Atlas of Habitats Beyond Earth. Architectural Solutions for Space Applications

Giacomo D'Amico[1] and Marina Tornatora[2]
Mediterranea University of Reggio Calabria, Reggio Calabria, Italy, 89124

The development of Space Architecture demonstrates how human settlement on planets beyond Earth is no longer science fiction, but a challenge to develop a specific architectural way of thinking, both technologically and conceptually. Ongoing research and design provide architects with new opportunities to experiment with orbital and planetary habitat spatial solutions, extending some architectural concepts to extreme environments such as the Moon and Mars. This paper describes a study conducted as part of a thesis with the purpose of tracing a path of research and design reflection through eighteen case studies selected from some of the extra-terrestrial habitat solutions proposed so far and attempts to develop the first Atlas of habitats beyond Earth. It is structured for constructive, morphological, and settlement types through examination, redesign, and comparison, with the aim of consolidating and defining characteristics necessary to structure a thinking process. The study also develops a design hypothesis for a settlement on Mars that tries to respond to the challenges in outer space environments while also reflecting on 'living in Space', a synthesis of consciousness and technology, while making use of Artificial Intelligence throughout the whole settlement process, from surveying and construction to living and maintenance. The lack of oxygen, the atmosphere, thermal excursion, cosmic radiations, micrometeorites, and the reduced sound propagation, are some of the factors that influence formal decisions made in a city concept that is no longer only thought of as a survival strategy in extreme environments. Rather, they serve as a constitution based on the ideas expressed by Paolo Soleri in the city of Arcosanti, Arizona, that propose critical models in the face of rampant consumerism, alternative expressions of a futuristic and sustainable architecture that dialogues with the environment without abandoning the founding architectural principles.

Nomenclature

AI = Artificial Intelligence
AIAA = American Institute of Aeronautics and Astronautics
CSA = Canadian Space Agency
ECLSS = Environmental Control and Life Support System
ESA = European Space Agency
ETFE = Ethylene tetrafluoroethylene
EVA = Extra Vehicular Activity
FSP = Fission Surface Power
HF = Human Factor
HSC = Hard Shell Case
ISRU = In Situ Resource Utilisation
ISS = International Space Station
JAXA = Japan Aerospace eXploration Agency
NASA = National Aeronautics and Space Administration
RKA = Rossijskoe aviacionno-kosmičeskoe agentstvo / Roscosmos
SATC = Space Architecture Technical Committee
USGS = United States Geological Survey

---

[1] Architect, Department of Architecture and Territory – dArTe, damicogiacomo@hotmail.com
[2] Associate Professor, Department of Architecture and Territory – dArTe, mtornatora@unirc.it

I. Introduction

The study focuses on the theme of Space Architecture and aims to identify the most recurring invariants and themes in this branch of architecture, as well as to identify ideas and projects for habitats to settle on celestial bodies. The research was carried out following an analytical and precise method. The publications *Out of This World: The New Field of Space Architecture*[1] by A. Scott Howe and B. Sherwood, and *Space Architecture. Human habitats beyond planet Earth*[2] by O. Bannova were of fundamental importance for the start of the research. The first had theoretical and practical relevance for the design and construction of spaces in Space, with particular focus on orbital architectures. Instead, the second illustrates architectural principles and strategies applied to the extreme environmental conditions present in Space.

Studies on space anthropology and the history of space exploration were also carried out to better understanding how the human body and psyche react to extreme conditions.

Focusing on the architectural sector, research was carried out on design solutions and habitat prototypes for Moon and Mars. During the research phase, forty-five projects were collected. The first sorting, which started the definition of the Atlas, was determined by the presence and acquisition of materials. The final selection, consisting of eighteen projects, is presented in this paper and compares the case studies through a system of cataloguing alongside graphic and functional analysis. The case studies contain and describe the different techniques of habitat creation. One of the key points for their classification has been based on the scheme proposed by K.J. Kennedy[3]. In this study, we attempted to improve this classification by showing that *classes* do not have crisp edges, by introducing the concept of *hybrids*.

Following the research and analysis phases, the common points between the case studies were deepened, with particular attention to structural typologies and construction techniques, applied shapes and geometries, typological environments, and aggregating possibilities.

The results obtained provided the starting point for the development of design concepts, with an attempt to provide effective design and housing solutions. The final phase of the study concerned the development of a conceptual project for a human settlement on Mars. Starting from the results produced in the previous phases, we hypothesized the development of the settlement in phases in the region of Arcadia Planitia, a flat area in the northern hemisphere. The base was designed and organised on a human scale, with hexagonal lots connected by underground tunnels. The central axis of the settlement will host the main functions of management, community, energy, telecommunications, and supply. The edges of the settlement house the connection networks and multifunctional houses. The settlement was designed to be self-sufficient and the use of 3D printing and In Situ Resources Utilisation (ISRU) [4] to build structures was suggested. The urban organization was based on the *15-minute-city model*[5], while as a social reference it was considered the housing model of *Arcosanti*[6] by Paolo Soleri.

II. Architecture for Outer Space

Settling on other celestial bodies beyond Earth has always fascinated architects and others, giving them the opportunity to imagine new ways of living.

In 1865, Jules Verne described a crew of three inside a spacecraft landing on the Moon in his novel *From the Earth to the Moon*. This event was impossible at the time, but a hundred years later, the Apollo Program was organized with a similar flight architecture and organization. On July 20, 1969, the Apollo 11 mission brought Neil Armstrong, Buzz Aldrin, and Michael Collins to the Moon.

In 1903, Konstantin Tsiolkovsky published a theoretical work that initiated rocket experimentation, thus becoming the father of astronautics[7]. He also conceived ideas such as the space elevator, space suits for EVAs (Extra Vehicular Activity), and inspired Werner von Braun to design a *Rotating Space Station*[8] to create artificial gravity using centrifugal force. The same concept was later taken over by Stanley Kubrick in his 1968 film *2001: A Space Odyssey*.

Another example of an orbiting city-station in the sci-fi imagination is the *Stanford Torus*, a 1975 NASA proposal designed to accommodate a population of 10,000 to 140,000 permanent residents. The Stanford Torus is derived from a 1929 concept by J. D. Bernal, known as the *Bernal Sphere*. In this case, 20,000 to 30,000 residents were assumed. The concept of the Bernal Sphere was recently revived by director Christopher Nolan in his 2014 film *Interstellar*.

The Space Architecture project currently in operation since 1998 is the International Space Station (ISS), which is also a perfect example of international collaboration. It is managed by NASA, RKA, ESA, JAXA and CSA-ASC. Its structure is based on modules, built by the various space agencies, which connect with each other through standardized docking systems. This has allowed its expansion to date. The environment is characterised by microgravity and make the entire station a research laboratory. Specifically, the crews carry out research and experiments in the biological, chemical, medical, physiological, and physical fields, as well as astronomical and meteorological observations[9].

