LUISS

Master's Degree in International Relations, Major in Security.

Course of Exogeography: Astropolitics, Space Economy

“ Comparative analysis of terrestrial socio-environmental adaptation and the challenges of human permanence on Mars. ”

Prof. Alfonso Giordano

SUPERVISOR

Prof. Michele Governatori

CO-SUPERVISOR

Francesca Chirieleison 654322

CANDIDATE

Academic Year 2024/2025

TABLE OF CONTENTS

CHAPTER 1: INTRODUCTION

1.1 Background and context

The human species, during its evolutionary history, developed the capability to adapt to challenging and different environment, which ensured its survival. Besides the inherent survival instincts, the movement from one place to another has sparked ongoing discussions regarding the reasons behind the initial human species' migration; the general consensus is that the first "homo" left Africa due to climate change, as it would have an impact on their lives and survival since there were less resources available[1]. Meanwhile, humans have learnt to adapt to differnt environments, also thank to technology, which has evolved alongside mankind, and has been essential in ensuring the adaptation and survival of the species. This co-evolution between man and technology has triggered an unprecedented acceleration, culminating during the mid-twentieth century, a period in contemporary history defined as the era of the "Great Acceleration". This period is marked by exponential growth in many aspects of human life, from industrial production and economic expansion to population growth. It is closely associated with the Anthropocene), the current geological epoch in which human activities became the dominant force disrupting the balance of nature (Steffen et al., 2015). [2]

The power and development of civilizations have been founded, over time, thanks to the conquest of the main terrestrial domains: the earth, the sea and the sky. Stephen J. Pyne, the author of “Space: a third great age of discovery,” contextualizes the history of humanity's exploration well; suggesting that humanity is entering a "Third Great Age of Discovery” (Pyne, 2016)[3]. The launch of the artificial satellite Sputnik 1 by the Soviet Union on October 4, 1957 started the "space race" between the Soviet Union and the United States, defining a new context of the Cold War (Del Canto Viterale, 2023). Space was no longer just a scientific progress, but became a real means of power for countries in geopolitics. The new frontier was dominated by a bipolar and simplified system, centered on the competition between the two superpowers

[1] Carto, S. L., Weaver, A. J., Hetherington, R., Lam, Y., & Wiebe, E. C. (2009). Out of Africa and into an ice age: on the role of global climate change in the late Pleistocene migration of early modern humans out of Africa. Journal of Human Evolution, 56(2), 139-151.; Groeneveld, E. (2017, May 15). Early human migration. World History Encyclopedia.

[2] << The beginning of the industrial revolution around the late 18th century is sometimes proposed as a start date for the Anthropocene>> (Crutzen and Stoermer, 2000); (Steffen et al., 2015)

[3] Pyne, S. J. (2016). Space: A third great age of discovery. Space Policy, 37, 113–119.

and space activities were mainly focused on military and strategic interests, with technologies developed for war and deterrence purposes. With the fall of the Soviet Union in 1991, the space domain changed to a multipolar space system. The new actors are not only states, but also private companies, think tanks and wealthy financiers. In the 21st century, space becomes a strategic sector for economic growth and innovation, thus creating a context between state and non-state actors, of international cooperation, technological competition and economic interests. [4]

This historical phase represents man with new aspirations, no longer linked to the conquest or exploration of space, but these are extended to potentially settling in it or creating a new space tourism. Among all the planets, Mars presents itself as a planet to explore, study, both for scientific progress and for strategic reasons for the survival of the human species (NASA, Humans to Mars)[5]. However, human permanence on Mars raises doubts on how our species will adapt on such different environment. The questions involve various dimensions of a scientific, physical, psychological, social and ethical nature [6]. How the geography of Mars, its landscape, resource distribution, and environmental constraint, will influence human settlement patterns, land use planning, and community formation? Will humans be able to adapt to extreme and prolonged conditions in a completely artificial and closed habitat? And above all, what governance models will exist?

In order to answer these concerns, it is required an interdisciplinary approach that that includes all of the various components of an adaptation process. Certainly, investigating long-term human permanence is more challenging and neccesitate larger data, which are currently lacking. However, this paper’s discussion focuses on humans' adaptability to extreme conditions in order to understand the possible challenges or solutions; and will limit itself to explore the process of adaptation as it exists today.

---

[4] Del Canto Viterale, F. (2023). Transitioning to a new space age in the 21st century: A systemic-level approach. *Systems*, *11*(5), 232.

[5] << Mars remains our horizon goal for human exploration because it is one of the only other places we know where life may have existed in the solar system. What we learn about the Red Planet will tell us more about our Earth’s past and future and may help answer whether life exists beyond our home planet.>> NASA. (n.d) Humans to Mars https://www.nasa.gov/humans-in-space/humans-to-mars/

[6] NASA. (n.d) Humans to Mars: Preparing for the Journey. NASA. https://www.nasa.gov/humans-in-space/humans-to-mars/#preparing

1.2 Research question

Curiosity and the will to explore are the main traits that allowed humanity to overcome its boundaries. However, this statement raises a genuine question: why are we so determined to reach Mars? The factors motivating this enormous goal are multifaced and include scientific, economic, political, and cultural aspects.

NASA states that exploring space holds great importance for humanity as it aids in tackling shared existential issues that have long been debated. Consequently, one of the primary motivations for our desire to explore Mars is to perform scientific research and gain a greater insight into the universe. Even with its distinct environmental features, this planet is among the rare locations in the solar system where life might have thrived; furthermore, it could function as a natural laboratory for examining Earth's evolution.[7] Along with the scientific aspect, there is a growing necessity to leave our planet for the survival of the human species. Indeed, the increase of terrestrial issues such as, climate instability, climate refugees, resource scarcity and population growth[8], encourage space agencies to consider expansion and permanence beyond Earth. All of this has resulted in further investments in the space sector, which is continuously expanding.

Still, the concept of permanence on Mars requires a greater understanding of the constraints and limitations of human adaptation to harsh environments, taking into account the enormity of the project. Before formulating plans for Martian colonies and social structures, it is critical to investigate what it will mean for humans to encounter drastically different climatic circumstances that will test our physical, psychological, and social resistance.

So consequently, this study will attempt to answer an essential query in the context of space exploration: "How can demographic adaptation strategies developed in extreme terrestrial environments contribute to the creation of human settlements on Mars?"

The study, which relies on an interdisciplinary approach, will bring together researches of various dimensions: geographical, physiological, psychological, social and political adaptability. On one hand, it is important to asses the physical geography of Mars, as its topography, isolation, gravity, resource distribution, and environmental constraints may

---

[7] NASA. (n.d) Humans to Mars: Preparing for the Journey.
[8]Roser, M., & Ritchie, H. (2023) Population Growth. Our World in Data. https://ourworldindata.org/population-growth

influence the process of human settlement. On the other hand, investigating on how humans have survived and organized themselves in extreme environments on Earth in isolation, such as the study of space agencies terrestrial analogs which create the critica conditions that we will encounter on Mars, and can provide concrete information on survival strategies. Thus, the research takes a multifaceted perspective by including: demographic and social dimensions, how humans would face closed and isolated habitats, and how they would start to manage decisions in a group—all of which are essential for building a stable and resilient society. It is not just about studying the technical aspects of survival, such as the physical and psychological characteristics of adaptation in a hostile environment. This kind of examination allows to comprehend the difficulties that people will face on the Red Planet in a more comprehensive way.

