A Sustainability by Design Lesson Learned from Space

Original
A Sustainability by Design Lesson Learned from Space / Sumini, Valentina; Rossi, Marta; Manuello Bertetto, Amedeo. - 437:(2024), pp. 775-783. (2nd Italian Workshop on Shell and Spatial Structures (IWSS) Turin (Ita) June 26-28, 2023) [10.1007/978-3-031-44328-2_81].

Publisher:
Springer

Published
DOI:10.1007/978-3-031-44328-2_81

A Sustainability by Design lesson learned from Space

Valentina Sumini [1] [0000-0003-2315-8786], Marta Rossi [1] [0000-0002-9712-2893],
Amedeo Manuello Bertetto [2] [0000-0003-1474-0176],

[1] Politecnico di Milano, Piazza Leonardo da Vinci 22, Milano 20133, Italy
valentina.sumini@polimi.it
[2] Politecnico di Torino, Corso Duca degli Abruzzi 24, Torino 10129, Italy

Abstract. Space architecture involves the integration of multiple research disciplines to establish a framework for planning secure human settlements in Low Earth Orbit (LEO), on the Moon, or on Mars. Designing sustainable and safe habitats for space exploration requires a diverse range of skills and knowledge. As humanity enters an era of venturing towards neighboring celestial bodies, NASA's Artemis program envisions establishing permanent settlements at the South Pole of the Moon. These settlements aim to serve as testing grounds for future generations, fostering collaboration in the creation of joint infrastructures akin to the International Space Station's cooperative model—a new paradigm of an "ideal city" in a unique environment. The challenge of designing in extreme space environments is being addressed through innovative approaches such as computational design tools, topology optimization processes, and circular design methodologies.

Keywords: Space Architecture, Sustainability by Design, Computational Design,

1 Introduction

Space architecture is an interdisciplinary field that emerges from the convergence of multiple domains, interlacing space sciences, architecture, engineering, robotics, industrial design, medicine, ergonomics, psychology, and art [1]. This dynamic discipline governs the design of habitats tailored for space missions, whether in Low Earth Orbit or on celestial bodies like the Moon or Mars. Prominent manifestations of space architecture include space stations, spacecraft, planetary habitats, and analog test structures [2-3].

Space architecture requires an engineering mindset that incorporates human factors and architectural principles [4]. It is essential to prioritize human requirements and construct structures capable of sustaining human life both physiologically and psychologically. Design considerations should prioritize safety and comfort, with a human-centered approach being paramount, as future astronauts residing in these settlements will experience prolonged periods of isolation and confinement. Consequently, architectural designs must accommodate human needs and provide spaces that promote comfort and wellbeing.

2 Space Architecture design challenges

The interdisciplinary nature of space architecture [5] presents challenges in creating a sustainable and resilient infrastructure to support human missions in LEO, on the Moon, or on Mars. Space architects leverage the technological expertise gained from the space industry to foster a collaborative environment capable of undertaking projects spanning various scales, ranging from urban planning to architecture and interior design. This integration of diverse fields enables the development of comprehensive solutions that can withstand the demands of space exploration.

One of the primary challenges that must be tackled pertains to the correlation between human activities and the resources required to sustain them [6]. Resource supply becomes a critical focal point in this context due to the exorbitant costs associated with transporting resources to outer space. Consequently, it becomes imperative to devise strategies that minimize the reliance on Earth-imported resources and instead foster the production of locally sourced goods. Developing a model that embraces this approach for space applications holds the potential to yield benefits for architecture on Earth, prompting a reframing of how we utilize the planet's resources and encouraging a more conscientious approach. Such an approach aligns with the goals outlined in the United Nations' Sustainable Development Agenda for 2030 [5] and introduces the practical implementation of the Sustainability by Design (SBD) concept.

Undertakings of this nature are characterized by their immense complexity, necessitating the consideration of multiple variables and requirements [7]. However, this challenge can be effectively addressed by leveraging the capabilities of computational design and multi-objective optimization tools. These tools enable the resolution of various objectives, including minimizing terrestrial mass, maximizing the utilization of in situ resources, implementing protective measures against radiation and micrometeoroids, and embracing the principles of sustainability, which should permeate the entire design process [6].