On October 12, 2002, in Houston, Texas, USA, the field of space architecture was officially born during the American Institute of Aeronautics and Astronautics (AIAA) Space Architecture Symposium. It would be defined by Osburg, Adams, and Sherwood in the following year as:

> "Space Architecture is the theory and practice of designing and building inhabited environments in outer space, responding to the deep human drive to explore and occupy new places. Architecture organises and integrates the creation and enrichment of the built environment. Designing for space requires specialised knowledge of orbital mechanics, propulsion, weightlessness, hard vacuum, psychology of hermetic environments, and other topics. Space Architecture has complementary relationships with diverse fields such as aerospace engineering, terrestrial architecture, transportation design, medicine, human factors (HF), space science, law, and art[10]."

Another outcome of the same symposium was to draw up an act containing the motivations and the contribution that architecture can give to space exploration, the necessary skills and a series of key-points acting as design guidelines. This document is known as *Millennium Charter Manifest* [11].

A. Millennium Charter: Team 11 Principles

The basic principles of Space Architecture fall into the Vitruvian triad: *firmitas, utilitas, and venustas*. Architecture is considered as a set of factors and variables, and not only from the point of view of the architectural artifact. The environment that houses the structure is one of the focal points that greatly affects the variables. These are then considered the so-called **subsystems** that must be designed to ensure both the Vitruvian principles and safety and survival. All environments are therefore considered single units, but as part of a non-hierarchical multidimensional system. The external environment is considered as the internal environment. This subsystem also includes vehicle support structures, such as rovers and the like.

The Millennium Charter lists eleven parameters that should be part of a good Space Architecture project: *Team 11 Principles*[12]*:*

> Sustainability, Human Interaction, The User, Human Factors (HF), Human Condition, Social Aspects, Environmental Conditions, Education, Life Cycle, Humility, and Benefits.

Cooperation (between individuals and disciplines) is the cornerstone of successful work. In an environment where no idea prevails over the others, but where individuals confront each other to progress in research, the focus is on the needs and desires of the user. At the same time, the aim is to improve the experience of human life and promote intellectual, spiritual, and social valuation.

The Millennium Charter also considers the implications of human presence in space, and the impression we want to leave. It should be noted that the discipline and intentions listed above, and the resulting knowledge and techniques, are essential for both space architecture and improving the quality of life on Earth.

III. Developing the Atlas

The main driver of this research was the desire to investigate how to live beyond Earth for prolonged periods. The space exploration programs Artemis and Mars 2020 have stimulated interest, placing a focus on thinking about housing solutions for future settlers of the Moon and Mars, and beyond.

As described in the Millennium Charter, "*We are responding to the deep human drive to explore and inhabit new places."* Understanding how to make this desire a reality has been a further impetus for carrying out this research.

Space Architecture is a recent and still developing discipline. This paper, the result of a master's thesis, proposes to investigate, research, and identify the invariants and most recurring themes in this branch of architecture. In addition, it questions whether there is a codification in the discipline of Space Architecture that highlights methodologies to be applied in the design process. To make this possible, it was essential to know the state-of-the-art by collecting and selecting projects to use as case studies.

The results of conferences, scientific publications, architecture magazines, architecture websites, and architectural studies portfolios, as well as press releases from international space agencies and digital archives, were consulted to create the reference sample, including dissertation results and contests for ideas or design. An initial survey was possible through the bibliographic list-archive[13] made available by the global network of SpaceArchitect.org[14], with documents written or recommended by the AIAA and the Space Architecture Technical Committee (SATC), which promotes research and dialogue about human life in space.

The next step in creating the atlas was to implement a first selection of projects, which were recovered with no little difficulty, with the intention of defining a first sample of cases. At this stage, planetary-type projects for the Moon and Mars were considered. On the other hand, orbital architectures projects were excluded because they were not in line with the goals of the thesis work. Preference was given to projects that had more resources at their disposal, which included graphics and/or reports describing habitats with a focus on structural and formal solutions applied, on the functions present, and the reasons for the proposed solution. The results of this first selection were obtained in **forty-six** case studies.

Once the reference sample had been defined, work was conducted on reconnaissance of the acquired materials describing these projects, and an attempt was made to find the primary sources whenever possible. Following this phase, a process of material reworking was started. An attempt was made to propose a method which would make it possible to compare the case studies of the sample, by reworking and analysing the projects graphically and analytically. The first operation conducted was in fact to redesign the projects in plan and section, to obtain the same language of reading. The re-draw of the projects has made it possible to better understand issues related to the measurement and size of habitats, their shape and applied geometries, which are also reflected at the structural choices.

This operation resulted in the second selection, as well as the final selection, which resulted in **eighteen** case studies:

> Lunar Habitation (2012); Mars Ice House (2015); Mars Ice Home (MIH) (2016); Mars Science City (2017); Dandelion Shelter (2018); Mars Cliff Settlement (2018); SinterHab 3D Printed Habitat (2018); Hassell 3D Printed Mars Habitat (2018); Mars X - House V1 (2018); Mars X - House V2 (2019); Marsha (2019); Cybele (MIH) (2019); Moon Village (2019); Mars LAB (2019); Lunark (2019); Nüwa City (2020); Project Olympus (2020); Mars Dune Alpha (2021).

A. Classification and Sorting of Habitats

Each case study was accompanied by an identification code (numbered sequentially according to the year of design), by a description that refers to the data, and by considerations referring on the analyses made. Finally, identification logos have also been created for each project to easily recognise each case. The first step to give order was to frame the case studies in accordance with the classification method of K.J. Kennedy [Figure 1], for which spatial habitats are divided into **three classes**:

- **Class I**: *Pre-integrated habitats*. They are fully assembled, integrated, and tested before launch. Volume is highly limited due to weight.
- **Class II**: *Prefabricated habitats*. This habitat class is assembled and implemented in situ using robots and/or upon arrival of the human crew. There are subsystems, so-called *critics*, that are integrated and tested pre-launch. The dimensions are less limited because of the volume and the reduced weight given by the possibility of inflatable structures.
- **Class III**: *In Situ Derived and Constructed habitats*. This type is built, assembled, and put into operation totally in situ by using local resources and with the help of robots. The test phases also take place in space. It requires the full integration of subsystems, which are developed and tested on Earth before launch. There is no restriction of volume or mass. It takes a long time for the construction and testing of structures.

At the same time, it is necessary to consider the duration of missions:

- **Short**: days to weeks;
- **Medium**: from weeks to months;
- **Long**: months to years.

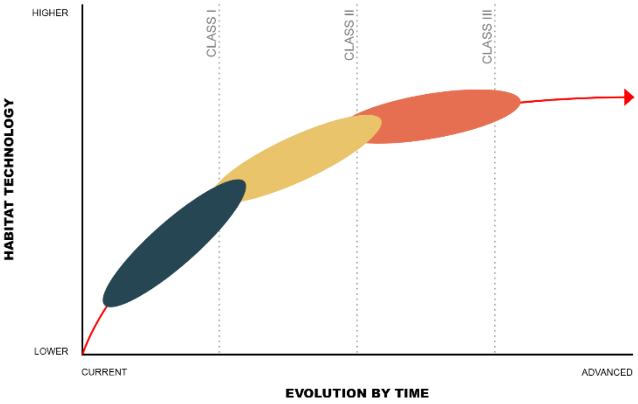

Figure 1. Redesign of K.J. Kennedy's "Habitation Technology Strategy" diagram.