1.3 Objective of the study

The main objective of the research is to identify, understand and predict the multifaced challenges that may overcome during long-term human adaptation to the Martian environment. To achieve this, the study is structured around four interconnected objectives, which are essential to evaluate whether, and under which conditions, sustainable human permanence on Mars may be possible.

1. **Environmental and geographical assessment:**
   The first objective is a precondition to human adaptation. It involves the study of the spatial and atmospheric constrains, as these criteria may help determine which areas could directly influence human future survivability. Specifically, according to NASA (2024), the following key scientific goals aim at understanding the habitability, potential for life, and therefore the suitability for human future missions[9]:
   The study involves the identification of signs of life as water, the most crucial extraterrestrial resource, considered the key to long-term human habitation beyond Earth (She, X., Wang, J., Xu, W., & Xiao, L. 2025). The search of it is aimed at understanding whether it existed, or it is still trapped under other forms, such as, ancient lakes, underground ice deposits, hydrothermal regions (Andrade, S. S. 2025). Moreover, understanding Mars' climate and geography is crucial to have a realistic

[9] Andrade, S. S. (2025). Spatial Suitability Analysis of Mars for Robotic Colonization and Future Human Settlement (Master's thesis, Universidade NOVA de Lisboa (Portugal)).

perspective of the physiological thresholds necessary for survival and understand the minimum standards for habitability. Analyzing surface features and mapping data allows researchers to define potential human settlement zones on maps that apply terrestrial cartographic standards to the Martian environment.

2. **Classification of critical survival factors:**

   As future human missions and settlements would become more frequent, it is essential to acknowledge the challenges of the adaptation of a hypothetical mass migration on Mars. Once the environmental conditions and the possibility of human permanence are understood, with challenges such as high radiation and extreme temperatures (Andrade, S. S. 2025); the research will address the impact of the possible settlement, by identifying critical factors of survival on a: physical, psychological, government and social dimension, through analogous terrestrial cases. This phase's aim is to identify and classify the main factors that, if not ensured, would directly compromise human survival on Mars.

3. **Comparative study of Earth-based adaptation models:**

   This objective serves as a way for better understanding how humanity could adapt to life on Mars, with the analysis of terrestrial cases, called ground based analogues and mission simulations. These analogues are natural laboratories that become conceptual models to anticipate how future Martian settlers might respond to some of the critical factor of survival already outlined, which could be categorized more broadly in physiologically, psychologically, and operationally. While for the governance dimension, rather than being investigated through analogue environments, it is informed by international treaty systems, institutional practices, and policy frameworks developed for extreme and remote domains.

   The case studies selected for the comparative study represent the four key dimensions of adaptation:

a. **Physiological adaptation:** The case chosen is the study of ground based analogues[10], specifically *The AGBRESA bed rest study*[11] to analyze how humans physiologically and psychologically de-condition under prolonged microgravity-analogue conditions, as well as to evaluate Artificial Gravity (AG) as a potential countermeasure. And, *Mars500 Project*[12], a confined habitat experiment of a 520-day mission to Mars, which is a mission simulation for studying the physiological and psychological effects of prolonged confinement and isolation, and the impact of prolonged stress on physiological functions.
b. **Psychological:** This dimension is a consequence of permanence in the outerspace. Human lives in a complete different environment and habitat from what it was usual, in addition, isolated and far from "home". These critical elements are stated as the "top risks" by NASA,[13] and can impact a crew member's sleep, morale, and decision making, along with contributing with the increase possibility of behavioral issues and psychiatric disorders, such as anxiety and depression. The Concordia Station[14] represents the terrestrial analogues of such consequences[15] in a hypothetical prolenged settlement on Mars:

   "The indoor environment is monotonous and offers limited mobility and stimulation : dysfunctional responses to stress, fatigue, lack of energy, conflicts and tensions, perceived loss of control, and decrements in attention and cognitive functioning (Leon, Sandal, & Larsen, 2011)" (Michel, N., Suedfeld, P., Weiss, K., & Gaudino, M. 2015).

   Also, Mars 500 mission provides comprehensive results on the isolation and confinement effects on crew's behavioural health.

---

[10] MacRobbie, M., MacRobbie, C., Stankovic, A., & Newman, D. (2025). Analogs as a research platform: Systems-based optimization approach to facility selection. Analog Astronaut® Research Journal, 1(1), 6-27.
[11] Clément, G. R., Crucian, B. E., Downs, M., Krieger, S., Laurie, S. S., Lee, S. M., ... & Zwart, S. R. (2022). International standard measures during the AGBRESA bed rest study. Acta Astronautica, 200, 163-175.
[12] Ushakov, I. B., Vladimirovich, M. B., Bubeev, Y. A. E., Gushin, V. I., Vasil'eva, G. Y. E., Vinokhodova, A. G. E., & Shved, D. M. (2014). Main findings of psychophysiological studies in the Mars 500 experiment. *Herald of the Russian Academy of Sciences*, *84*(2), 106-114.
[13] NASA 2025. https://www.nasa.gov/reference/risk-of-behavioral-conditions-and-psychiatric-disorders/#:~:text=What%20are%20the%20top%20risks,confined%20environment%20over%20multiple%20months.
[14] Michel, N., Suedfeld, P., Weiss, K., & Gaudino, M. (2015). Affective, social and cognitive outcomes during a one year wintering in Concordia. *Environment and Behavior, 48*(7), 1073–1091.
[15] Migaki, W., Doki, S., Kanai, N., Oi, Y., Schastlivtseva, D., Takahashi, T., ... & Sasahara, S. I. (2025). How isolated and confined-environment missions shape human interactions: SIRIUS-21. Acta Astronautica.

The discussion of this objective will cover not only the challenges, but also the possible solutions that could overcome from the use of plants, to colors and architecture. [16]

c. **Resource sustainability:** Human performance on Mars cannot be measured only through results on physiological or psychological models but instead must be viewed as an emergent property of interactions among humans, technology, architecture, and operational systems. The Crew Health and Performance Exploration Analog (CHAPEA) program[17] was specifically designed to explore this aspect of human adaptation. In addition, NASA's ISRU analog[18] missions with the goal of minimizing the amount of material launched from Earth and transported to the Moon or Mars for construction purposes.

d. **Governance and legal frameworks:** Diplomacy is becoming increasingly important in space, as the "new space race" opens possibilities. The analysis of this section has to consider a plurality of international treaty systems that can offer both positive and negative insights, such as the Antarctic Treaty System, the Outer Space Treaty and its susequent treaties, the Space Act and the Artemis Accords.[19]

The ATS (1961)[20]: is an international agreement that regulates activities in Antarctica. What is relevant to Mars, is that it offers an example of cooperative governance without sovereign ownership, by promoting knowledge sharing and the peaceful use of space. However it cannot be considered futher than this, because it

[16] NASA Astrobiology. (2023). Life at low pressure: Planetary protection and the habitability of Mars. NASA Astrobiology Institute.; Giordano A., (2025) "Human Migration, Settlements and Life in Outer Space: Some Initial Reflections on an Imagined Population Exogeography", in Casagrande G., D'Ascenzo A. (a cura), Oltre la Terra, Verso l'Esogeografia, Memorie della Società Geografica Italiana, Rome: Società Geografica Italiana.

[17] Yashar, M., Glasgow, C., Mehlomakulu, B., Ballard, J., Salazar, J. O., Mauer, S., & Covey, S. (2022). Mars dune alpha: A 3D-printed habitat by ICON/BIG for NASA's Crew Health and Performance Exploration Analog (CHAPEA). In *Earth and Space 2022* (pp. 976-984).

