; Orbital Mechanics/Aerospace Engineering, Technical University of Madrid and JPL Research Associate - Pavlo Rudakevych; Roboticist and Aerospace Engineer, Aviator - Markus Scheucher; Physics and Space Sciences, Karl Franzens University of Graz - Pieter Sijpkes, Associate Professor (ret.), School of Architecture, McGill University Special Thanks: - Dr. Ron Turner, ANSER Distinguished Analyst - Lawrence W. Townsend PhD, Chancellor's Professor of Nuclear Engineering, University of Tennessee		- Sam Austin, PhD, CEAmerica - Daniel Case, University of Colorado - Jeffrey H. Hoffman, MIT Department of Aeronautics and Astronautics **- Lance LeBlanc, LeBlanc Design** - Matt Melnyk, Nous Engineering - Modulus Consulting - Robert Moses, NASA Langley Research Center - Edward J. Roberts, LERA - Jeffrey Schantz, Sector Leader of Science + Technology at EYP Inc.

3.3. Design Proposals Overview

The team has provided three different proposals during the challenge. The first one, Mars Ice House, has been developed for Phase 1 of the challenge in 2015. After the finalization of Phase 1, the team has also worked with Kevin Kampton from NASA Langley Research Center in developing another concept using H_2O printing. However, the competition has progressed by minimizing or eliminating the use of water for 3D-printing. The second and third proposals, Mars X House V.1 and V.2, are proposals using mostly regolith-based materials, which have been submitted for Level 1 and

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[391] Melodie Yashar, email.

Level 4 of Phase 3. The team publishes papers demonstrating the research and considerations regarding the proposals. The papers include a wide range of design considerations from providing psychological and physiological well-being of human to the material composition of the shell. Additionally, their presentations of the proposals include many aspects that are regarded necessary for building on Mars, from the design of the 3D-printer that could fit in the launch vehicle to the methods of material collection for construction on Mars. While this thesis highlights the human-related design considerations of the proposals more, it should be noted that the research of the team includes analysis regarding site selection, material composition, autonomous printing techniques, robotics, structural capabilities, and the provision of radiation protection of the habitat... Both quantitative and qualitative evaluation of design decisions are being discussed by the team in their presentations and research papers.

3.3.1. Mars Ice House

> In designing a habitat for human Mars mission, the concern is not entirely based on structural optimization, nor in environmental conditioning, but also in human experience. After establishing a baseline for the essential human needs, and requirements of the habitat to be made from in-situ materials that would provide radiation protection, thermal comfort, volumes for human habitation, and creating transcendent spaces for celebrating our collective aspiration to pioneer and explore Mars. Based on these requirements and the availability of the material, H_2O was selected as a possible candidate construction material.[392]

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[392] Michael Morris et al., "Mars Ice House: Using the Physics of Phase Change in 3D Printing a Habitat with H2O," in *AIAA SPACE 2016* (Reston, Virginia: American Institute of Aeronautics and Astronautics, 2016), https://doi.org/10.2514/6.2016-5528.

The most significant characteristic of the project might be signified as the choice of building material: H_2O. The team delineates the reason for this particular choice through the realization of the risks of using regolith, radiation protection, availability,[393] and finally, providing translucency may be above all.[394] The emphasis on translucency requirement is regarding human well-being. The team argues that, even if the artificial replacements to natural light are widely studied, "artificial substitutes do not hold the same circadian variance or ability to balance a crew's mental and physical health as does experiencing the sun's actual and unmediated daily cycles."[395] Therefore, to be able to make use of natural light cycles on Mars, the protective shell has been designed to have a level of translucency (Figure 3.2). To prevent the sublimation of water into the low-pressure atmosphere of Mars, the pressure boundary has been placed on the exterior. The team has explored the opportunity of 3D-printing within a pressurized volume through the spatial configurations.

A noteworthy feature of the proposal might be the spatial arrangement to create and outdoor-like environment within the pressurized volume. This volume has been designed as a "front yard pocket" in between the core of the habitat and the outer environment.[396] By providing a "neutral zone that is not entirely interior or exterior," the project aims to enable an "outside experience" to the habitants without the requirement of donning a suit.[397] The in-between space is also defined to be thermally separated from the "interior,"[398] which could support the experience of being outside. On the other hand, creating two shells is also stated to be used for providing redundancy.[399] To disrupt the potentially monotonous living conditions, a vertical

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[393] H_2O was proposed to be used as an in-situ material, the design was foreseeing the source of the material as Martian atmosphere or Martian surface ice.

[394] Morris et al., "Mars Ice House: Using the Physics of Phase Change in 3D Printing a Habitat with H2O."

[395] Morris et al.

[396] Morris et al.

[397] Morris et al.

[398] Morris et al.

[399] Kelsey Lents, "Building a Home: From Earth to Mars" (Frankfurt: TEDx Talks, 2017), https://youtu.be/BCDRvBk7XPc.

"greenhouse" around the central core has been included in the design. The greenhouse has also been suggested to use as a supplement for food and oxygen and for supporting thermal control.[400]

Figure 3.2. Mars Ice House

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[400] Morris et al., "Mars Ice House: Using the Physics of Phase Change in 3D Printing a Habitat with H2O."