The application of this method of classification has highlighted a relevant issue. Referring to the descriptions of the Classes, some case studies under consideration simultaneously fell into several Classes for the adopted design solutions. This aspect has shown that the classes do not in fact have sharp edges, hence the need to hypothesize a classification that integrates the so-called **hybrids**.

B. Principles and Methods for a New Architecture

The research phase highlighted the multidisciplinary nature of Space Architecture, drawing on expertise from fields such as engineering, architecture, and psychology. The cooperation between different areas is a key point for a clever design, from small to large scale. Engineers need to work with architects to ensure that the structures they design are safe and functional, while psychologists need to work with architects to ensure that the spaces they design are comfortable and conducive to human habitation.

Studies of spatial anthropology have shown that humans are naturally drawn to spaces that are on a human scale. This is why the *Modulor*, a system of proportions developed by Le Corbusier, has been so influential in architecture. The *Vitruvian man*, a drawing by Leonardo da Vinci, is another example of a work that emphasizes the importance of human scale in design. To live and survive in extreme environments, such as space, you need to know the environment in which you are, the risks to which space settlers will be exposed, such as radiation and microgravity, the effects and repercussions on the psyche, and that spaces are necessary to ensure the best possible liveability.

C. Environment & Anthropology

The design of space habitats, both orbital and planetary, must focus on the needs of the crew. An artificial and limited environment can alter not only sensory perception, but also sensations related to physical and psychological needs[15]. **Physical needs** include: (a) *survival*, which must be guaranteed by Environmental Control and Life Support System (ECLSS) systems; (b) *comfort of the environments*, which must be designed correctly at all scales; (c) areas for *physical exercise* to prevent muscle and bone atrophy. **Psychological needs**, include the need for: (d) *private spaces* that guarantee the intimacy of each crew member; (e) *common spaces* for socialization, both for work and leisure, in order to avoid isolation and foster cooperation between users; (f) the facilitation of *orientation*, in space and time, through (g) *sensory stimuli* provided by colour, light, sound, and leisure activities.

In both orbital and planetary missions, it is essential to ensure the optimal health of each astronaut. The physical, temporal, and psychological distance from home, that is, Earth, and the extreme and extraneous environment in which they are implanted put a strain on the body and mind and can easily compromise the success of the missions.[16]

In conclusion, the role of architecture thus becomes essential and important. The principles of the Vitruvian triad, as indicated in the Millennium Charter, are once again the best starting point for good architecture. Despite changing conditions or even the celestial body of reference, fundamental human needs will remain a constant in space and time, and architecture can only be a representation of the inevitable evolution or, better, adaptation.

D. Design Parameters

Especially in extreme conditions, the human body needs adequate technological support to identify and solve problems related to long-term permanence and space travel. The organization and optimization of the spaces in which to live, at any scale, in the context of spatial settling takes on an even more incisive meaning. The primary characteristic of space habitats is that they are designed as self-sufficient artificial organisms capable of ensuring the survival of astronauts, since the missions are thought to be of long duration and the conditions of environmental stress are quite special. Habitat design should therefore take account of human needs first, and technological needs later. These will support the life of the settlers.

In microgravity conditions, the vestibular system is defective, and the predominant sense is sight. It helps with orientation and exploits the following components: *light*; very saturated *colours*[17]; presence of *curved surfaces*; arrangement of *local main axes*; presence and quantity of *portholes and windows*.

Studies on colour and the contribution it can make to the conquest of space are already found since the time of the *race to space* and the design of the first spacecraft. Between 1957 and 1975 two main models of spacecraft were developed, which will be used in the years to come, and in a specific case still today. The two models in question are European-US and Russian, quite different from each other. The first is characterized by modularity, formal environments, white or blue light, orientation using written indications; the second instead has a unified structure, more familiar environments, and the colours brown (floor), white (ceiling) and green (walls) which contribute to orientation along with lines (which act as guides)[18].

An aspect not to be underestimated in the design of spatial habitats is to **scan the time**, giving it a measure. The importance of designing habitats also in measure of time comes from the need to avoid altering the circadian rhythm, in fact this would lead to the production of fatigue, drowsiness, reduction of reaction and performance times, memory and attention difficulties, as well as cognitive disorders due to chronic sleep loss[19].

From the analysis of the case studies, we can draw conclusions about the design approaches with respect to the ideas of the architects, the requests of the clients and the conditions of the extreme environments in which the various projects were conceived.

1. Structural types

Structural types in space architecture are often related to the class of habitat they belong to. For example, Class I habitats typically use Hard-Shell Cases (HSC), which are pre-integrated and ready-to-use modules. Class II habitats may use prefabricated structures, including inflatables, which may or may not be integrated with a double shell. Class III habitats typically use the In Situ Resource Utilisation (ISRU) construction technique.

The extreme environmental conditions in space have helped designers define hypotheses of shapes and geometries that can best respond to the forces acting on structures. Due to the different forces of gravity, the presence or absence of atmosphere and the strong thermal excursions, curved surfaces are preferred to better distribute the loads acting. The most common are:

- The **HSC** is a rigid structure that is typically made of metal or composite materials. It is designed to withstand the harsh conditions of space, including the vacuum of space, radiation, and micrometeoroids. The HSC is a modular structure, which means that it can be assembled in different configurations to meet the needs of the specific habitat.
- The **bunker** is a type of habitat that is designed to protect its occupants from the harsh environment of space. It is typically made of thick concrete or steel and has a rounded shape to deflect impacts. The bunker is often used as a temporary shelter or as a base for further exploration.
- The **beacon/tower** is a type of habitat that is designed to provide a communications and navigation beacon for spacecraft. It is typically made of a tall, slender structure that is topped with a light or radar reflector. The beacon/tower is often used in remote or dangerous areas of space.
- The **dome** is a type of habitat that is designed to provide a pressurized environment for its occupants. It is typically made of a lightweight material, such as aluminium or plastic, and has a curved shape to distribute the weight of the structure evenly. The dome is often used as a habitat on the Moon or Mars.
- The **torus** is a type of habitat that is designed to provide a comfortable and spacious environment for its occupants. It is typically made of a lightweight material, such as aluminium or plastic, and has a donut-shaped shape. The torus is often used as a habitat on the Moon or Mars.
- The **underground/hypogeum** is a type of habitat that is designed to be buried underground. It is typically made of a durable material, such as concrete or steel, and has a rounded shape to deflect impacts. The underground/hypogeum is often used as a shelter from radiation or as a base for further exploration.