[18] Reagan, M., Janoiko, B., Johnson, J., Chappell, Ph. D, S., & Abercromby, A. (2012, January). NASA's analog missions: Driving exploration through innovative testing. In *AIAA SPACE 2012 conference & exposition* (p. 5238).; Sanders, G. B., & Kleinhenz, J. E. (2022, September). NASA envisioned future priorities for in situ resource utilization. In International Astronautical Congress (IAC).

[19] Blair, J. A. (2011). Private spaceflight, public interest: Regulating commercial space tourism through a new application of the public function test. Georgia Law Review, 45(2), 585–623.

[20] Antarctic and Southern Ocean Coalition. (n.d.). *Who governs Antarctica? Understanding the unique governance of the continent.; Berkman, P. A., Lang, M. A., Walton, D. W. H., & Young, O. R. (Eds.). (2011). Science diplomacy: Antarctica, science, and the governance of international spaces. Smithsonian Institution Scholarly Press.*

does not contemplate permanent settlements or the commercial exploitation of resources, limiting its applicability in a permanence context.

The Outer Space Treaty (1967)[21]: the most significant treaty in the history of international space law. Article I of the Treaty provides the general principle that the exploration and use of outer space, including the moon and other celestial bodies, shall be done for the benefit and in the interest of all of humanity. It involved others non-state actors in the space domain.

The U.S. SPACE Act (2015)[22]: it granted U.S. citizens the authority to engage in the commercial exploration and recovery of space resources, including water and minerals, subject to the exception of biological life, without asserting sovereignty over celestial bodies. This act created a comprehensive still ongoing debate, on the practical aspect of the provision.

The Artemis Accord (2020)[23]: an agreement sustained by NASA and US Government. It establish principles for the peaceful exploration of the Moon, based on the 1967 Outer Space Treaty. They include the use of safety zones, data sharing, and the protection of space assets. It is relevant on Mars for its support for the private sector and promotes standardization, along with multilateral cooperation. However, it could present risks of multipolar and fragmented governance.

The growing role of private entities play a central role in projecting lunar and Martian habitats, launching infrastructure, and developing resource extraction technologies.

The aim here will be the understanding of a sustainable martian governance that will integrate international cooperation, private economic development, and an inclusive regulatory framework.

4. **Demographic and long-term sustainability planning:**

   This conclusive obejctive will be extensively discussed in Chapter 3, where there will be a proufound study of the imaginated population that will inhabit the Martian base.

[21] Iliopoulos, N., & Esteban, M. (2020). Sustainable space exploration and its relevance to the privatization of space ventures. *Acta Astronautica*, *167*, 85-92.

[22] liopoulos, N., & Esteban, M. (2020). Sustainable space exploration and its relevance to the privatization of space ventures. *Acta Astronautica*, *167*, 85-92.

[23] NASA. (2024). The Artemis Accords: Principles for a safe, peaceful, and prosperous future. National Aeronautics and Space Administration.

The issues that will be stated are linked to projected demographic expansion, birth rate challenges, and the sustainability of the first permanent colonies. The evaluation of such critical issues of a permanence will be build on the assumptions already outlined in the survival factors segment. The prior identification of the main critical survival factors and the information obtainded from terrestrial case studies will be helpful for the understanding of the continuity and propagation of the human species. Specifically, the themes in discussion revolve around the life cycle in closed environments (eg. reproduction, child development, education systems, and the maintenance of intergenerational sustainability), following a trajectory from departure to destination. [24] This analysis will give a broader discourse on how to make Martian settlements enduring and ensuring that future generations can prosper in the outerspace.

1.4 Theoretical and methodological framework

The thesis is grounded in an interdisciplinary approach for the literature and methodological framework that integrates insights from theoretical models, scientific literature, data driven research, real-world case studies, and international legal frameworks in the socio-political domain. It follows a multi-layered methodological approach as well, by first examining the motivations and patterns of human migration to arrive at the focus of why and how humans have historically adapted to hostile or remote conditions on Earth. This serves as a meaningful insight to inform the risks and strategies for a future of human permanence on Mars, an environment that is even more extreme. The first level of analysis revolves around human geography and socio-anthropological frameworks, reflecting on the concept of exogeography, to understand the drivers of migration and settlement of the human species. The theoretical framework of "exogeography", appears as a "geography to come" in this context of comprehending human presence and behaviour in alien environments (Casagrande, 2025.)

[24] Giordano A., (2025) "Human Migration, Settlements and Life in Outer Space: Some Initial Reflections on an Imagined Population Exogeography", in Casagrande G., D'Ascenzo A. (a cura), Oltre la Terra, Verso l'Esogeografia, Memorie della Società Geografica Italiana, Rome: Società Geografica Italiana..; Salotti, J.M., Labache, L., Pellet, E., Riffaud, P., Chator O. (2015). Human Factors Issues for a Sustainable Settlement of Mars. 9th IAA Symposium on the Future of Space Exploration, Turin.

The metaphor “Our planet is the cradle of intelligence, but one cannot eternally live in a cradle.” (K. Tsiolkovsky 2006. p. 114) [25] gives a reflection on why human species migrates. There is behind the idea that although Earth has been the place where human intelligence first emerged and developed, it is not intended to be its exclusive and permanent home. The core subject of geographical studies is human presence and action in the spaces where they occur (Casagrande, 2025). Humankind, in the past centuries, have migrated and expanded geographically all over the world, conquering the domains of lands, sea and sky, which are all within the physical limits of the Earth. Yet, a new era began with the start of the space age, that according to (Casagrande, 2025), was symbolically marked by Yuri Gagarin’s orbital flight on April 12, 1961, and later by the historic Moon landing of Apollo 11 in 1969. These “conquests”, although they were a demonstration of geopolitical powers during the Cold war, were signing the first steps into an extraterrestrial spatial dimension and laid the groundwork for a new term: exogeography. Although these initial missions had limited long-term sustainability, human activity in outer space has progressively evolved into a structured presence; by “colonizing” first the Low Earth Orbit, through space stations and satellite networks, and now by expanding the idea of human actual permanence on Mars to extend the duration of the missions.

Space is now a reality that is also present in our daily life, especially for the technologies’ innovation.[26] It constitutes an actual geographical shift. According to Yi-Fu Tuan, a twentieth-century humanist geographer that stated the concept of "experiential perspective," where highlights how "space" becomes "place" when humans attribute meaning to it. Therefore, a person does not need to be physically present in that space for it to become a place for a community (Casagrande, 2025). In this context, celestial bodies (e.g. Mars, Moon) can already be considered as places, despite the scarcity or absence of human presence. This development occurs along two parallel axes:

- Observation: the systematic collection of data through sensors, telescopes, satellites, and experiments.