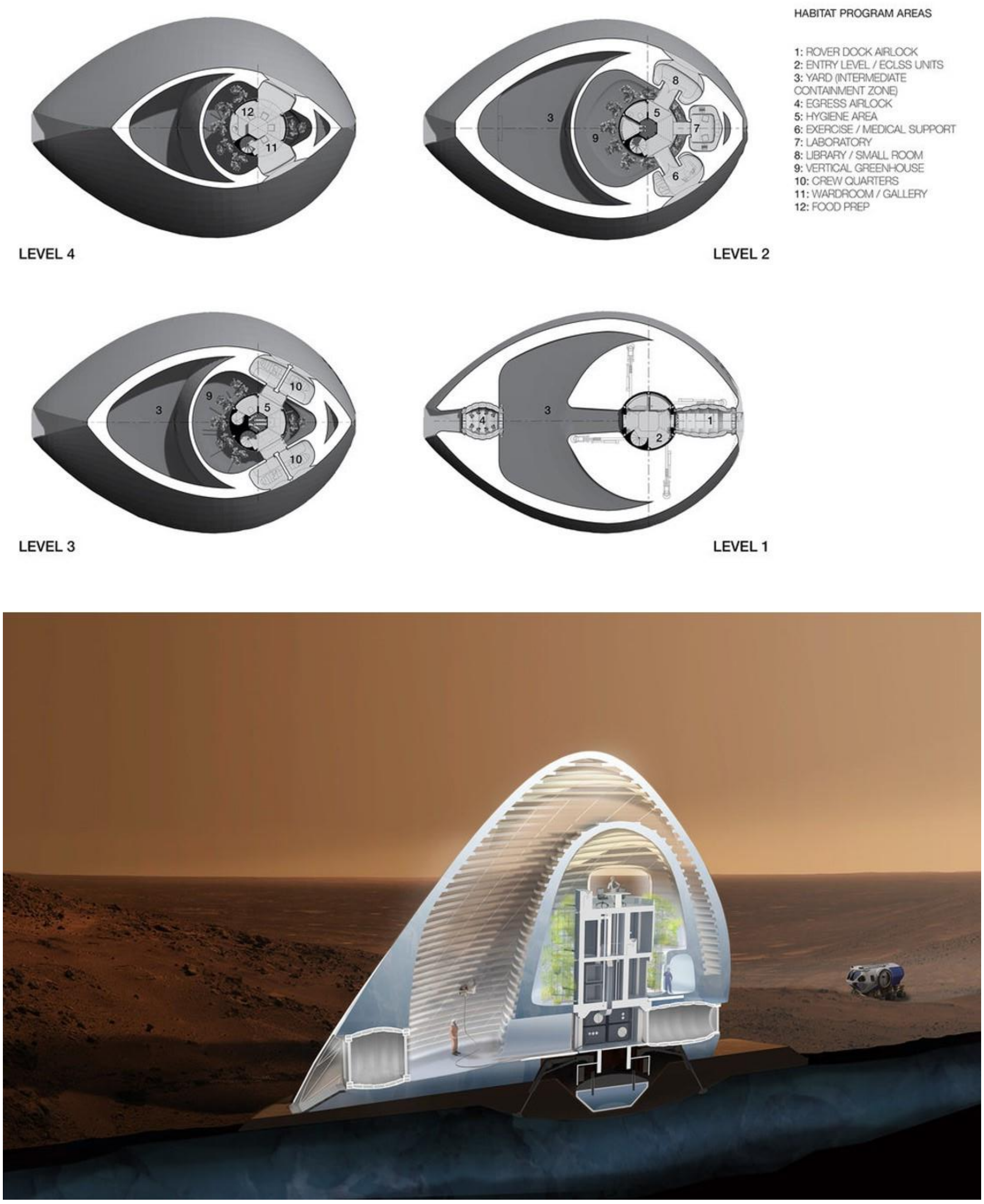

Figure 3.3. Mars Ice House: Spatial allocation

Figure 3.4. Mars Ice House: The use of translucency of the shell

Furtherly, the team elaborates on the meaning and the conceptual benefits of the building technique. They emphasize that the potentials of 3D-printing include the opportunity of not necessarily designing floors, ceilings, and walls, but defining programmatic “hollowed-out” spaces (Figure 3.3).[401] Interestingly, the team also puts emphasis on the symbolic meaning of the habitat. The use of translucency is important to them both for letting the sunlight in, and for letting the light of the habitat out (Figure 3.4). “[T]he architecture celebrates the presence of a human habitat as a beacon of light on the Martian surface creating a landmark for human habitation that would create an inspirational vision for those remaining home on Earth.” [402]

3.3.2. Mars X House V.1

Design considerations regarding human well-being are preserved. As the use of H_2O was restricted by the revised competition rules,[404] the design has been made to respond to the same considerations by different means (Figure 3.5). The concept provides the pressure boundary with a composite system of 3D-printing and inflatables. The printed regolith shell is used mostly for radiation shielding, while the inner layer is responsible for the pressure seal. This decision has been driven by the team’s caution about the protective structure. Pressure difference being the force the structure needs to resist; they have preferred the use of a tensile structure over a compression-intensive structure.[405] The form of the habitable volume has been chosen to withstand the force of pressure. “Formally, inflatables are vertically oriented pill shape structures. This pressure form shows little increase in tension stresses on the pressure body, while creating more opportunity for habitable floor space.”[406] The thickness of the printed shell has been arranged to provide necessary radiation protection, and the functional layout within the shell has been evaluated accordingly (Figure 3.6).[407] The location of the site has been selected in a valley, to make use of radiation protection the

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[401] Morris et al.

[402] Morris et al.

[404] “NASA’s 3D-Printed Habitat Challenge - Phase 3.”

[405] Melodie Yashar et al., “Mars X-House: Design Principles for an Autonomously 3D-Printed ISRU Surface Habitat,” in *The 49th International Conference on Environmental Systems* (Boston, Massachusetts, 2019).

[406] Yashar et al.

[407] Yashar et al.

atmosphere might provide under 30° above the horizon.[408] The areas in which it is expected for the crew to spend more time have been located where the shell provides more radiation protection.[409] On the other hand, greenhouses have been designed where the crew had visual access through inner windows, with the attempt to create a sense of "looking outside."[410] To provide redundancy, the architectural layout of the habitat has been defined to have two separate airlocks with access to the two main habitable volumes and to the exterior (Figure 3.7).[411] The airlocks have been designed identical of size as well as the habitable enclosures, "to introduce manufacturing efficiencies anticipating future scalability of the design."[412]

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[408] Yashar et al.

[409] Yashar et al.

[410] Yashar et al.

[411] "X-House: Level 1 Submission SEArch / Apis Cor," 2019, https://vimeo.com/spacexarch/xhouse.

[412] Yashar et al., "Mars X-House: Design Principles for an Autonomously 3D-Printed ISRU Surface Habitat."