2. Aggregation

The choice of class, type, and geometry for the design of a habitat determines the development of any aggregation. The aggregative variants therefore depend strictly on the project. The identified and recurrent aggregative variants in the case studies are the following:

- **No aggregation**: This option includes Class I structures, which are separate bodies and, given the brevity of the missions for which they are intended, tend to have no aggregation system.
- **Single lots**: This option maintains the singularity of the single habitat and aggregation between them takes place by proximity and shape of the lots that host them. The connection between individual units would be by displacement with EVA or otherwise using rovers.
- **Airlock-tunnel**: It is the ideal solution to connect two structures close together, thus creating a unique and continuous organism composed of various and smaller parts that can accommodate different environments.
- **Continuous space**: This is an aggregate type for settlement, or settlement, is thought to be a city connected by tunnel-corridors comparable to roads (Nüwa model) or developed under a dome structure (Mars Science City model).

Designing spatial habitats following an aggregative forecasting approach is a strong signal of will and desire to think of settlements as stable cities in the future and not as temporary and ephemeral structures.

3. Functional environments

Another recurring element is defined by the environments that constitute a habitat. In almost all case studies, the following areas can indeed be found:

- **Warehouse**. This area is used to store supplies and equipment. It is important to have a large enough warehouse to store all the supplies that the habitat will need, as well as any equipment that may be needed for repairs or other activities.
- **Machine room**. This area houses the systems that support life in the habitat, such as the Environmental Control and Life Support System (ECLSS) and the power distribution system. The ECLSS system is responsible for maintaining the air, water, and temperature in the habitat. The power distribution system is responsible for providing electricity to the habitat.
- **Laboratories/work areas**. These areas are used for scientific research and other activities. They should be well-equipped with the necessary tools and equipment for the work that will be done in them.
- **Communal areas**. These areas are used for recreation and relaxation. They should be comfortable and inviting, and they should provide a place for the crew to socialize and unwind.

- **Private spaces**. These areas are used for sleeping and personal activities. They should be private and quiet, and they should provide a place for the crew to relax and get away from the hustle and bustle of the habitat.
- **Toilets**. These areas are used for waste disposal. They should be clean and well-maintained, and they should provide a place for the crew to use the restroom in privacy.
- **Outdoor equipped area**. This area is used for activities such as EVA and power generation. It should be large enough to accommodate the necessary equipment and activities, and it should be well-protected from the elements.

E. Creation of the Abacus

The first operation was to redefine the classification proposed by K.J. Kennedy in such a way as to include also the hybrids defined above, that is, all those habitats having characteristics that fall simultaneously into several Classes. To do this, it was thought to build an alphanumeric code that described the class of belonging through the letter, and the temporal positioning with the number.

For clarity, the proposed code is organized as follows:

A: *Class I;*
B: *Class II;*
C: *Class III;*
X: *Class I-II hybrid;*
Y: *Class I-III hybrid;*
Z: *Class II-III hybrid.*

The second operation was the development of an abacus [Figure 2] that also visually ordered the results obtained from the research. In this case, the operation carried out was to group the recurrent characteristics among the case studies in seven topics:

(1) *Classification*;
(2) *Structure*, considering construction methods and materials;
(3) *Typology and functions*, internal distribution, and external geometries;
(4) *Site*, the celestial body for which the habitat was designed;
(5) *Aggregation*;
(6) *Light*, natural and/or artificial;
(7) *Associated services*.

For the visual recognition of individual case studies, the respective identifying logos and names were added.

After defining this abacus, a comparative and interpretative reading of the case studies was carried out using redesigns [Figure 3] which further clarified the conclusions obtained from the previous phases, especially regarding the founding principles of Space Architecture that this research has sought to identify and highlight and that have been described above.

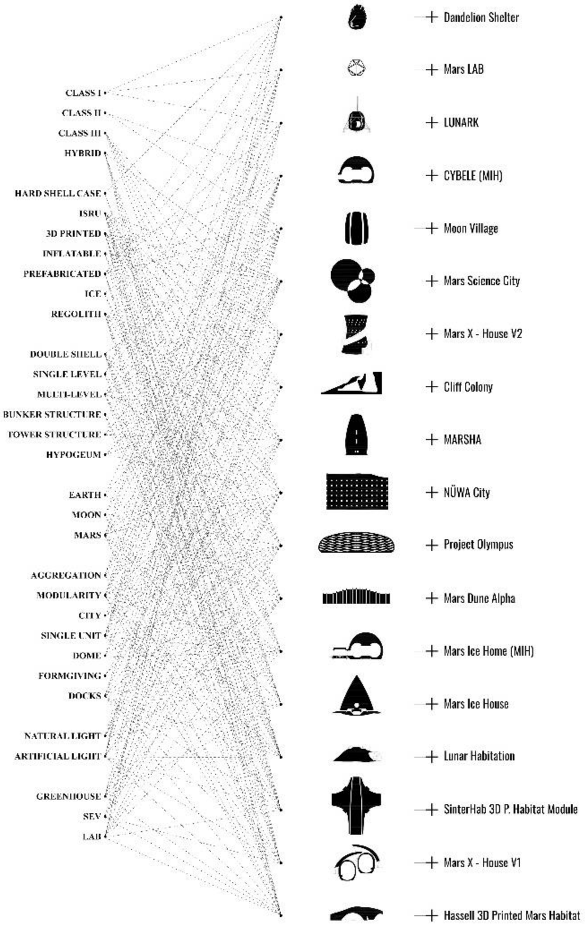

Figure 2. Abacus of case studies.

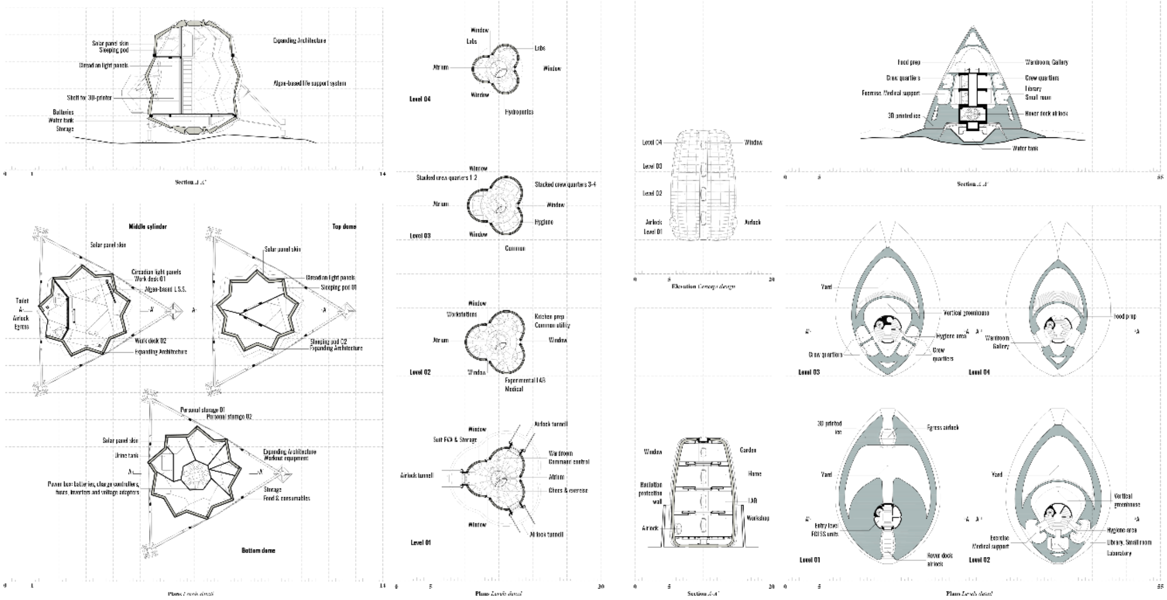

Figure 3. Drawing comparison between Lunark, Moon Village, and Mars Ice House.