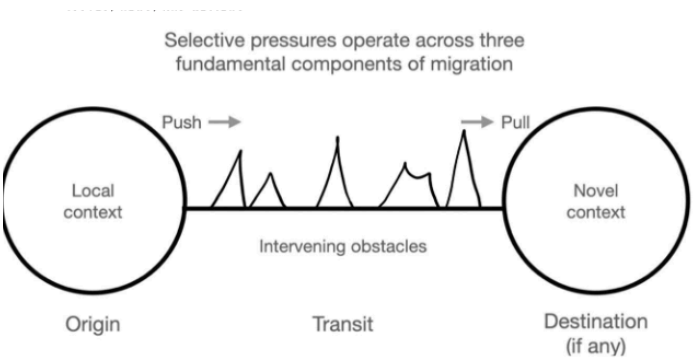
[25] Casagrande, G. (2025), “Looking out of the cradle. Possible geographical perspectives on the beginning of human expansion in outer space”, in Casagrande, G., D’Ascenzo, A. (a cura), Oltre la Terra verso l’Esogeografia, Società Geografica Italiana, Roma, 71-93

[26] “Generations of different technologies enabled to use these devices for communication, Earth observation, global positioning, only to mention the most common cases. A vast majority of these technologies is in place to serve industrial, commercial and political purposes” (Casagrande, 2025)

- Analogy: the construction of simulated or surrogate experiences that allow humans to imagine, act and adapt in environments not yet habitable.

Cartographic representation is an additional tool of transformation of space into place. Mapping is a cognitive and strategic way to build models of territory, identify critical issues and guide decisions on where to settle, although initially based on remote sensing. In exogeography, mapping is not only a tool used to describe, but also, to anticipate habitable conditions; in the future, topographical and functional mapping of Mars could present the same functions that maps have performed throughout human history.

Migration[27], in this context, is perceived as adaptive model where the adaptation to Mars can be interpreted as a new form of ecological migration, since it represents one of the most powerful mechanisms through which humanity has faced extreme, unknown and hostile environments throughout its evolution. Anthropological and evolutionary studies (Bell, A. V. 2023) show that Homo sapiens has always faced extreme environments through natural selection, physiological, cognitive and cultural adaptation. The origins are presented within three mechanisms: push and pull factors, and in the middle, transit; following Lee's push and pull migration theory.



1. **Origins or Push Factors:** The origins of migrations are forces that lead individuals or groups to leave their original environment (e.g. overpopulation, scarcity of resources, conflict or climate change). Similarly, the desire of expand in the outer space can be drawn to a response to similar pressures, as the degradation of the Earth's environment, or the need to ensure the long-term survival of the species.[28] About this, it is important

[27] Bell, A. V. (2023). Selection and adaptation in human migration. Evolutionary Anthropology: Issues, News, and Reviews, 32(6), 308-324.
[28] Roser, M., & Ritchie, H. (2023) Population Growth. Our World in Data. https://ourworldindata.org/population-growth

to mention in the context of forced land migrations, the issue of ***climate refugees*[29].** The report (Climate Refugees, 2023) documents how millions of people around the world are already forced to leave their territory due to extreme weather conditions. On one hand the Internal Displacement Monitoring Centre (IDMC) collected disaster displacement data from 2008 and has reported 359 million internal displacements due to weather-related hazards, an average of 22.4 million per year; demonstrating how climate shocks threaten development gains.[30] On the other hand, the Intergovernmental Panel on Climate Change (IPCC) projects that more than one billion people globally could be exposed to coastal-specific climate hazards by 2050, potentially driving tens to hundreds of millions of people to leave their home in coming decades (IOM, 2022; IPCC, 2022). This experience offers a powerful empirical basis for reflecting on future scenarios of interplanetary migration, highlighting the potential scale of cross-border movements if adaptation and mitigation efforts fail. It is notable the impact of environmental disasters on Earth, becoming one of the most frequent push factors and, as well how it could be a critical survival factor also in the Martian environment.

2. **Transit:** This phase represents a moment in which the group that decide to migrate have developed remarkable biological and cultural plasticity that resulted in a rapid adaptation to new environments through physiological responses and cultural, technological solutions. In the context of the research, this moment is particularly useful for interpreting the importance of simulation and simulations and analogous terrestrial environments. In the process of adaptation, humans had to innovate the existing technologies, strategies to become more flexible to their condition, similarly, in future space missions' humankind may have to combine advanced technological tools with operational knowledge and adaptive practices.
3. **Destination or Pull Factors:** The actual settlement phase deeply depends on the ability of migrants to acquire, adapt or transform local knowledge. In a Martian context, it corresponds to success of reimagining habitat construction or developing local survival strategies not only technical but also socially relevant, by integrating scientific knowledge with human adaptation.

[29] Climate Refugees. (2023). Forced to Move: A Climate Story. Climate Refugees. https://www.climate-refugees.org/forcedtomove;
[30] Internal Displacement Monitoring Centre. (2024). Internal displacement in 2024: Monitoring the crisis, measuring progress.

By continuing with the research, yet before stepping into the second level of the analysis, it is necessary to provide an overview framework of Mars' environmental and physical conditions, based on NASA's reports and (Andrade, S. S. 2025) studies. This is helpful as laying ground for the successive level of analysis which is the adaptive responses.

Mars is the second planetary neighbour and shares similar characteristics in its dynamic and water-rich nature with Earth. Differently, it has a very challenging environment with extreme low temperatures averaging around – 63 °C. The temperature on Mars can be as high as 70 degrees Fahrenheit (20 degrees Celsius) or as low as about -225 degrees Fahrenheit (-153 degrees Celsius). This because the atmosphere is very thin, so heat from the Sun easily escapes this planet gases (NASA 2025)[31] . The thin atmosphere is composed by 95% of carbon dioxide and doesn't offer much protection from impacts by meteorites, asteroids, and comets. About climate, winds on Mars create dust storms that cover much of the planet, but after these, it can be months before all the dust settles. There are areas in the southern hemisphere that are highly magnetized, indicating traces of a magnetic field from 4 billion years ago (NASA 2025)[32]. These data suggest all that the planet is an extreme environment, despite this, it is the most likely platen with Earth in the Solar System as it offers crucial resources (e.g. shelter, mineral, water) making the idea of permanence conceivable (Andrade, S. S. 2025). Water, which is the sign of life found on Mars, is found from ancient river valley networks, deltas, and lakebeds, as well as rocks and minerals on the surface that could only have formed in liquid water. Some features suggest that Mars experienced huge floods about 3.5 billion years ago (NASA 2025)[33]. Today, this important resource does not exist for long on the surface due to the thin atmosphere it quickly vaporizes; however, there are terrestrial experiments that could become important insights for a future on the planet.

These information serves as the starting point of the next analysis on human adaptation in similar terrestrial environments. This is the reason why the research has chosen four case studies, demonstrating each the relevance with the critical factors of survival acknowledged previously. The physiological, psychological, social (resource sustainability) and governmental will be explored in depth through scientific literature and experimental models of resilience, which provide experimental data on various aspects relevant to space colonization and conditions that mimic what future Martian settlers may encounter. The papers selected in

[31] NASA 2025. https://science.nasa.gov/mars/facts/#h-structure
[32] Ibidem.
[33] Ibidem.

this research provide technical and physiological benchmarks for evaluating habitability and the minimum conditions necessary for the sustainability of a human colony. While, through theoretical and normative references in the field of space governance, the research aims to understand a context in which there are no consolidated models of Martian governance yet. The absence of a recognized territorial sovereignty on Mars requires the construction of new forms of extraterritorial government, based on cooperation, sharing of resources and respect for human rights.