Figure 3.5. Mars X House V.1

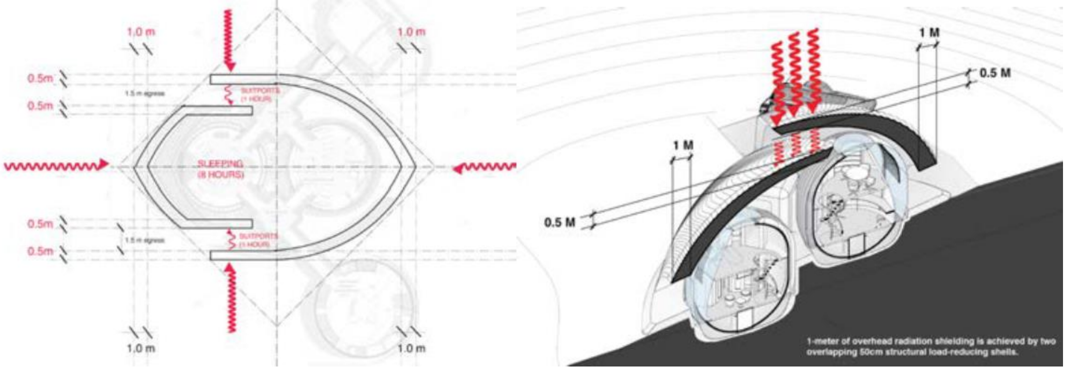
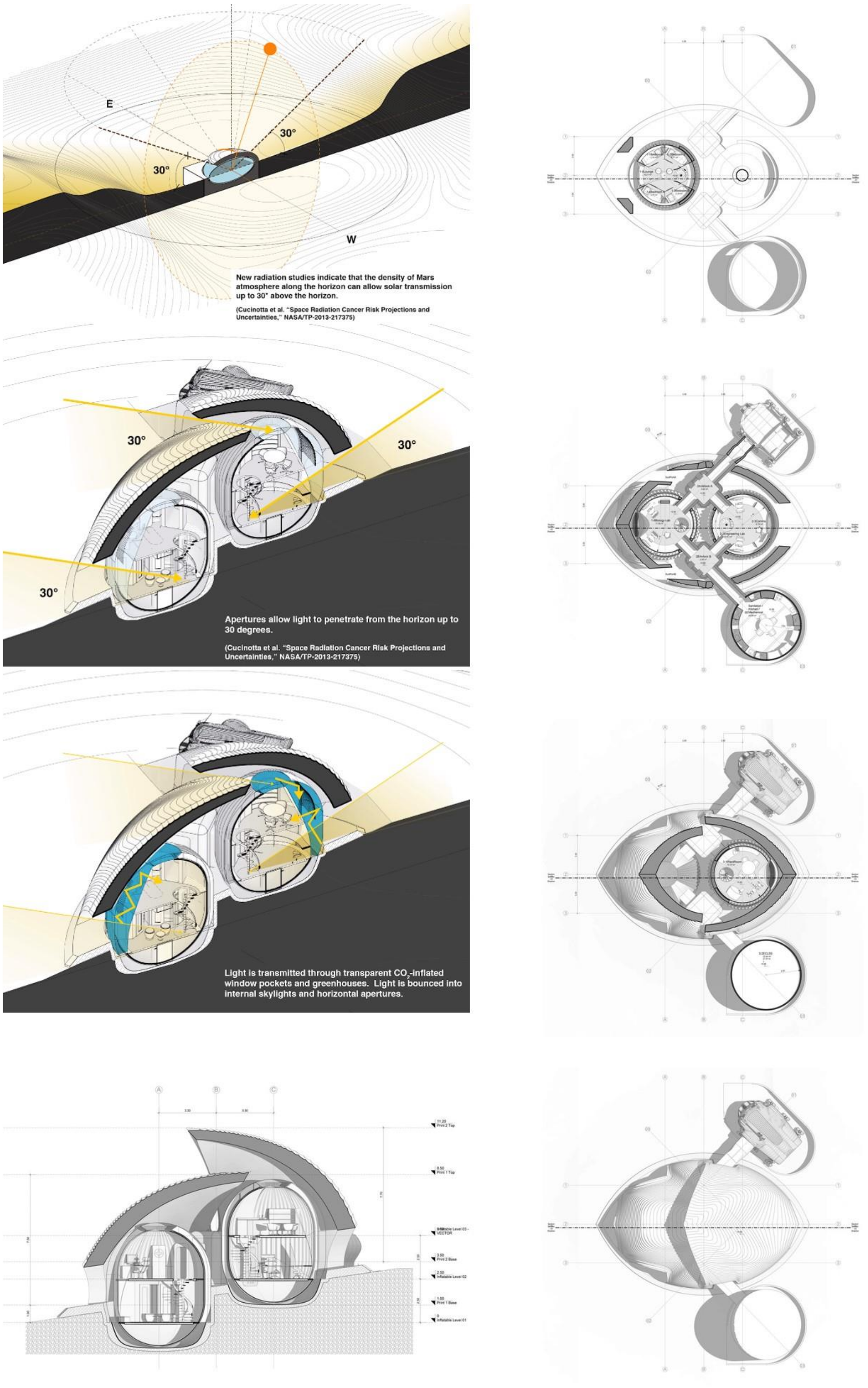


Figure 3.6. Mars X House V.1: Radiation protection



New radiation studies indicate that the density of Mars atmosphere along the horizon can allow solar transmission up to 30° above the horizon.

(Cucinotta et al. "Space Radiation Cancer Risk Projections and Uncertainties," NASA/TP-2013-217375)

Apertures allow light to penetrate from the horizon up to 30 degrees.

(Cucinotta et al. "Space Radiation Cancer Risk Projections and Uncertainties," NASA/TP-2013-217375)

Light is transmitted through transparent CO_2-inflated window pockets and greenhouses. Light is bounced into internal skylights and horizontal apertures.

Figure 3.7. Mars X House V.1: Spatial allocation

3.3.3. Mars X House V.2

The most significant difference of the second Mars X House Concept from the first one might seem like the form of the habitat (Figure 3.8). However, the redefinition of the form is based on the shift of one of the main design decisions. Mars X House V.2 uses the printed shell alone as the proposal "assumes and supports the competition challenge brief that the 3D-printed structure may also provide the necessary pressure boundary."[413] To comprehend the pressure difference without a tensile structure, the 3D-printing material composition and shell layers have been reevaluated, while the form of the habitat has been redefined as a hyperboloid cylinder, and to resist the upward force caused by inner pressure, the water bladder of the habitat placed on the top of the structure (Figure 3.9).[414] The functions have been allocated within the redefined habitable volume (Figure 3.10). Human well-being related design considerations remaining the same, visual connection to the exterior has still been provided, the 3D-printed habitat included windows. The depths of the windows have been arranged to maintain radiation protection to a level, while the light entrance angle maintained at lower degrees.[416] The distribution of the spatial functions has been done according to the time to be spent in the volume for radiation protection.[417] Vertical hydroponic greenhouses have been placed within the MEP walls with a harvesting opportunity through the central staircase. The bedroom windows have been provided with the view of the greenhouse.[418] To provide redundancy in a one enclosed volume, mechanical services have been cellularized, and divisions between separate areas have been provided by airlocks that can be used in case of an emergency.[419] The design has

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[413] Yashar et al.
[414] "SEArch+/Apis Cor - Phase 3: Level 4 of NASA's 3D-Printed Habitat Challenge" (NASA Marshall Space Flight Center, 2019), https://youtu.be/W4pxp5AGeNE.
[416] Yashar et al., "Mars X-House: Design Principles for an Autonomously 3D-Printed ISRU Surface Habitat."
[417] "SEArch+/Apis Cor - Phase 3: Level 4 of NASA's 3D-Printed Habitat Challenge."
[418] Yashar et al., "Mars X-House: Design Principles for an Autonomously 3D-Printed ISRU Surface Habitat."
[419] Yashar et al.