Indeed, the support for a Human Space Mission (HSM) entails a multitude of phases, encompassing habitability requirements and the utilization of In Situ Resources (ISRU). Both technical and human factors hold significant importance in the space architecture design process. Principles rooted in Human Factor Design guide the development of architectural solutions that prioritize human psychological and physiological well-being. Moreover, construction automation stands as a vital aspect that complements and supports human efforts in space endeavors. Lastly, the concept of Sustainability by Design (SBD) enables the creation of structures founded on strategies centered around the principle of 'less is more', a concept that holds potential applicability in terrestrial projects as well.

3 Space Habitats classification

NASA has defined three primary categories of habitat structures for lunar, Martian, and other celestial body exploration, taking into account mission requirements and reliance on Earth-based materials and technology [3].

Class I habitats involve fully constructing the structures on Earth prior to their departure for outer space. These habitats are pre-integrated and ready-to-use upon lift-off from the ground, eliminating the need for deployment upon arrival at the destination. The concept of pre-integrated structures was initially conceived for the Apollo missions (Figure 1), wherein habitable spacecraft were entirely assembled on Earth. These structures were designed to provide comprehensive support to astronauts for a duration of 14 days, serving as a viable construction approach for the initial phases of human planetary exploration.

Fig. 1. Apollo lander (Credit: NASA).

The current International Space Station has been designed and built upon several Class I modules that have been assembled in LEO.

Class II habitats encompass prefabricated structures that necessitate deployment and assembly upon reaching their designated location. This approach offers several advantages, including increased habitable volume while maintaining the same available volume within the transporting vehicle. By deploying and assembling these structures on-site, greater space for human habitation can be achieved, optimizing the efficiency of the available resources. The structures used for habitats can be compactly packaged, occupying a smaller volume compared to their assembled form. This type of habitat design allows for integration and enhancement by combining Earth-made technology with In Situ Resources Utilization (ISRU) constructions. For instance, lunar or Martian regolith (soil) can be utilized to build radiation shields or accommodate additional equipment. Class II habitats serve as an intermediate step in human space exploration as they can provide shelters for longer durations.

There are several noteworthy projects involving Class II habitats for both lunar and Martian exploration. A collaborative effort between ESA, Foster+Partners, Monolite Ltd, Alta SpA, and Scuola Superiore Sant'Anna took place from 2009 to 2015. They developed a hybrid concept comprising an inflatable structure connected to a pre-integrated section. The project also incorporated a radiation shield, leveraging existing 3D printing technology known as D-Shape and adapting it for space applications [8]. Another example is derived from the NASA 3D Printed Habitat Challenge held in 2018. Hassell Studio, in collaboration with Eckersley O'Callaghan (EOC), presented a project featuring multiple inflatable pods covered by a regolith shell. The regolith shell would be 3D printed prior to the arrival of astronauts [9].

Another notable Class II project is the Moon Village (Figure 2), a concept jointly developed by ESA, Skidmore, Owings & Merrill, and MIT. This design incorporates inflatable vertical structures that feature three bladder systems connected to a rigid structural element [10]. The research team devised a masterplan for the entire village, with one of the primary objectives being to find a solution for the integration of multiple modules, allowing for incremental growth over time. The Moon Village encompasses various distinct areas based on their functions, including the habitation zone, an activity band, and the energy and transportation zone [11].

Fig. 2. Moon Village by ESA, SOM, MIT [11].

Class III habitats are constructed entirely using resources sourced or produced in situ, representing the most advanced technology for space habitats. However, the feasibility of this approach has yet to be fully demonstrated, and extensive testing and experimentation are required due to the relatively low Technology Readiness Level (TRL) of current examples in this class. This type of technology holds significant potential for future colonization phases, as it would substantially reduce the need for resources transported from Earth [12].