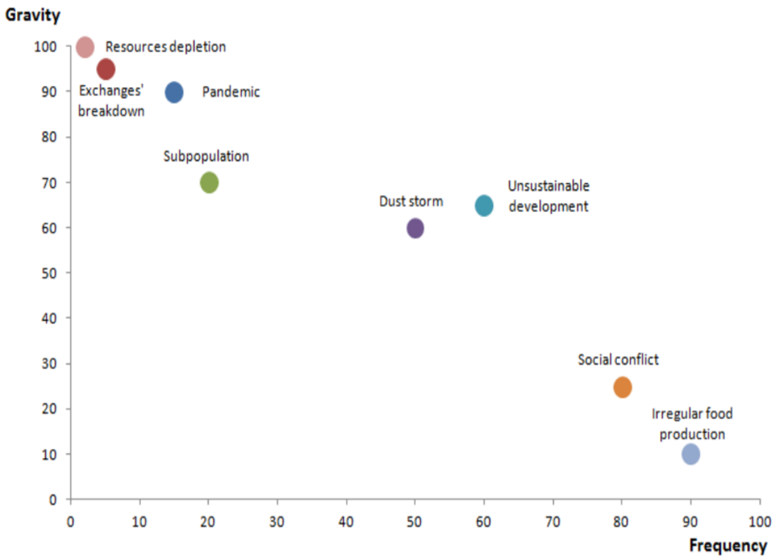
In order to construct a coherent framework for analysing the sustainability of human life on Mars, this research adopts the methodological assumptions presented by (Salotti et al., 2015), that the long-term human settlement depends on a complex interplay of environmental, physiological, psychological, technical, and socio-political variables.
The factors that will be classified can be grouped into logical categories drawn from the analysis of the scientific literatures of (Giordano, 2025; and Salotti et al., 2015), and will be used to build a reference model for comparison with terrestrial adaptations.
Several foundational assumptions must be stated, in order to continue with the classification of the critical survival factors on Mars:

> << One study (Salotti et al., 2015) assumed establishing **a Mars base of several hundred people (I)**, which would serve as the starting point for a global colonisation process. It has also been suggested that **interplanetary transport exists between Earth and Mars to allow the import of complex goods and systems (II).** However, **without major technological breakthroughs, such imports will be rather limited (III)**, and it is assumed that **industrial development will be required to exploit local resources and meet basic settlement needs (IV)**.>> (Giordano, 2025).
>
> These human factors are identified by considering the major risks, by evaluating their gravity and frequency, and by classifying them in terms of their direct and indirect impacts on other parameters (eg. resource availability, quality of life and psychological well-being, social organization and cohesion and development's sustainability).

Table 1. Identification of risks.

Risk	Description of the risk.
Resources depletion	Lack of water, food, air or any other important mineral resources, due to poor managing, inappropriate anticipation, eventually combined with degradations or disasters.
Pandemic	Illness imported from earth or unknown Martian disease.
Exchanges' breakdown	Lack of goods, systems and materials imported from earth, which might be caused by transportation problems or disagreements with Earth leaders and economic embargo from Earth. It is anticipated that the importation of goods will be increased with the number of settlers but that it will be less and less accepted by Earth populations.
Subpopulation	Not enough human resources to implement necessary and unescapable activities, eventually combined with problems in transportation of Earth immigrants, inappropriate distribution of skills or insufficient training capabilities.
Dust storm	Unpredictable meteorological events, eventually longer and stronger than expected with possible impact on power supply, plant growths and industrial efficiency.
Unsustainable development	Overpopulation due to a lack of birth control or too many Earth immigrants in regards of number of habitats, life support systems capability, food production or water resources.
Social conflict	Important disagreements on governance, social organization, task sharing, distribution of responsibilities, communication problems, etc. The consequence could be the destruction of habitats, greenhouses or industrial buildings, murders, civil war.
Irregular food production	Food stocks decrease due to overestimations of agriculture production or inappropriate exploitation of plants or animals in Martian environment conditions.

(Fig 1: Table of identification of risks and description of each. Salotti et al. 2015)



(Fig 2: Risks frequency and gravity assessment. The figure presents a qualitative risk assessment matrix plotting potential risks according to their frequency of occurrence (x-axis, percentage) and severity or gravity of impact (y-axis, percentage). Salotti et al. 2015)[34]

These data are the analysis of the multidimensional risks that could compromise human permanence in Mars settlement; helpful to identify the minimum thresholds for the survival and sustainability on the Red Planet.

[34] Salotti, J.M., Labache, L., Pellet, E., Riffaud, P., Chator O. (2015). Human Factors Issues for a Sustainable Settlement of Mars. 9th IAA Symposium on the Future of Space Exploration, Turin.

The thesis will conclude with an insightful discussion and analysis on demographic scenarios giving space to issues of reproduction, child rearing, education and intergenerational sustainability in indoor environments, relying mostly on two papers: *"Human Migration, Settlements and Life in Outer Space: Some Initial Reflections on an Imagined Population Exogeography", in Casagrande G., D'Ascenzo A. (a cura), Oltre la Terra, Verso l'Esogeografia, Memorie della Società Geografica Italiana, Rome: Società Geografica Italiana.*" (Giordano, 2025) and *"Human Factors Issues for a Sustainable Settlement of Mars. 9th IAA Symposium on the Future of Space Exploration"* (Salotti, et Al., 2015).

To conclude, the literature used may be helpful for predicting the challenges that may arise in the settlement process on Mars, where small groups, distant from direct assistance from Earth, will need to live together for an extended period and in closed habitats. This thesis has not the aim of ensuring conclusive answers, yet it may establish a basis for a thoughtful discussion on how humanity can create a society in an adverse environment, utilizing the cultural, technological, and normative resources available to them. The difficulty of adapting, that could be due to climate, solitude, or political instability, is not merely technical but inherently human and would demand a unified perspective on survival, coexistence, and enduring sustainability.

CHAPTER 2: TERRESTRIAL ANALOGUES AND CONDITIONS FOR MARS ADAPTATION

2.1 The physical and environmental geography of Mars

Over time, interest in Mars has steadily increased, fueled by successful technological advancements in explorations and major space agencies' investments from all over the world.

From a scientific point of view, the reason behind such focus lies on the belief that Mars, despite its extreme conditions, remains the planet most similar to Earth within the Solar System, espacially to Early Earth.
The ninetheenth century was characterized by diverse scientific inquiries with the aim of finding evidences of life on Mars. Until today, contemporary researches continue through the

use of telescopes and landings, aiming at detecting traces of water, soil biosignatures and surface rock and biomarker gases in the atmosphere, such as methane.

The most significant ongoing astrobiology project is ExoMars, a joint mission of the European Space Agency and the Russian Space Agency, designed specifically to search for evidence of Martian life.