also included an exterior stair maintaining a connection in between floors and to the exterior if needed (Figure 3.10).[420]

Figure 3.8. Mars X House V.2

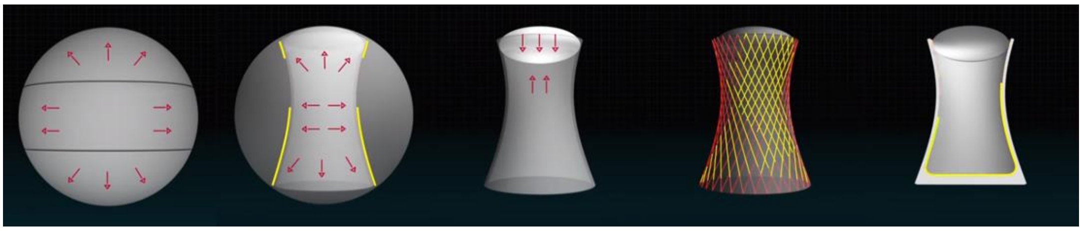

Figure 3.9. Mars X House V.2: Form definition

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[420] Yashar et al.

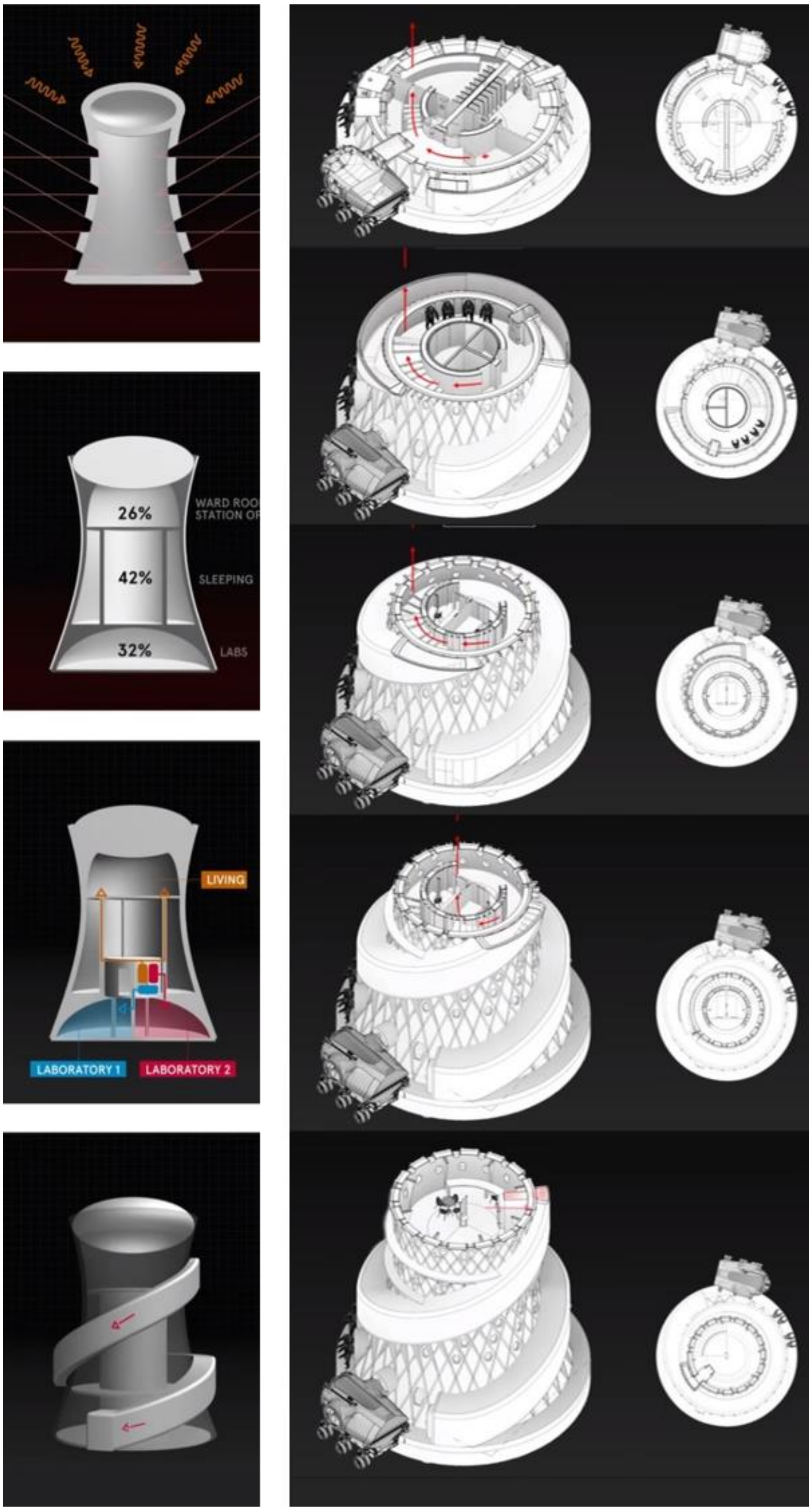

Figure 3.10. Mars X House V.2: Spatial allocation

3.4. Case Analysis: Design Considerations and Design Process

As being defined by the mission specifications and design requirements by the competition organization (*Table 3.5*), some of the design considerations, as well as the habitat design issues, have been fixed. Figure 3.11 is illustrating some of the key design considerations of all three proposals which are in interest of the thesis study. It might be observed that the definition of the environmental factors and human factors as the design drivers have not changed significantly, while the means of addressing those factors by the design of the habitat have altered. As expressed by the team, "the rigorous and evidence based design development process led to different and specific results out of the same human-centered approach for health and safety with material and methods for autonomous fabrication at the core."[421]

The team frequently states that the design proposals intend to support humans to thrive, not just to survive. This emphasis constitutes an important asset in the definition of shared considerations. The need for the alteration in addressing those considerations is observed to be closely associated with the changes or redefinitions in the requirements of the competition in the first place. Initially, the materials that can be used have not been signified, but only the requirement of using indigenous materials has been included in the rules of the competition.[422] After the Mars Ice House has won Phase 1 unanimously, Yashar says that there has been a strong objection by a senior technologist in the Advanced Products Development, as the offered technology has not found mature enough to work with by him.[423] Consequently, the competition has not proceeded with the Phase 1 winner concept as it had been planned, rather the competition has been reinstated from scratch for Phase 2, including rules inhibiting the use of water.[424] It might be important to note that there has been an interest in the same concept from the Game Changing Development

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[421] Morris et al., "Mars Ice House: Using the Physics of Phase Change in 3D Printing a Habitat with H2O."
[422] Yashar, "Personal Interview."
[423] Yashar.
[424] Yashar.