An exemplary instance of a Class III habitat is the Lunar Lantern, developed within the context of Project Olympus by ICON, Search+, and Bjarke Ingels Group (BIG) as part of NASA's Moon to Mars Planetary Autonomous Construction Technologies (MMPACT) initiative. The project envisions a vertical habitat constructed entirely from in situ materials, comprising an inner fabric liner, a 3D-printed vessel, and an outer Whipple shield [13]. This pioneering endeavor showcases the potential of utilizing local resources for the creation of self-sustaining habitats in space exploration missions.

4 Sustainability by Design

4.1 Decreasing dependence on Earth’s resources

To facilitate future space exploration missions, reducing reliance on resources from Earth will be imperative. Missions that extend beyond Low Earth Orbit (LEO) will necessitate facilities with increased self-sufficiency. Currently, human space missions aboard the International Space Station (ISS) heavily rely on regular resupplies from Earth. The proximity of the ISS to Earth and the relatively low cost of shipping cargo make this feasible. However, the challenges escalate when considering missions to the Moon, which typically take three days for transportation, or Mars, which requires a journey of approximately 6 to 8 months. Compared to the ISS, shipping cargo to these distant destinations becomes technologically and economically more demanding [14].

To thrive on celestial bodies beyond Earth, it will be crucial to harness and utilize in situ materials. This involves processing resources available on these bodies to produce construction materials, fuel, and even oxygen [15]. NASA has already made significant progress in this regard, successfully extracting oxygen from the thin Martian atmosphere through the Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE). MOXIE has demonstrated the capability to extract 10 grams of oxygen per hour [16]. The ultimate objective is to establish a closed-loop system, where resources are efficiently recycled and reused. To achieve this, it will be necessary to incorporate a food production facility that enables the cultivation of plants capable of generating consumable resources and nutrients to support human life. This aspect becomes particularly crucial for Martian missions, where resupply from Earth would be exceedingly challenging. Therefore, astronauts must possess the ability to sustain themselves autonomously throughout the entire duration of the mission.

4.2 Leveraging on Autonomous Construction Systems

Automation plays a fundamental role in construction within space architecture projects as it enables the construction of structures without the need for human presence. Utilizing technology during the preliminary phases is crucial for studying the conditions of future settlement locations and initiating the construction of initial structures. Given the high levels of radiation on Mars and the Moon, it becomes necessary to commence the construction of radiation shielding before human arrival. Additionally, various other operations, such as excavations and soil sintering, can be carried out autonomously to prepare the ground for habitats and the infrastructure connecting the entire system [17].

There are multiple approaches to achieving automated additive construction using lunar or Martian regolith. Numerous technologies have been tested on Earth and can be adapted for space applications. One example involves combining regolith with additives like sulfur, Portland cement, or plastics, employing a cementitious construction method. Sulfur, when combined with regolith, performs well in vacuum conditions, making it a viable solution for space construction. However, transporting additives to Mars or the Moon presents challenges. Therefore, an alternative automated construction method called microwave melting could be utilized. This technique involves melting regolith within a chamber and subsequently extruding it [6]. By leveraging automation and additive manufacturing techniques, construction processes can be optimized for space exploration missions.

4.3 Generating novel computational design tools

Computational design in architecture entails utilizing computer software, algorithms, and other digital tools to aid in the design and analysis of projects at various scales. This includes employing building information modeling (BIM) software and multi-physics simulation and analysis tools to assist architects and engineers in exploring diverse design options, assessing structural and environmental performance, and optimizing building systems. Furthermore, computational design techniques enable the generation of intricate geometric forms and shapes that may be challenging or even impossible to achieve through traditional design methods, facilitating the exploration of complex systems.

In the field of Space Architecture, mathematical methods such as Multi-Objective Optimization (MOO) are essential for exploring and identifying the best solutions among a range of possible outcomes, where multiple objectives or goals are simultaneously optimized. The multidisciplinary nature of Space Architecture necessitates striking a balance among various objectives, such as minimizing resource usage and mass transfer from Earth, while maximizing protection against micrometeoroids, Galactic Cosmic Rays, and solar flares, as well as ensuring structural performance, energy efficiency, habitable volume, and the utilization of autonomous construction systems [18]. By leveraging computational design and optimization techniques, space architects can address the intricate challenges involved in creating sustainable and efficient space habitats.