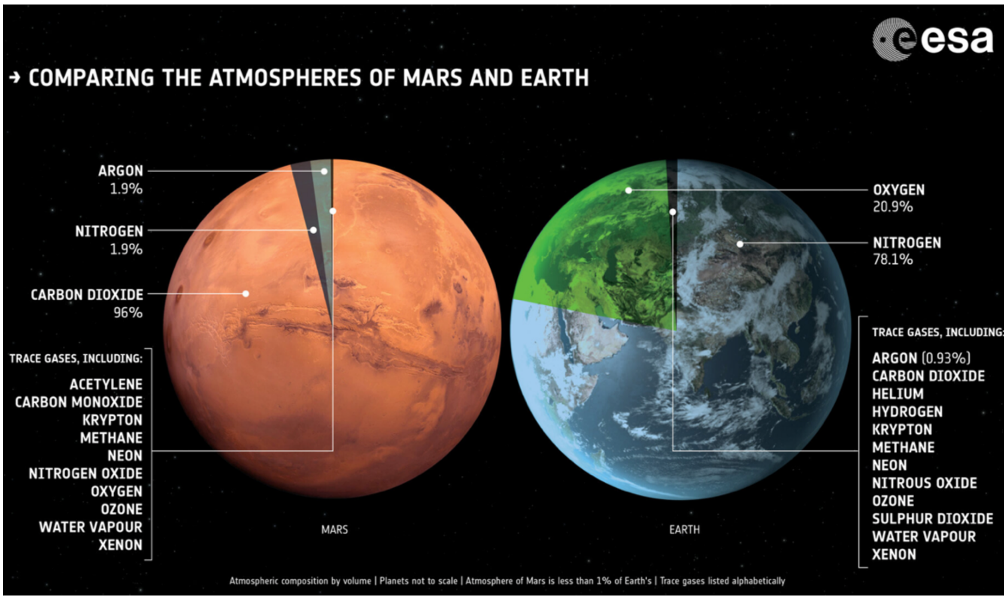
However, even if scientific research is still guided by this astrobiological viewpoint, Mars has progressively gained a new and wider significance among state and non-state actors. Therefore, this section is essential for assessing both the limits and the possiblities of the future perspective of human adaptation in the extraterrestrial environment. It identifies, along with general planetary descriptions, also the key environmental thresholds that define the habitability of Mars.

Mars' current atmospheric state is the consequence of a prolonged evolutionary degradation.

The gradual loss and disappearance of its magnetic field which once protected the planet from solar wind erosion, caused the slow release of atmospheric gases and a drastic reduction of surface pressure. Indeed, according geological and mineralogical evidence,

during the Noachian period, Mars used to possess a denser atmosphere capable of sustaining liquid water on its surface and useful condition for microganisms.[35] Additionally, the Curiosity rover, in 2017, detected an essential ingredient for life on Earth, called boron, further supporting the possible suitability of Mars for life. Although, the existence of living conditions does not necessarily imply the presence of life, and the subsequent loss of thermal and magnetic protection transformed the planet into the arid and cold world observed today.

[35] Petrescu, R. V., Aversa, R., Apicella, A., Kozaitis, S., Abu-Lebdeh, T., & Petrescu, F. I. (2018). There is life on mars?. American Journal of Engineering and Applied Sciences, 11(1), 78-91.)



(Fig. 3: Comparison of the atmospheric composition of Mars and Earth. European Space Agency [ESA], 2018)

The first impediment to human survival is the environment, and as Figure 3 shows, one of Mars' most notable characteristics is its incredibly thin atmosphere in comparison to Earth's. Its gaseous composition is predominantly made of carbon dioxide (96% ≅), with smaller amounts of nitrogen (1.9%), argon (1.9% ≅), and traces of oxygen, ozone, and water vapor (ESA, 2025). This composition of gases results in a weak effect of greenhouse warming, providing only a limited warming (about of 5-6 K[36]) in relation to Earth. In addition, the lack of significant ozone layer as on Earth, due to the scarcity of molecular oxygen, makes the atmosphere more vulnerable to ultraviolet radiation. [37]

From a human adaptation perspective, these circumstances encompasses high survival thresholds. The exposure to Mars' environment would be lethal, due to its high concentration of CO_2, low atmospheric pressure, and intense radiation. Indeed, an unprotected human would rapidly lose consciousness caused by hypoxia, while the extremely low pressure would cause rapid degassing of body fluids—an effect comparable to extreme decompression sickness among divers. Even the most resilient microbial spores can be destroyed by the biologically damaging UV flux on Mars, which is thought to be more than a thousand times stronger than on Earth. Furthermore, a constant stream of solar energetic particles and galactic cosmic rays

---

[36]"The kelvin, symbol K, is the SI unit of thermodynamic temperature." https://www.nist.gov/pml/owm/si-units-temperature#:~:text=One%20Celsius%20degree%20is%20an,on%20the%20Fahrenheit%20temperature%20scale.

[37] European Space Agency. (2018). Comparing the atmospheres of Mars and Earth [Image]. ESA. https://www.esa.int/ESA_Multimedia/Images/2018/04/Comparing_the_atmospheres_of_Mars_and_Earth

bombards the surface, resulting in cumulative radiation doses that far exceed terrestrial safety limits.

Again, the atmospheric pressure represents another critical constraint for sustaining life. Since the triple point of water is close to the typical surface pressure of about 610 Pa, liquid water is unable to remain stable under these thermodynamic circumstances; instead, it either freezes or sublimates.While, on Earth water is present naturally in all three phases and is the foundation for all known biological systems, it instability on Mars therefore poses one of the most fundamental barriers to habitability.

In the study conducted by Nazari-Sharabian et al. (2020),[38] the planet's hydrological cycle is confirmed to be primarily driven by sublimation and condensation.

So, water is found to be in polar ice caps and subsurface permafrost, with smaller amounts possibly existing as saline brines within the regolith. However, traces of salts indicate that under extremely cold conditions there can be transient liquid water, because these compounds can depress the freezing point to about −70°C. Also, radar observations from the European Space Agency's Mars Express mission suggest the existence of liquid water under the south polar ice cap, because of combined effects of pressure, geothermal heat and salinity. Such discoveries are important from an astrobiological point of view, as they could provide analogues for self-contained ecosystems relevant to future human habitats.

Another severe constraint regards the planet's extreme thermal variability that causes sharp day–night fluctuations, thus creating major challenges for both human physiology and equipment durability. In addition, dust storms composed of electrostatically charged particles can last for months and can cause problems by damaging systems, reducing visibility, and contaminating machinery.

The study conducted on exoplanet habitability [39]states that to determine such possibility it is essential to note the balance between atmospheric composition, magnetic protection, geological activity, and stellar energy. These interconnected processes gives the planet the capacity to sustain liquid water and a stable climate, which are two necessities for biological

[38] Nazari-Sharabian, M., Aghababaei, M., Karakouzian, M., & Karami, M. (2020). Water on Mars—A literature review. Galaxies, 8(2), 40.

[39] Meadows, V. S., & Barnes, R. (2018). Factors Affecting Exoplanet Habitability. Annual Review of Astronomy and Astrophysics, 56, 389–429.

living. However, the majority of these stabilizing elements are absent from Mars, due to its low mass (only a tenth of Earth's).

However, all these parameters are environmental factors and do not make settlement impossible but require advanced mitigation systems such as radiation shielding and pressurized habitats. Indeed, Puumala et al. (2023) refer to them as soft feasibility constraints.
This is the reason why, despite these environmental constraints, Mars remains at the center of ambitious scientific and technological efforts.