Program, leading to a feasibility study in Langley Research Center.[425] It might be interpreted as the concept has been found promising, but not applicable in the short time challenge offers. Yashar states that the intention of the competition at the time has been exploring potentials of using polymer-based materials instead of cementitious 3D-printing, which requires the use of water.[426] However, when it has been observed that this decision prevents printing fast enough, eventually, water has been re-introduced for Phase 3 while the cementitious 3D-printing has been recognized as a viable technology.[427] This process might shed light on the decision to change the design from Phase 1 to Phase 3. As ice-printing not being an option, Mars X House V.1 and V.2 have been designed with the use of regolith for the structure. The levels these proposals have been submitted are also referred to as "60% Design" and "100% Design," indicating the expectation of transition from design development to construction drawings. However, unlike the other participants, the team has changed the whole concept. Yashar explains this decision has been driven by the feedback they have had, which has been specific on the issue that the primary pressure membrane of the habitat should be the 3D-Printed shell, and adds: "The objective was to test the construction prototyping as well as the design: whether 3D-printed structures can actually create an air-tight volume containing atmosphere and have a pressurized interior."[428] As a result, even if the team believes that the proposal with the composite shell is a valid concept, regarding the competition objective and brief, they have switched to a system that provides the seal with the 3D-printed structure.[429] From their research papers and the presentations, it can be tracked how the change of the structural definition affects the form and consequently almost all design decisions.[430]

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[425] "A New Home on Mars: NASA Langley's Icy Concept for Living on the Red Planet," 2016, https://www.nasa.gov/feature/langley/a-new-home-on-mars-nasa-langley-s-icy-concept-for-living-on-the-red-planet.

[426] Yashar, "Personal Interview."

[427] Yashar.

[428] Yashar.

[429] Yashar.

[430] See 3.3.

Table 3.5. *The given specifications and requirements of the 3D-Printed Habitat Challenge*

mission specifactions	year	2035
	crew	4 people jobs: geologists, land surveyors, propectors, biologists, and engineers
	duration of stay	1 year
	site	to be specified by competitors: construction site on Mars and analog location for the Earth-based training habitat
requirements	total habitable area	92.9 m2 (1000 ft2)
	specified equipment	minimum of 3 x 1.3 m3 (45ft3) volume allocated for ECLSS equipment
	other specifications	Everything needed to comfortably sustain human life including cooking areas, sleeping quarters and bathroom facilities should be considered. Use of the space must be optimized for the comfort and utility of four resident astronauts. Consideration should be given to life sustaining needs, research tasks, and recreational activities.
	structural requirements	self-supporting structures that incorporate a foundation (must be self-supporting in 1G for testing availability)
	construction method	semi-autonomous 3D-printing 3D-Printer shall be self-contained, transportable, and deployable
	materaial	in-situ resources (material table are given in Phase 2 and 3)
	mechanical & electrical plans	locations of electrical outlets, fluid supplies and drains, and ventilation registers (submission of detailed electrical, plumbing and ducting plans are not required)
submission	architectural concept and construction method representation (text and drawing sheets)	
	3D BIM modeling 4D BIM modeling (optional)	
	explanatory video under 5 minutes	
	3D-printed physical scaled model	

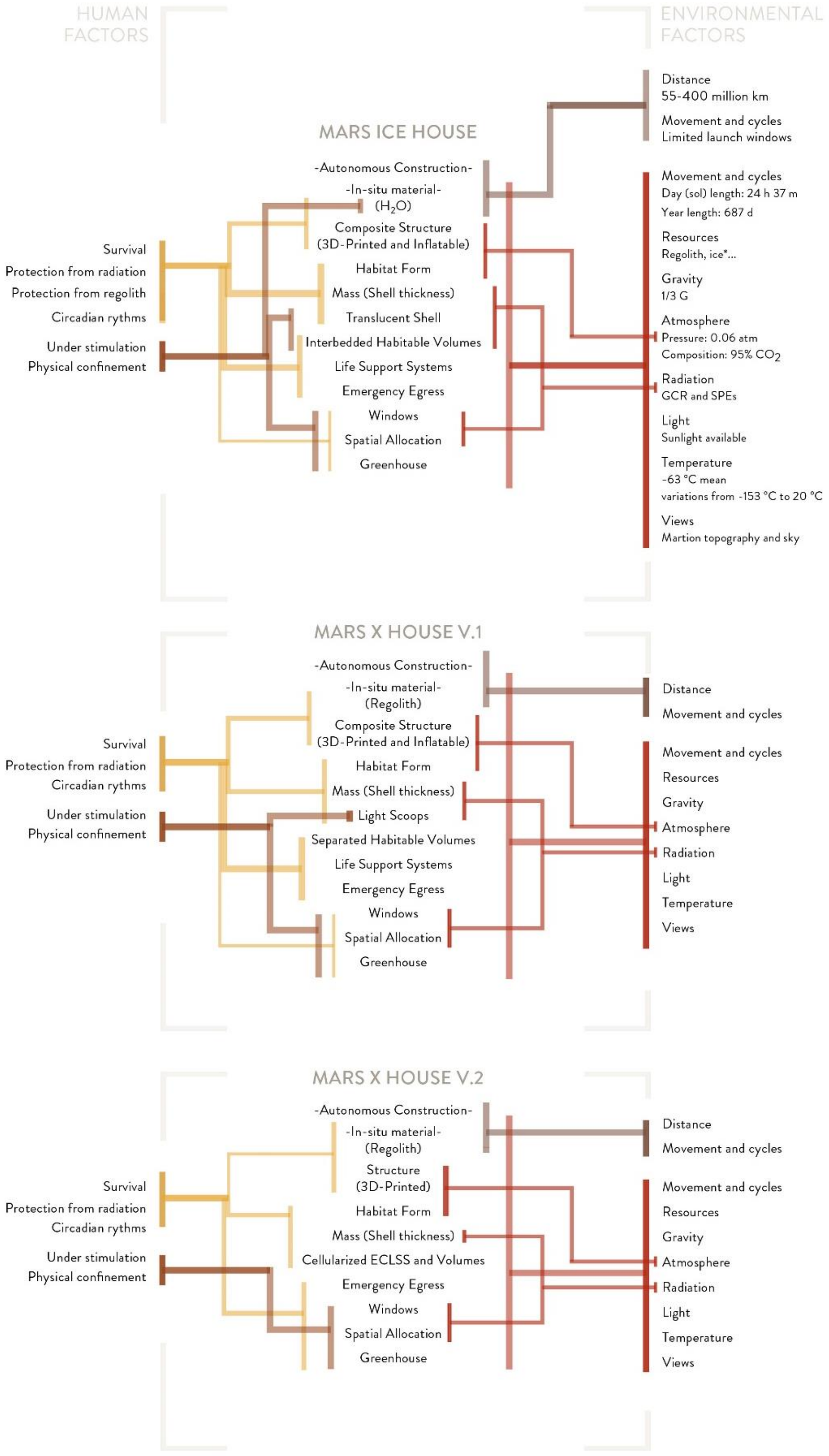

Figure 3.11. Some considerations that are addressed by the proposals (by author)