F. Example of Case Studies Comparison

Analysing more in detail some case studies such as LUNARK, Moon Village, MARSHA, Nüwa, and Mars Ice House. They show that there are always different solutions to solve different design requests or challenges to address.

For example, the design of [A6] **LUNARK**[20] responds to the need to create a habitat that can occupy as little space as possible and at the same time be ready to use once placed in situ. The solution proposed by the studio SAGA Space Architects was to design and build a structure with a rigid outer shell in carbon fibre and the supporting structure with an aluminium frame, developed following the principle of origami. With these design choices it has been possible to guarantee both lightness and portability of the habitat. It is a Class I habitat and incorporates a harmonious set of technological solutions to facilitate the well-being of astronauts: dynamic system of circadian light, to give rhythm to the days; coating in solar panels, to ensure energy self-sufficiency; batteries, water tanks and storage; private and common spaces; life support system.

Remaining in lunar territory, the [B3] **Moon Village**[21] is a project signed by the SOM group (Skidmore, Owings & Merrill) in collaboration with MIT (Massachusetts Institute of Technology) and the ESA. Moon Village offers a view of cities on the lunar landscape, organised for individual housing units interconnected by airlock tunnels. Among the main objectives is self-sufficiency. The housing units are Class II. The structure is a rigid-soft hybrid double shell: rigid externally and soft-inflatable inside. The habitat is organised on four levels in which the various functions of housing, work and research are divided. All levels are equipped with windows that offer a wide view of the lunar panorama and facilitate the supply of natural light. Vertical connections are arranged in the central core, referred to as Atrium, by means of vertical ladders.

Moving on to Mars, an emblematic case study is [C8] **MARSHA**[22], designed by AI Space Factory. It is a project based on the use of in-situ resource utilization (ISRU), which is combined with 3D-printing technology. MARSHA is characterized, like Moon Village, by a double-shell beacon structure to isolate the habitable spaces from the structural stresses caused by the extreme temperature fluctuations of Mars. The habitat is organized in functional areas distributed on four levels, differentiated by colours and furnishings, to break down the monotony. There are: a storage area, a laboratory, private pods, a garden and communal area, and a sky-room. The sky-room is located at the highest level of MARSHA and offers a view to the sky for astronomical studies and serves as the main source of natural light.

In 2020 ABIBOO Studio presented [C11] **Nüwa City**[23], a self-sufficient and sustainable city capable of accommodating 250,000 people per module, for a total of 1 million inhabitants. The main technique is that of ISRU, but in a wider spectrum of applications. The project was designed as a plant to be developed and built in the presence of the Martian cliffs, with partially hypogeal plant. This design solution derives from the need to have natural light input and, at the same time, protection from micro-meteorites, cosmic radiation, and uniform distribution of internal pressure of the structure. The reef chosen for Nüwa is Tempe Mensa, an area with abundant water, a vital resource for human survival. The plan is divided into three macro areas:

- *The Wall*, which houses most of the facilities and activities;
- *The Mesa*, or a large flat area dedicated to energy and food production infrastructure;
- *The Valley*, where social interaction pavilions, warehouses and laboratories are located.

At the same time in Nüwa, other cities based on the same system have been planned: Abalos City (at the Martian North Pole) and Marineris City (in the *Valles Marineris*).

Another case study is [Y3] **Mars Ice House**[24] by SEArch+ and CloudsAO. This project was the winner of 1st place at the NASA 3D Printed Habitat Centennial Challenge in Virtual Design in Phase 1 and stood out for using Martian ice as a building material. The structure includes a double shell to minimize contamination of/from Mars. The outer shield is 3D printed with ice and imagined as a series of nested domes and enclosed by an ETFE (Ethylene tetrafluoroethylene) membrane. Moreover, the transparency of the ice allows a high amount of natural light. The habitat can accommodate four people and is equipped with an ECLSS for the ventilation of the rooms and a Hydroponic Greenhouse to be used both as a vegetable garden to grow food to support the crew, and to do research experiments.

G. AI + Space Architecture

Artificial Intelligence (AI) has a wide range of possible applications in space exploration, offering the opportunity to perform different tasks autonomously. The most recent and successful example of the use of AI for space exploration is represented by the rover Perseverance, which has the main task of "looking for signs of ancient life and collecting rock samples and regolith (stones and soil) for a possible return to Earth". In this case, AI was used for: the landing manoeuvres, which are impossible to do manually due to the excessive distance between Earth and Mars; to explore the territory delimited by the mission, the Jezero Crater; and to select with extreme precision the samples to be analysed and send the data to Earth.

As with Perseverance, there are many other examples of using AI in space[25]. For example, the AI-powered system called OSIRIS-REx, which is currently orbiting the asteroid Bennu, is using AI to help it identify and collect samples from the asteroid's surface. Additionally, the AI-powered system called Lucy, which is scheduled to launch in 2021, will use AI to help it explore a group of asteroids called the Trojan asteroids, which orbit the Sun in front of and behind Jupiter.

We would like to clarify that the use of Artificial Intelligence (AI), as this technology is constantly evolving, even in the aerospace and Space Architecture fields, has been considered in this research as a tool to support human activity. This is because human rationality and the skills of professionals are essential to make the most of the data available, capturing even minimal nuances and implementing cognitive processes not yet achieved by AI. Thus, although it is a tool that offers a wide range of applications, it has been considered as such and not as a substitute for human activity.

AI has the potential to revolutionize many aspects of our lives, including the way we design and build space habitats. However, it is important to remember that AI is a tool, and like any tool, it can be used for good or for bad. It is up to us to ensure that AI is used in a way that benefits humanity and does not harm it.

One of the ways that AI can be used to support human activity in space is by aiding with tasks such as planning, design, and construction. It can also be used to generate and evaluate different design options[26], identify potential problems, and optimize the construction process. This can help to save time and money, and it can also help to ensure that space habitats are designed and built to the highest standards. AI can also be used to provide support to astronauts during their time in space. AI-powered systems can be used to monitor astronauts' health and well-being, provide them with information and entertainment, and help them to complete their tasks. This can help to reduce the stress and workload of astronauts, and it can also help to ensure their safety and health.