This planet offers from its challenges actual opportunities. Indeed, missions such as ExoMars, developed by the European Space Agency and Roscosmos, aim to detect trace gases like methane (CH_4) and formaldehyde, which could indicate past or present biological or geological activity (Petrescu et al., 2018). While, from a technological perspective, the abundance of CO_2 in the atmosphere can serve as a raw material for oxygen and fuel production through in-situ resource utilization (ISRU). Also, understanding water dynamics is essential for the design of closed-loop life-support systems that can recycle and clean water on their own. Even geological diversity can be studied for adaptation strategies; as the surface displays vast volcanoes, impact craters, and ancient riverbeds (Andrade, 2025). Prominent among these topographic structures are the Olympus Mons, the tallest volcano in the Solar System, and Valles Marineris, a canyon system stretching over 4,000 km (NASA, 2025). These formations are not just of scientific interest, but are also strategically important for human settlement in terms of the stability of land, exposure to radiation and resources. Geological and topographic mapping would allow researchers to identify sites for potential settlements and therefore focus on the first stage of extraterrestrial spatial planning.
For instance, the existence of lava tubes[40] - underground tunnels formed by ancient volcanic flows - on the flanks of Olympus Mons, Arsia Mons, and Pavonis Mons are among the most promising natural habitats for future settlers because they offer natural protection from radiation and meteorite impacts as well from huge temperature fluctuations (She et al., 2025). These sites may in fact preserve some local humidity and water ice, which can be used, firstly, as astrobiological targets and secondly, as potential bases for human exploration; with the same potentuality are low-elevation terrains such as Hellas Planitia and Valles Marineris, that gives

[40] She, X., Wang, J., Xu, W., & Xiao, L. (2025). Research on the impact of extraterrestrial lava tube environments on human survival and countermeasures. Space Habitation, 1(1), 100002.

advantages with slightly higher atmospheric pressure and reduced radiation fluxes. (Orosei et al., 2020)

The development of high-resolution maps, made thanks to important missions like Mars Reconnaissance Orbiter (MRO), Mars Express, and ExoMars Trace Gas Orbiter, has allowed the creation of detailed digital elevation models (DEMs) and multispectral maps showing the distribution of key environmental parameters (Andrade, 2025; Orosei et al., 2020). These spatial datasets provide the basis for classifying the Martian surface into distinct zones of relative environmental risk, allowing for an evidence-based evaluation of habitability potential.

In the context of this work, exogeography[41] represents an innovative scientific approach to extend fundamental concepts in geography beyond our own planet earth, and recognize outer space as a developing geographical, political, economic, and cultural environment. This is important because it demonstrates that human activity in outer space is no longer simply a scientific or technological issue; it is a process of territorialization. For example, Earth's orbital zones have developed into full-fledged geographical areas of interaction among states, private interests and military organizations that operate under rules, treaties, and competitive pressures. Low Earth Orbit (LEO), for instance, has been transformed into a dense environment of strategically and economically valuable, as well as symbolically valued, infrastructures that are similar to those on Earth. As such, satellite constellations like GPS, Galileo, Glonass, and Starlink are integral components of the global geographic infrastructure that impact communication, economy, and security. Thus, from a natural standpoint, Earth's geography extends to outer space. Therefore, establishing a "human geography of space" means we need to investigate key issues related to the location, available local resources, and ways to support adaptation and self-sufficiency of future human groups in space. In addition, collecting geographic and climate data on planets and satellites, such as that obtained during Mars missions and/or through the Lunar Reconnaissance Orbiter, is critical to the planning of extraterrestrial territory. Exogeographic maps, therefore, will not only provide descriptions of planetary/satellite environments, they will also be used operationally: to locate bases, manage

[41] Casagrande, G. (2025), "Looking out of the cradle. Possible geographical perspectives on the beginning of human expansion in outer space", in Casagrande, G., D'Ascenzo, A. (a cura), Oltre la Terra verso l'Esogeografia, Società Geografica Italiana, Roma, 71-93

resources, simulate environments and prevent risk. Terrestrial-based missions such as those conducted in Antarctica, deserts, and sub-glacial stations have been previously used as experimental models to understand interactions between environmental, physiological and social factors. Examples of multimodal simulation and testing in isolation environments by NASA represent examples of how exogeography can integrate knowledge of environment, society and technology to prepare for expanding human presence in outer space.

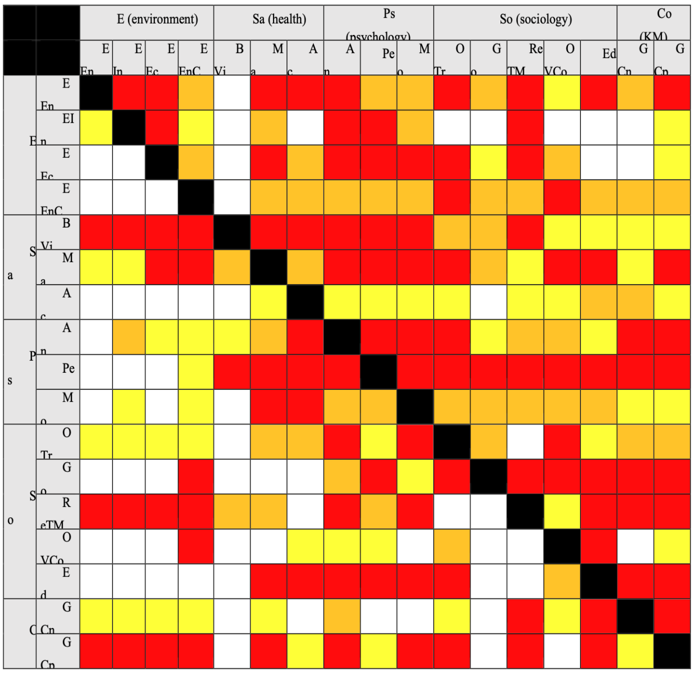
2.2 Critical factors for human survival on Mars

Building on the theoretical model developed by Salotti et al. (2015), this section provides a systemic perspective in which survival on Mars depends not only on the physical and geographical limits of settlement, but also on the ability of humans to adapt, firstly, physiologically, then psychologically, socially, and resourcefully to the new planetary context. According to Salotti et al. (2015) any sustainable Martian settlement will inevitably face a complex multidimensional interplay of constraints: environmental, physiological, psychological, technical, and socio-political variables. These, in turn, must be managed simultaneously through interdependent subsystems.
They focus on identifying the main risks related to human factors, their severity and probability, and the direct and indirect impacts (or influences) they have on other fundamental parameters such as the quantity of resources, quality of life, well-being, the organization of society and the sustainability of development.

Salotti et al's (2015) model, based on a cross-impact analysis of 25 key variables, demonstrated that sustainability depends on a few major drivers: vital needs (BVi) such as food, water, and air, diseases (Ma), encompassing both physical and mental health; Earth–Mars relations (ReTM), and skills management (GCp). These variables, though developed in a systems-engineering context, provide a valuable foundation for understanding the adaptive processes that would enable human permanence on Mars.

Category	Variables group	Variable	Acronym	Typical measurement
First category : Human individuals not fully involved	Environment (E)	Energy	**EEn**	Power supply / power needs
		Industry	**EIn**	Industrial prod. / industrial needs
		Ecosystem	**EEc**	Life support / life requirements
		Built environment	**EEnCa**	Habitability / hab. requirements
Second category : Human individuals fully involved	Health **(Sa)**	Vital needs	**BVi**	Life support needs
		Diseases	**Ma**	% ill persons
		Accidents	**Ac**	% disabled persons
	Psychology **(Ps)**	Anxiety	**An**	% persons needing psyc. support
		Fear	**Pe**	% persons willing to escape
		Motivation	**Mo**	% persons willing to stop work.
	Sociology **(So)**	Organ. of work	**OTr**	Efficiency at work
		Governance	**Go**	% persons not respecting rules
		Earth – Mars rel.	**ReTM**	Agreement difficulties
		Common life organ.	**OVCo**	% persons complaining
		Education	**Ed**	Education and training capab.
	Cognitive sciences **(Co)**	Knowledge man.	**GCn**	KM efficiency
		Skills man.	**GCp**	Skills acquisition / skills requir.