It might be observed that the team has attempted to respond to both “hard” and “soft” design considerations through their proposals. One addition might be the consideration of introducing value “in the near term on Earth and in the long term for Space,” especially for the progressive and speculative projects, not to “just make drawings.”[436] Their design approach might be outlined by the statement of Melodie Yashar: “This is not like a conceptual design phase for us; the research is the whole project.”[437] The research include contribution from planetary geologists, astrophysicists, structural engineers, mechanical engineers, electrical engineers, roboticists... Yet, “how” this collaboration has been achieved could not be followed from the presentations and research papers. At that point, the interviews with the team members have provided beneficial insight into the design-making process.

Firstly, Yashar suggests that the practice of architecture and architectural design should not be different on Earth and in Space, the important concept is designing for people.[439]

> . . . apart from learning the environmental conditions, what Space is and what is different about Space, you are not doing anything different as an architect. The information you should know is just a little bit broader.[440]

As also indicated by the literature review, this “broadness” in the knowledge and understanding seems undeniably crucial for Space architects and designers. In particular, for the examined design process, the knowledge base, in addition to the openness for understanding and questioning, might be claimed to constitute a few of the main assets providing the collaboration during the design process.

> There is a need for having a kind of vocabulary and an understanding of what other fields need from you as an architect in order to collaborate with them.

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[436] Yashar, “Personal Interview”; Melodie Yashar and Masayuki Sono, “The Universe and Living in This Extreme Environment” (Innovative City Forum, 2016), https://youtu.be/s4C7iZnjNdc.

[437] Yashar, “Personal Interview.”

[439] Yashar, “Personal Interview.”

[440] Yashar.

> Sometimes you just need to be listening to them to just understand what exactly is required . . . We [Architects] are always in position to hear, listen, synthesize and come up with something that could be the best possible solution . . . We do not gain anything as a designer by telling someone what to do. We need to be able to assure that we can learn from them. We should learn everything that we need to know. Then we can move forward. . . [442]

Additionally, the variety of the skill set of the architects of the team seems to provide them to better interact with all actors of design. Yashar states the large skill set enables them to look at every aspect of the project holistically.[443] She illustrates the initial phases of the design as one of the team members sketching the ideas that have been discussed, as the drawings have evolved through the discussions in the room that includes scientists, engineers, and architects (Figure 3.12).[444] To her interpretation, at those phases, "drawing has become the way of communicating at all."[445] She emphasizes the power of immediate visual feedback and being in the same room as all design-makers. This process, even might be seen as "ordinary," can be considered as one of the fundamental drivers letting the contribution of all actors of design, including engineers and scientists, beginning from the decision-making phase.

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[442] Yashar, "Personal Interview."
[443] Yashar.
[444] Yashar.
[445] Yashar.

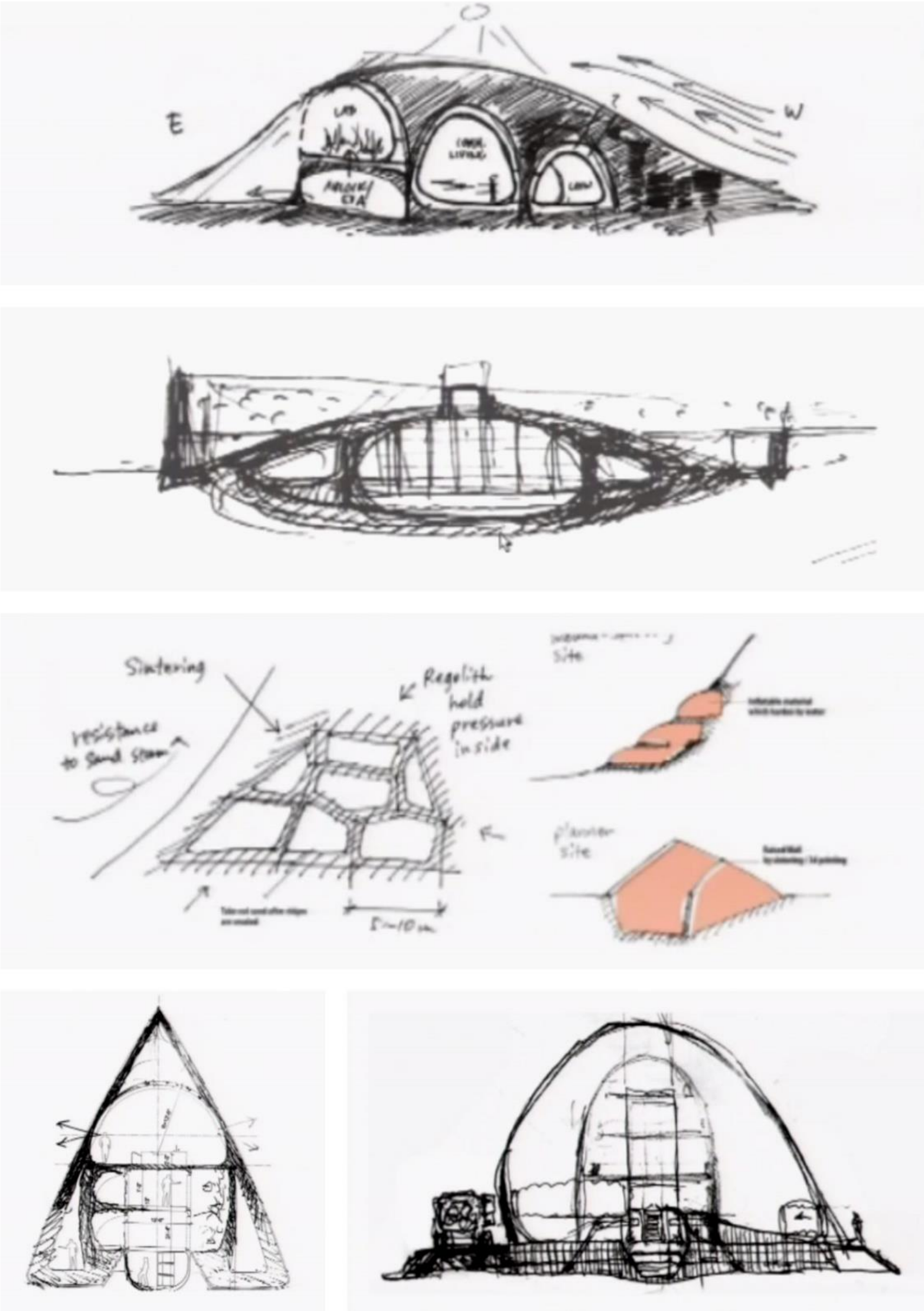

Figure 3.12. Examples of the sketches from Phase 1[446]

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[446] Yashar and Sono, “The Universe and Living in This Extreme Environment.”