Overall, AI has the potential to play a significant role in space exploration, offering the opportunity to perform different tasks autonomously and helping to reduce the risk of human error.

IV. Design Application: Project Omega

After the research and reconnaissance phase of the case studies, the abacus was built and the classification code was developed, including the founding principles that define a Space Architecture project for planetary settlements, the thesis work went further by trying to apply the knowledge acquired and the results obtained in a project concept: Project Omega.

Mars was chosen for the development of this project. The reasons for this choice were both technical and formal. The technical reasons were the interest shown by space agencies in locating a base on Mars in the near future, the similar characteristics that the Red Planet has with Earth, and the fact that it is the second celestial body on which to install a base after the Moon. The formal reasons were that in the study phase there was a greater interest in the case studies set on Mars.

However, it has been assumed that the same design principles could be adaptable to other celestial bodies, in line with the goals of the research.

A. Executive phases

The planning of a settlement also requires due planning both in the short and long term. For the proposal of this design concept, a development organized in stages that could be assimilated to a chrono program has been suggested. These phases are therefore to be understood as overlapping in time.

- **Phase 00. Map**: this is a pre-construction phase in which the sites most suitable for housing a settlement is identified. At this stage, satellites, rovers, and drones are of paramount importance as they will help produce detailed maps and surveys of areas of interest, analysing multiple features and providing the necessary data to the next steps.
- **Phase 01. Trace:** the construction phase would begin. The management would be entrusted to robots with the task of preparing the sites and starting the construction of the first units of the outpost. Among the main tasks will be those of soil testing and preparation of the launch pad.
- **Phase 02. Supply:** simultaneously with Phase 01, a cargo mission would provide units for energy supply. There are many possibilities, namely Fission Surface Power (FSP)[27], solar panels, and vertical wind turbines (Vortex Tacoma[28]).
- **Phase 03. Establish:** the crews will have the task of starting the outposts for the permanent establishment. Among the first tasks will be to pressurize the habitats, furnish the environments of the habitats, as well as connect and verify the proper functioning of energy sources.
- **Phase 04. Explore:** the organization of the settlement is defined and functioning. Crews alternate cyclically, outposts continue their expansion and prepare to accommodate more settlers, including civilians.
- **Phase 05. Visit:** outposts continue to expand and populate, including civilians who remain for short periods. During their stay, however, they will have to perform useful tasks for the community.
- **Phase 06. Multiply:** technological progress and new research ideas can be used in new outposts scattered around the planet or on satellites. Each site identified contains unique features such as preparation for the emergence of new settlements. The intention is therefore to propose a model of city and community effective and adaptable to the needs that will arise.

B. Mapping Mars

As described above, the preliminary phase is to develop a map to be analysed and from which the site of the outpost will be chosen. In the case of Mars, the planetary map retrieved from the official site of the United States Geological Survey (USGS)[29] was used as the basis for making assumptions about the choice of site. It is an altimetric map showing the Martian surface by means of a colour scale, bordered by contours that facilitate the reading of craters, plains, canyons, and ripples [Figure 4]. Identification logos were used to highlight the areas of interest of international space agencies[30].

Interests in a particular site may be multiple. In fact, there are sites where there is greater scientific interest and other sites that are more suitable for landing operations that reduce the risk-benefit rate. However, all the areas identified represent a potential starting point in which to hypothesize the creation of a settlement.

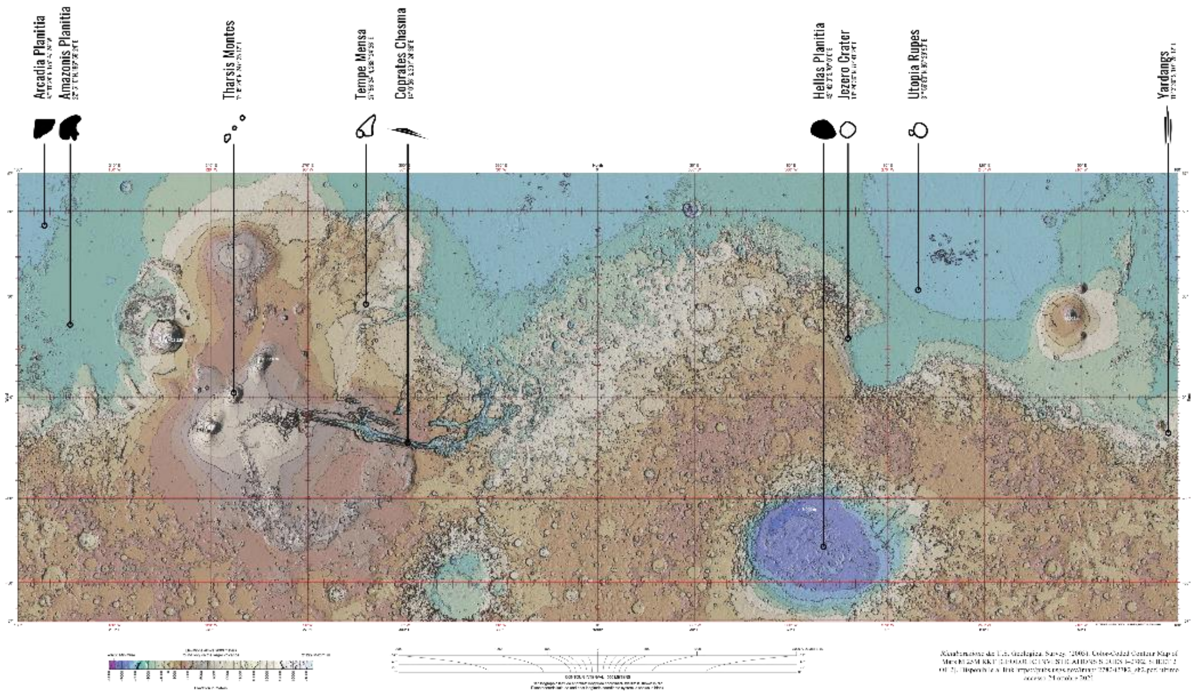

Figure 4. Sites of interest for a settlement on Mars.

C. Concepts & Design Approach

The combination of the results of the atlas construction and the knowledge of the possible sites in which to insert a design proposal has allowed the development of concepts that propose hypotheses of urban structures and aggregative solutions. The settlements were developed based on the 15-minute-city model[31], which allows residents to reach every functional area of the settlement within 15 minutes, and on the idea of the settlement as a living organism in which all the activities and structures essential for human life are channelled. This approach is also useful for creating communities.

The urban base is developed on a hexagonal mesh with a territorial sizing equal to a diameter of 1,500 meters, which is a distance that can be easily covered on foot within 15 minutes. The model of city-community to which reference is made and from which inspiration was drawn is that of Arcosanti[32] designed and built by the visionary architect Paolo Soleri in Arizona, USA. In Arcosanti, the community spirit is indispensable and has continued to drive the development of the town since 1970 [33]. To create a well-functioning organism, we decided to differentiate the lots into functional areas that cooperate with each other. Concepts were hypothesised with possible aggregate scenarios and types of land in which it would have been ideal to graft the settlement. From inline cities to radial cities, from flat areas to craters and gullies, from hybrid structures to hypogeal hypotheses.