In literature, numerous projects leverage computational design techniques in conjunction with Multi-Objective Optimization (MOO) algorithms to guide the form-finding process for lunar or Martian habitats or settlements, addressing a range of essential requirements across different scales. One prominent software tool in this domain is Rhinoceros© [19, 20], a 3D modeling software offering a comprehensive set of modeling tools, including NURBS (Non-Uniform Rational B-Splines), meshes, and surfaces. Rhinoceros© is complemented by Grasshopper3D©, a visual programming platform. Within Grasshopper©, various plugins support form-finding and optimization processes.

Fig. 3. Project "Martian Formicary" of the course "Architecture for Human Space Exploration" at Politecnico di Milano (A.Y. 2021-22) by Prof. Valentina Sumini, T.A. Marta Rossi. Students: Angelova M., Bitik D., Cihan Alkan M., Lichocik K., Marticorena Angela V., Mileni Munari M., Pedrazzini S.

For example, Kangaroo Physics© [21] enables dynamic relaxation and multi-physics interactions, facilitating the exploration of complex behaviors. Karamba3D© [22], a parametric structural engineering tool, allows for structural form-finding and optimization, offering accurate analysis of spatial trusses, frames, and shells. Ameba© [23], a topology optimization software based on Bi-directional Evolutionary Structural Optimization (BESO) technology, enables topology optimization processes. Another valuable plugin is Octopus©, which allows users to define design variables and constraints, employing different optimization algorithms to identify optimal solutions that fulfill specified objectives. It also facilitates the visualization and analysis of optimization results and trade-offs within the Pareto Front. The final designs generated through these tools (Figure 3) can be further analyzed and prepared for fabrication.

By employing these computational design techniques and software tools, researchers and practitioners can explore innovative design solutions, optimize performance, and evaluate trade-offs in the development of lunar or Martian habitats and settlements.

5 Conclusions

The emergence, rapid evolution, and continuous expansion of a robust "space economy" globally, focusing on the scientific and economic utilization of outer space, including the Moon and eventually Mars in the coming decades, highlight the necessity for a structured educational framework. Such a framework would encompass the various technological aspects mentioned above and serve as a platform for dedicated learning activities.

The common thread running through all the aforementioned learning activities is the utilization of computational design tools, enabling students from diverse backgrounds and educational levels to communicate through a universal language.

These community tools, often open source, possess captivating features that generate a widespread and enthusiastic interest among younger generations. They perceive these design activities as a fresh canvas, where they can envision their future using innovative tools and approaches.

Furthermore, the imperative to maintain a careful balance and effectively manage limited resources such as energy, water, air, and food reinforces the need for a heightened awareness of sustainability. Applying similar principles and criteria when addressing sustainability concerns on Earth can contribute to guiding humanity towards a secure and prosperous future.

References

1. C. Adams, O. Arenales, M. Cohen. “The Millennium Charter”. space architecture workshop by AIAA DETC Aerospace Architecture Subcommittee, Houston, USA, 2002, 12 October.
2. S. Häuplik-Meusburger Bannova. Space Architecture Education for Engineers and Architects Designing and Planning Beyond Earth. (San Francisco: Springer, 2016).
3. A.S. Howe, B. Sherwood. *Out of this World The New Field of Space Architecture*. (Reston: American Institute of Aeronautics and Astronautics, Inc., 2009.
4. M.M. Connors, A.A. Harrison, F.R. Akins. *Living Aloft Human Requirements for Extended Spaceflight*. (Washington DC: US Government Printing Office, 1985).
5. “Transforming our world: the 2030 Agenda for Sustainable Development”, United Nations, accessed September 1st, 2022, https://sdgs.un.org/2030agenda.
6. R.P. Mueller et al., “Automated Additive Construction (ACC) for Earth and Space Using In- Situ Resources”, presented at the *Fifteenth Biennial ASCE Aerospace Division International Conference on Engineering, Science, Construction, and Operations in Challenging Environments, Orlando, April 11-15, 2016,* https://oro.open.ac.uk/45865/1/3Dadditive_paper_final.pdf.
7. X. D. Kestelier, E. Dini, G. Cesaretti, V. Colla, and L. Pambaguian, “3D printing regolith as a construction technique for environmental shielding on the moon”, *Fabricate 2014: Negotiating Design & Making*, (2017): 198-205