When asked about the trade-offs and the determination of the weights of the various factors, she says, “It is a really good question, and I wish I had a good answer for that,” and continues:

> . . . essentially, we just talked a lot. We had regular meetings and we just talked over what we feel is going to be the most successful. We considered everything; we had so many concepts. . . . but it was not like how it is done in aerospace engineering, in which trade-offs are extremely well documented, sort of quantified. We do not really work like that. We just go with what we feel as a group, and because we are all equals [in the group], sometimes one person said more than another because they were just more involved in the project. But it really just evolved kind of naturally.[447]

The only phase of the design to be mentioned to proceed “separately” by Yashar is the structural and radiation analysis, as they have handed over the designs to the specialists and waited for the results.[448] Still, supported by the prior discussions on the subjects with the specialists that have been done in the earlier phases of design, she states that they have been able to anticipate the results to come out roughly.[449]

Another highlight of the interviews is the importance of the software. LeBlanc draws attention to the abilities the BIM software has provided for the communication between him and the team.[450] He describes the design process considerably more collaborative when compared to his work as a “practicing engineer.”[451] He associates this collaboration with “walking through” the BIM model together with the architects while simultaneously talking on the phone, besides the understanding and knowledge base of the architects.[452] Yashar also accentuates the potentials provided by software use, while mentioning the limitations in the present day, such as not having robust or

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[447] Yashar, “Personal Interview.”
[448] Yashar.
[449] Yashar.
[450] Lance LeBlanc, “Personal Interview,” 2019.
[451] LeBlanc.
[452] LeBlanc.

fast enough programs.[453] Furthermore, she believes that the advancements on the softwares that support collaboration in between design actors will possibly alter the practice of architecture:

> I think that the way which could be defined as waterfall is changing, I think the way that we envision architects and subcontractors working together is going to change. This will mostly be enabled by the collaborative software that we can use to work remotely but also more collaboratively. We are working in smarter way. There is no reason why mechanical design cannot appear with the interior design. . . . There is no reason why we cannot do teleconferencing, and modelling, and have the all update in real-time. The only limitation is to having work with the softwares you have.[454]

The organization of the team has been "a little bit messy," as described by Yashar.[455] She underlines that they were a small team, and there was not any hierarchy; some of the team members have been involved in every aspect of the project, while the others being more involved in specific areas, regarding the background and skillset of them.[456] Even if supported by many contributors, being a small team at the core, is stated to let them act or decide in ways that might not be possible in a larger organization.[457] Stating that they were apt to take risks, she gives the example of changing the whole concept from 60% Design and 100% Design levels in Phase 3. As a result, she does not classify the design process of the team as a waterfall approach.[458]

It is also observed that not fixing the systems supporting the design has provided flexibility for making modifications if needed. LeBlanc states that the design process offered the possibility of revisions if needed, as the finalized calculations have not been required.[459] It might be argued that until the software-based capabilities increase

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[453] Yashar, "Personal Interview."
[454] Yashar.
[455] Yashar.
[456] Yashar.
[457] Yashar.
[458] Yashar.
[459] LeBlanc, "Personal Interview."

in a degree to let revisions be made easily, keeping the design at a conceptual level until a considerable amount of the requirements met might be an approach preventing additional constraints.

Last in order but not of importance, one of the noteworthy findings might be the observation of some decisions that might seem intuitive in different phases of the design. One prominent example might be given as the idea of printing with H_2O in Phase 1. The initial intuitions have directed the research of the team to explore the feasibility and potentials of the idea. If the research with the contributions of many fields have supported, then the inclusion of the idea has been considered. As a result, it might be argued that as much as the research have informed the design, "designerly ways of knowing" have informed the research.

3.5. Chapter Summary and Discussion

The emphasis made by SEArch+ and the collaborators on the human-centered design is observable in all design proposals of theirs. Furthermore, the team states that the human psychological and social considerations are often considered secondary to environmental conditioning in the design of Space habitats.[460] They argue that:

> If for a moment, we were to equate these requirements . . . we offer ourselves the opportunity to challenge our conceptions of what an extraterrestrial habitat should be, one that is more than shelter alone.[461]

Based on their statement, which might be argued to be supported by the case study, it might be interpreted that the design approach of the team presents an attempt to evaluate the design considerations of Space habitat design in a manner that all design considerations being included from the initial decision-making phase, an attempt

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[460] Morris et al., "Mars Ice House: Using the Physics of Phase Change in 3D Printing a Habitat with H2O."

[461] Morris et al.

which might not be possible to see in the present-day aerospace industry.[463] That alone might offer an innovative point of view to the field, even if "for a moment." Consistent with the previous research of the thesis, Melodie Yashar says that it might still be early to implement such understanding in the aerospace industry, as the design considerations are overwhelmed by the weight of other considerations in present day:

> The technical demands are just too great, and the cost of hardware is so significant that obviously design is the always the thing that get cut. I think in the next ten years architecture will become more important within the aerospace industry in general. Right now, user-centric design, user experience design, and architecture is very small – even insignificant – portion of what the aerospace market is.[464]

Particularly for the examined design process, the flexibility offered to the design might be easily associated with the lesser pressure of the realization-based considerations. Monsi Roman states that they have been aware of the fact that they could not cover all the things that might be needed to cover, so they have limited the focus of the challenge to a few technological advancements that are known to be needed: "We emphasized the most important goals we have: the autonomy of the hardware and the materials that will be used."[466] Yet, the requirements cannot be considered light enough to let the development of concepts that might be evaluated as speculative by some. The example might be given as the refusal of proceeding the competition with a concept includes H_2O 3D-printing, as the technology has been found immature for the purposes of the challenge. Therefore, it might be argued that the proposals carry the qualities that could let them be evaluated for the development of "real" concepts.

As much as the objective of the challenge has been generating needed technology developments, the inclusion of the architects has proved to be beneficial, and even has affected the organization of the competition. Roman states that even if in the early

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[463] See 2.4.
[464] Yashar, "Personal Interview."
[466] Roman, "Personal Interview."

phases there have not been any architects amongst judges, they have taken part in the latter juries. She explains the necessity as:

> We included architects in the follow-on phases because we increased the level of complexity and having them as part of the judging team made the team stronger and included the right set of skills needed to judge the competitors.