The site selected for Project Omega is Milinkovic Crater, a crater located in the northern hemisphere of Mars, part of the area known as Arcadia Planitia. The location of this area therefore has multiple advantages:

- Flat terrain
- Presence of surface ice
- Scientific interest of the area

For these reasons, the JPL has included the area of Arcadia Planitia among the best candidates to start colonization of the Red Planet. Another reason that favours the grafting of bases in the northern Martian hemisphere, thanks to the vast plains, is the ability to land in the area with relative simplicity and then be able to manage several stages in a simple way, reducing the cost of missions and making it possible to finance additional consignments.34

The presence of constant surface ice throughout the year guarantees multiple security to the success of the missions. It is an excellent building material and a perfect insulator for cosmic radiation. Moreover, ice processing would literally be a source of life for the settlers because from this oxygen can be synthesized, indispensable for the survival of man.

D. Project Omega

The settlement is designed to be a self-sufficient 3D-printed city. It is organized in a concentric and radial way [Figure 5], with the Mission Control Centre [Figure 6]and the habitats branching off from it. The Mission Control Centre is responsible for managing the settlement and its missions. It is also home to laboratories, control rooms, hydroponic greenhouses, and storage. The habitats are designed to be modular and can be expanded as the settlement grows. They are also equipped with hydroponic greenhouses and other facilities to support the settlement's food production.

The Edge Buildings [Figure 7] are multifunctional buildings that are located along the edges of the hexagonal lots. They are designed to house a variety of functions, including storage, communal areas, laboratories, sanitary areas, gyms, vegetable gardens, cultural hubs, entertainment areas, and relaxation areas. The ground floor of the Edge Buildings is designed to accommodate storage, goods, and vehicles. It also houses ECLSS, which is responsible for providing the settlement with oxygen, water, and food. The first floors of the Edge Buildings house a variety of community activities, research, and recreation. The central floors house the residences, which can accommodate both single and shared units. They are dimensioned to comply with the ideal directives of habitability of 20m^3 per person[35]. The top floor of the Edge Buildings is a panoramic walk that offers a 360° view of the Martian landscape.

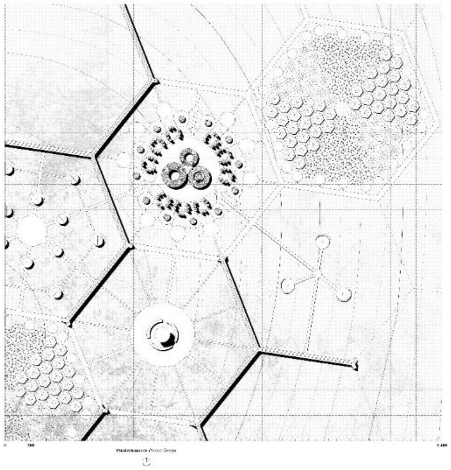

Figure 5. Planovolumetric Phase 3 Project Omega.

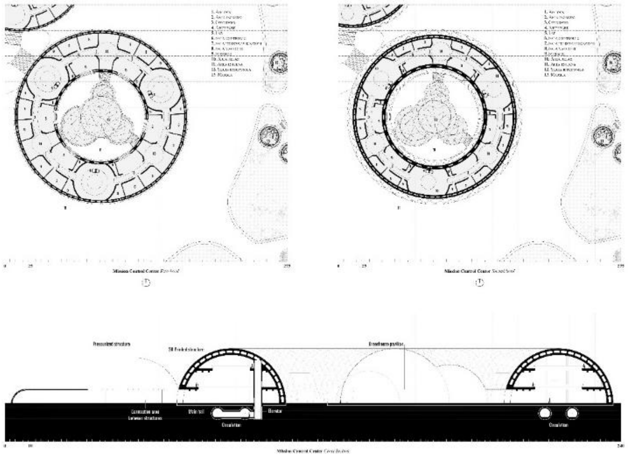

Figure 6. Mission Control Centre plans and section.

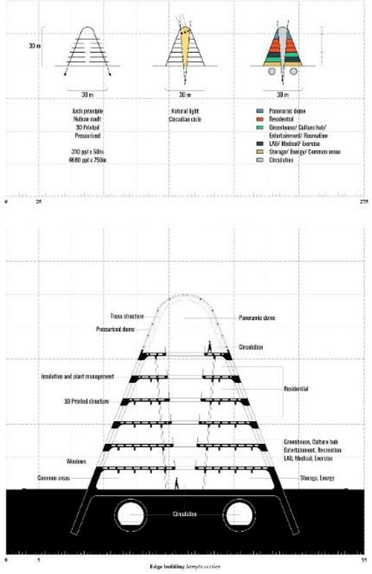

Figure 7. Edge building sample section.

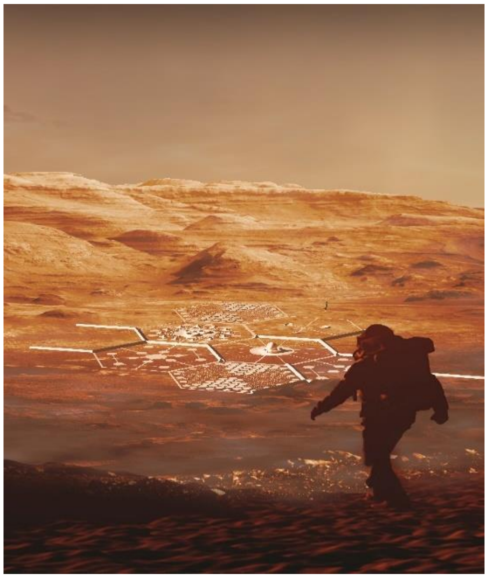

Figure 8. Artwork of Project Omega.

V. Conclusions

Architecture plays a key role in the aerospace environment. Thinking about living, measuring, and creating communities are just some of the topics that architecture can fit into. The study of materials and construction processes can now be evaluated and interpreted with a different vision from that with which we have up to now. For example, the duality between parametric design and 3D printing has infinite potential to create new, perhaps even utopian realities.

Multidisciplinary and collaboration are the keystone combination. The union between apparently distant subjects and studies that, with the same goal, manage to dialogue and find a unique and strong solution. These two terms are found both in the design and in the application phases, placing a new duality as architecture can be with AI. Instead, on a more human scale, we refer to the concepts of cities as an organism and the birth of new communities, with the hope and the need to break down the barriers still present today, to ensure the success of the missions.

The research presented in this paper has brought out all those recurring features present in the case studies identified. The drawings, the structural analysis and the construction methods, the functional study of the environments and the distribution solutions; were all useful elements to organize an Atlas of habitats beyond Earth. Another result obtained in this research is to have created a code that helps identify and catalogue an organism, a habitat. Knowing the state-of-art becomes fundamental to be able to propose efficient design solutions from multiple points of view: architectural, social, economic.