8. G. Cesaretti, E. Dini, X. D. Kestelier, V. Colla, and L. Pambaguian. “Building components for an outpost on the Lunar soil by means of a novel 3D printing technology”. *Acta Astronautica*, no. 93 (Jan. 2014): 430–450.
9. “NASA 3D Printed Habitat Challenge”, Hassell Studio, accessed January 13, 2023, https://www.hassellstudio.com/project/nasa-3d-printed-habitat-challenge.
10. G. I. Petrov et al. “Moon Village Reference Masterplan and Habitat Design” presented at *ICES-2019-280, 49th International Conference on Environmental Systems*, Boston, Massachusetts, 7-11 July, 2019, https://ttu-ir.tdl.org/bitstream/handle/2346/84487/ICES-2019-280.pdf.
11. D. Inocente, C. Koop, G. I. Petrov, J.A. Hoffman, V. Sumini, A. Makaya, M. Arnhof, H. Lakk, B. Lamaze, A. Cowley, D. Binns, M. Landgraf, P. Messina & C. Haigneré. “Master Planning and Space Architecture for a Moon Village” presented at *IAC-2019-D4,1,2, 70th International Astronautical Congress (IAC)*, Washington, DC, 21-25 October, 2019.
12. “Technology Readiness Level”, NASA, accessed August 8th, 2022, https://www.nasa.gov/directorates/heo/scan/engineering /technology/technology_readiness_level.
13. M. Yashar et al. “Project Olympus: Off-World Additive Construction for Lunar Surface Infrastructure” presented at *ICES-2021-96, 50th International Conference on Environmental Systems*, Lisbon, Portugal, 12-15 July, 2021, https://ttu-ir.tdl.org/handle/2346/87095.
14. C. Calles. “The electrostatic environments of Mars and the Moon”. *Journal of Physics Conference Series: Conference series,* (2011).
15. N. Labeaga-Martínez, M. Sanjurjo-Rivo, J. Díaz-Álvarez, and J. Martínez-Frías, “Additive manufacturing for a Moon village”, *Procedia Manufacturing,* no. 13 (2017): pp. 794–801.
16. “Moxie”, NASA, accessed January 13, 2023, https://mars.nasa.gov/mars2020/spacecraft/instruments/moxie/.
17. R.P. Mueller et al., Automated Additive Construction (ACC) for Earth and Space Using In- Situ Resources, Proceedings of the Fifteenth Biennial ASCE Aerospace Division International Conference on Engineering, Science, Construction, and Operations in Challenging Environments (Earth & Space 2016), American Society of Civil Engineers (2016).
18. A.J. Keane, P.B. Nair, Computational Approaches for Aerospace Design: The Pursuit of Excellence, John Wiley & Sons, Ltd, Chichester, 2005.
19. M. Ericson, Review: Grasshopper Algorithmic Modeling for Rhinoceros 5, Journal of the Society of Architectural Historians, (2017) 76 (4): 580-583.
20. McNeel, Robert. Rhinoceros. Seattle, WA: Robert McNeel & Associates, 2018.
21. "Kangaroo." Grasshopper, McNeel, Robert, and Associates, https://www.food4rhino.com/app/kangaroo-physics (accessed January 15, 2023).
22. Preisinger, Thomas. "Karamba3D User Manual." Food4Rhino, https://www.food4rhino.com/en/app/karamba3d?lang=it (accessed January 15, 2023).
23. "Ameba." Kancloud, https://www.kancloud.cn/woshiyaoyuan0318/ameba_en/582345 (accessed January 15, 2023).