Another important issue which is emphasized by Roman is the nominations being made to the teams that have fulfilled the main objectives of the challenge, which were technology development focused. She says:

> There were some priorities of the competition. The team that won met the primary goals, which were the autonomous construction and proposing the material to be the closest to the one that we could do on the surface of Mars. They won because they met the highest goals: autonomy and the materials.

There might be observed that the focus of the organization of the competition has been more on the technical and scientific factors, whereas the team having architects in the core attempted to address all considerations regarding designing for human habitation on Mars. It might not be presented any proof or approval regarding fulfilling the promise of human based considerations other than the research. On the other hand, the nomination of the proposals of the team might be interpreted as the approval of satisfaction of the considerations regarding technical constraints. As a conclusion, the case study might be argued to illustrate that, a holistic design approach equating the design considerations regarding human-centered design and the environmental conditioning, potentially lead to a result that might satisfy both ends for the Space habitat designs.

It might be argued that such a design process is not solely beneficial for Space habitat designs but could be seen as essential for many kinds of design. It might be observed that the main characteristics of the approaches that can respond to the complex design problem – Space habitation, as examined in this study – are the need for contribution by various fields, and the need for methodologies to provide the collaborative work in between those fields. The design considerations might alter for the examined issues. For Space habitation, these considerations are mostly related to the human needs in an isolated and confined environment and range due to the specific aim of the habitation. Present-day design processes for Space habitats are under the influence of the current capabilities of realization of the design, not only regarding the technology and experimentation capability, but the project costs and dominant design approaches. Therefore, the design process leads to the inclusion of additional factors to the design considerations. As it is argued in regards to the case study findings, a holistic approach might better define the design problem to lead solutions responding to various aspects. For Space architecture, this might mean an increase in the role of architects to advance architectural design thinking, while it might mean the opposite for conventionalized architectural design methodologies, to let the inclusion of more disciplinary fields into the design.

CHAPTER 4

CONCLUSION

The study has started with the initial enthusiasm of finding methods and means of interdisciplinary collaboration, examining the interactions in between human and her/his environment, questioning the influence of built environment on humans, and as a result, exploring paths for addressing human needs by architectural design through Space architecture. This rather optimistic enthusiasm has been stimulated by the apparent potentials of the necessity of contribution by many disciplines in defining and solving the complex design problem of Space habitation, and the extensive research on human – environment interaction as a part of the attempts of defining this problem.

In reviewing the literature, it has been observed that the human – environment interaction is a very broad subject, referring to an excessive amount of interrelated aspects. It has been seen that the effect of – built, natural, or cyber – environment on humans is acknowledged by many. This acknowledgement might suggest that architecture is not only responsible for providing a functional and aesthetic built environment but should respond to many facets of its effects on humans. However, it is also observed that neither the means of these effects nor the human needs might be distinguished in a rationalized way – at least with the present-day knowledge. Yet, the literature includes increasing amounts of studies indicating that the qualitative needs of human might become as equal importance to the needs that might be quantified. The hitherto human spaceflight experience seems to suggest the same.

As a consequence, the aerospace industry has long accepted the relevance of the field of architecture in designing Space habitats. Yet, the literature also demonstrates that the design considerations in the industry are not only shaped by the research on human

– environment interaction, but the problem definition is also being made by excessive amount of requirements and constraints needed to be taken into consideration, which are not necessarily in a direct relation to the product requirements. It might be claimed that the problem definition is overwhelmed by such considerations. Relevantly, it is observed that the architects' contribution to the field could only be realized as long as it could be rationalized. In this context, it might be questioned if architecture can be "rationalized" when human – environment interaction cannot. The literature includes many examples in which the latter experience and research provide validation for the intuitive suggestions of architects and designers, most of which had been received with objection at first. In that manner, it might as well be argued that the "intuition" of the architect should be valued in the present day when supported by research, even if not yet rationalized. This is not a suggestion to imply disregarding the design considerations by any means.

At that point, few things might be needed to emphasize. First, the field of Space architecture is a newly emerging field and has not been fully established yet. It might be safe to assume that its establishment would be shaped by current studies and approaches. Second, the variety of the research area of architects and designers contributes within the field is noteworthy. The presence of them might be seen while discussing the meaning of human presence in Space, as well as in the production of highly technical concepts. They might collaborate on research with psychologists on the one end, and planetary geologists on the other. Throughout the thesis, "architecture" is used in a manner to refer the studies relevant to human habitation design with contributions by many fields. This is a deliberate choice induced by the acknowledgement of the necessity of evaluation of knowledge from various fields for designing for human habitation in Space. However, if the communication and understanding between those fields are failed to be achieved, it might not be expected to address all considerations of a design. Yet, even the aerospace industry has accepted the relevance of the field of architecture, the acceptance of the holistic design approach that architecture might be able to provide do not seem to be recognized commonly.

The issue might become especially relevant in the present day, in which the only currently inhabited spacecraft is about to come to the end of its lifetime, while the plans for future inhabitance of Space are being evaluated with the initiatives of both public and private industries. The current situation might provide flexibility with the relief to a degree on the constraints regarding the removal of the obligation of designing with already produced hardware and equipment. There might appear a brief timespan to let the searching of alternative design approaches that might lead to the design solutions that are not eliminating or suppressing the habitat design issues regarding human well-being while still fulfilling the requirements regarding technical considerations. At that point, architects' one of the most beneficial contribution to the field might be their "designerly ways of knowing."

Space architecture needs to take its considerations from various disciplinary fields. It is by no means argued that architects alone might be able to define and solve the complex problem of Space habitation as a whole. On the contrary, this immanent feature of designing Space habitats is appreciated and valued, as this feature might be argued to necessitate blurring the lines in between various disciplinary fields. The means and methods of providing such interdisciplinary collaborations are seen to be related to various assets. While sharing the same space with all design actors – especially during the decision-making phase – is observed to be important, and the technological advancements on software might support the collaboration by providing a communication tool, more on latter phases. The significance of architecture, in that manner, might firstly be associated with the tendency for synthesizing many considerations of design. Furthermore, broadness in the knowledge-base, openness for understanding, ability to communicate with actors from different disciplinary fields through various media might be claimed to be the key features of the architect in providing interdisciplinary collaboration. Space architecture, instead of positioning in a narrow gap between architecture and engineering, carries the potential of holding a key place in blurring the lines in between many disciplinary fields. This might become one of the biggest "spin-off" that Space architecture might provide.

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