The dimensioning of the city and the organization of the functional areas, as well as the urban scale organization of the settlement were therefore based on solid concepts and principles of architecture. Creating a city, potentially metropolis, on a human scale is of fundamental importance in extreme environments such as Mars. Equally important is the relationship Architecture-AI that has been hypothesized and proposed for the management of all the phases of design, construction, and habitability of the settlement.

In conclusion, this research is intended to be a starting point that can inspire and guide those who are approaching the space sector and, to architects who want to know more about the Space Architecture with a clear and organized key of interpretation, also providing design ideas at different scales.

References

[1] Howe, S. A., & Sherwood, B. (2009). *Out of This World* (Library of Flight) (Illustrated ed.). AIAA.

[2] Bannova, O. (2021). *Space Architecture: Human Habitats Beyond Planet Earth* (Vol. 127). DOM Publishers.

[3] Kennedy, K. J. (2009). *Chapter 2 - Vernacular of space architecture*. In A. S. Howe & B. Sherwood (Eds.), *Out of this World* (pp. 7–10). AIAA.

[4] NASA. (n.d.-b). *Overview: In-Situ Resource Utilization*. https://www.nasa.gov/isru/overview/

[5] Moreno, C. (2020). *Droit de cité: De la "ville-monde" à la "ville du quart d'heure."*

[6] Arcosanti. (2021). *Arcosanti | The World's First Arcology Prototype & Urban Laboratory*. https://www.arcosanti.org

[7] *Konstantin Tsiolkovsky*. (n.d.-b). https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Exploration/Konstantin_Tsiolkovsky

[8] *Von Braun Station.* (n.d.). http://www.astronautix.com/v/vonbraunstation.html

[9] *ISS: International Space Station. (n.d.).* https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/International_Space_Station/ISS_International_Space_Station

[10] Osburg, J., Adams, D., & Sherwood, M. (2003*). Space architecture: A systems engineering approach*. Reston, VA: American Institute of Aeronautics and Astronautics

[11] *Millennium Charter Manifesto, Space Architecture Mission Statement*, AIAA Space Architecture Symposium & Workshop, World Space Congress, Houston, Texas, USA, 10-12 October 2002

[12] AIAA Space Architecture Technical Committee (SATC). (2002, October). *The Millennium Charter. Fundamental Principles of Space Architecture.* Houston, Texas, USA. http://spacearchitect.org/wp-content/uploads/2020/06/The-Millennium-Charter.pdf

[13] SpaceArchitect.org. (n.d.). *Bibliography*. https://spacearchitect.org/pubs/pub-biblio.htm

[14] SpaceArchitect.org. (2022). *SpaceArchitect.org*. https://spacearchitect.org/#:~:text=SpaceArchitect.org%20provides%20an%20inclusive,living%20in%20space%3A%20Space%20Architecture.

[15] Tiziani, M. (2013). *The Colonization of Space: An Anthropological Outlook*. Antrocom Online Journal of Anthropology, 9 (ISSN 1973–2880), 225–236. http://www.antrocom.net/upload/sub/antrocom/090113/21-Antrocom.pdf

[16] Masali, M., Ferrino, M., Argenta, M., Ligabue Stricker, F., & Micheletti Cremasco, M. (2010). *Anthropology: Physical and Cultural Adaptation in Outer Space*. Springer-Verlag. https://doi.org/10.1007/s00779-010-0324-6, in Benaroya Haym (edit by), Lunar Settlements, CRC Press, Boca Raton, USA

[17] Schlacht, I.L., Brambillasca, S. & Birke, H. *Color Perception in Microgravity Conditions: The Results of CROMOS Parabolic Flight Experiment.* Microgravity Sci. Technol 21, 21–30 (2009). https://doi.org/10.1007/s12217-008-9063-y

[18] Meuser, P. (2014). *Galina Balaschowa: Architektin des sowjetischen Raumfahrtprogramms* (German ed.). DOM Publishers.

[19] Rathjen, T. & Whitmore, M. & McGuire, Kerry & Goel, Namni & Dinges, David & Tvaryanas, Anthony & Zehner, G. & Hudson, J. & Dismukes, Key & Musson, D.M. (2008). *An introduction to human factors in aerospace*.

[20] SAGA Space Architects. (2019). *LUNARK.* https://saga.dk/projects/lunark

[21] Petrov, G., Inocente, D., Haney, Katz, N., Koop, C., Makaya, A., & Arnhof, M. (et al.). (2019). *Moon Village Reference Masterplan and Habitat Design.* 49th International Conference on Environmental Systems

[22] *MARSHA.* (2019). AI Spacefactory. https://www.aispacefactory.com/marsha

[23] ABIBOO Studio. (2020). *Nüwa Martian City, Explained Explicación de la ciudad de Nüwa, Marte*. https://abiboo.com/nuwa-mars/

[24] Morris, M., Ciardullo, C., Lents, K., Montes, J., Yashar, M., Rudakevych, O., Sono, M., Sono, Y. (2016). *Mars Ice House: Using the physics of phase change in 3D printing a habitat with* H_2O. 46th International Conference on Environmental Systems

[25] ESA. (2021). *Artificial intelligence in space.* Esa.Int. https://www.esa.int/Enabling_Support/Preparing_for_the_Future/Discovery_and_Preparation/Artificial_intelligence_in_space

[26] Chaillou, S. (2022). *Artificial Intelligence and Architecture: From Research to Practice*. De Gruyter.

[27] NASA. (n.d.). *Fission Surface Power*. https://www.nasa.gov/mission_pages/tdm/fission-surface-power/index.html

[28] Villarreal, D. J. Y. & Vortex Bladeless S.L. (2018). *VIV resonant wind generators.* https://vortexbladeless.com/wp-content/uploads/2018/10/VortexGreenPaper_en.pdf

[29] USGS. (2003). *Topographic Map of Mars*. https://pubs.usgs.gov/imap/i2782/

[30] Link4universe. (2021). *Missioni con umani su Marte: Dove atterreranno?* [Video]. YouTube. https://www.youtube.com/watch?v=EW-cdrQYeZk

[31] Duany, A. R. S. (2021). *Defining the 15-minute city*. CNU. https://www.cnu.org/publicsquare/2021/02/08/defining-15-minute-city

[32] Doglio, F., & Tosoni, P. (2013). *Paolo Soleri. Paesaggi energetici. Arcologie in terre marginali*. Lettera Ventidue.

[33] Sicilia, A. (2015). *Le architetture di Paolo Soleri. Un viaggio in Arizona*. Malcor D'.

[34] Boyle, A. (2017, March 21). *Arcadia on the map: For future Mars landing sites, SpaceX thinks ice is nice*. GeekWire. https://www.geekwire.com/2017/arcadia-planitia-mars-landing-spacex-ice/

[35] Bannova, O. (2021). *Design guidelines: Influencing factors*. In Bannova, O. *Space Architecture: Human Habitats Beyond Planet Earth* (Vol. 127). (pp. 143-2015). DOM Publishers.