(Fig 4: table of the list of variables. Are represented two categories, variables group, specific variables, their acronym based on French vocabulary and typical measurements. Salotti et al's 2015)



(Fig 5: Table representing the cross-impact matrix of the variables. Blank = no impact on other variables; Yellow = low impact; Orange = medium impact; Red = high impact.; Salotti et al., 2015)

The effects of an unmanaged decline in human skill development (GCp), poor relationships with Earth-Mars (ReTM), failure to meet basic survival needs (BVi) and disease outbreaks (Ma) could rapidly erode health and morale. All these human issues serve as multipliers of system risk by potentially amplifying each other risk to a Martian settlement, e.g., resource depletion and social unrest. The study also outlines additional risk models for a Martian settlement and illustrates its potential fragility. Events such as pandemics, governance failures, or resource scarcity could destabilize the social structure or compromise the life-support system. These "systemic collapse" scenarios reveal that survival on Mars is not solely a technical challenge but a profoundly human and organizational problem, where psychological and social resilience are as crucial as engineering robustness.[42]

The present research therefore follows the assumption[43] made by the reference study to evaluate the principal variables affecting human survival on Mars. In addition, it uses the critical survival factors identified by Salotti et al. (2015) not to modify their framework, but to interpret their human implications through a comparative and adaptive lens. If survival depends on the ability to maintain vital needs (BVi), control disease (Ma), preserve psychological stability (An, Pe, Mo), ensure governance coherence (ReTM), and retain essential skills (GCp), then these domains reveal the fundamental dimensions of human adaptation required for living on Mars.

On this basis, the present study identifies four main dimensions of human adaptation:

(1)Physiological Adaptation,

(2)Psychological Adaptation,

(3)Governance (Social) Adaptation and,

(4) Resource (Cognitive) Management,

---

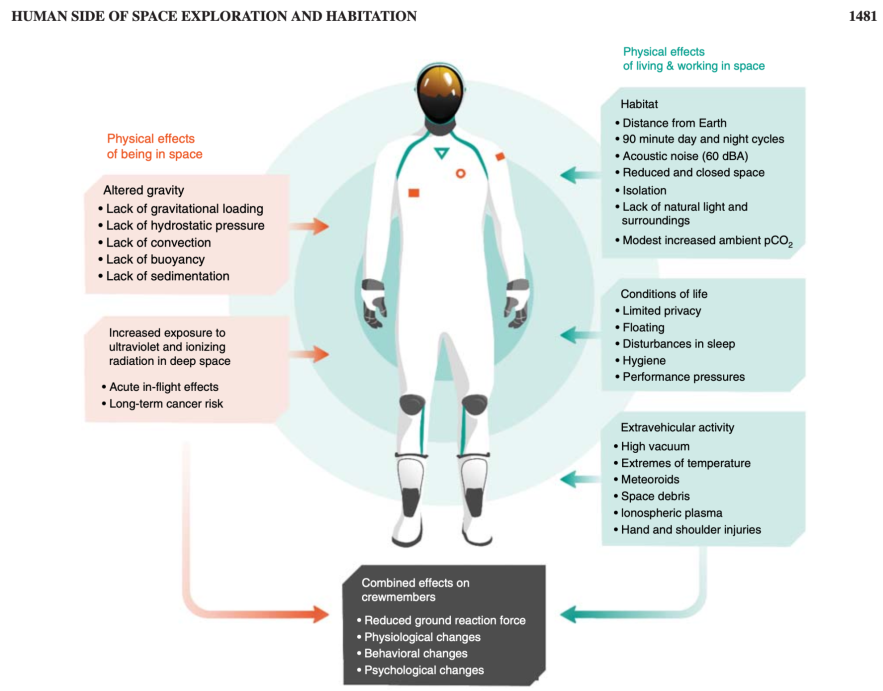
[42] (Szocik, K., Abood, S., & Shelhamer, M. (2018). Psychological and biological challenges of the Mars mission viewed through the construct of the evolution of fundamental human needs. Acta Astronautica, 152, 793-799.)
[43] The research is built on the assumption of:

I. the establishment of an initial settlement composed of several hundred people—an "intermediate-size colony"
II. the existence of an interplanetary transport Earth-Mars, in order to be capable of supporting a self-sustaining social and economic system.
III. imports being limited, without major technological breakthroughs.
IV. an industrial development being essential to exploit local resources and fulfill the basic needs of the colony.

(Salotti et al., 2015, p. 3)

to which a demographic analysis will later be added as a transversal component. These dimensions do not replace the variables mapped by Salotti; rather, they synthesize them into a human-centred framework that highlights the types of adaptation required to mitigate the systemic vulnerabilities described in the reference study.

The success of the mission and the optimal well-being of the crew will depend on the satisfaction of basic human needs, which remain constant regardless of location and time.



(Fig 6: summary of the individual and combined effects of being, living and working in space for LEO and deep space exploration; Duda et al., 2021)

1. Physiological Adaptation:

This dimension derives directly from Salotti's emphasis on vital needs (BVi) and disease (Ma). These risk factors are relevant for physiological adaptation, as it is the biological capacity of the human body to survive and function under Martian conditions. For this reason, it includes environmental parameters and how all the body's basic biological needs must be met to ensure optimal performance and well-being of crew members on a long-duration mission, such as the one to Mars. As well as medical risks and long-term perspectives.

The body's basic biological needs include energy intake, energy conservation and restoration and maintenance and growth. Physiological resilience determines the colony's immediate survivability and influences long-term issues such as reproduction, nutrition, and disease control. The human body is a complex system that reacts immediately to drastic changes, as the environmental parameters that will be faced on Mars and during space travel. Astronauts have minimum, two 6–8-month segments of travel in "deep space" before and after a nominally 18-months stay on the surface of Mars. On the trips to and from Mars, the crew will be exposed to micro-gravity, near-weightless condition, and to radiation levels much more severe than that experienced at the International Space Station (ISS) in low Earth orbit. This results in challenging health and survival issues. First, the low level of gravity does not protect bone density and strength causing bone demineralization, while also the lack of physical mobility might result in muscle atrophy. Then, microgravity causes a headward fluid shift with the body interpreting this as fluid overload and responds by reducing thirst and increasing diuresis, which leads to lower circulating blood volume and cardiac remodelling. Upon returning to a gravitational field, several astronauts have shown signs of orthostatic intolerance; lightheadedness, dizziness, blurred vision, fatigue, rapid heart rate, etc. In flight, it appears that astronauts lose their balance and a reference point for a gravity vector, disrupting the otolith and semicircular canal systems. At the beginning of flight, both space motion sickness (disorientation, nausea) and hand-eye coordination will be significantly impaired. Most of this adaptation will occur after about 2-3 weeks as the crew develops an internal sense of "up" or "down," and there is less conflict between the sensory information they receive from their inner ear and the visual information they see from the exterior environment. However, in deep space, the major concern for the health of the astronaut relates to the risk posed by galactic cosmic rays and solar particle events because astronauts, without the Earth's protective magnetic field, are exposed to: chronic exposure to high energy galactic cosmic rays that can penetrate the outer shell of a spacecraft and the biological cells of the astronauts, resulting in DNA damage, cellular mutation and cancer initiation; acute exposure to solar protons would produce lethal amounts of ionizing radiation to astronauts within hours; radiation at the micro-cellular level can impede the normal functioning of DNA repair enzymes resulting in genomic instability with long lasting consequences, including again increased risk of cancer, decrease in fertility, impact on cognitive functions and accelerated aging. Research indicates, as well, a degree of sex-based sensitivity to radiation induced cancer development, and therefore, sex specific dosimetry and protection levels need to be considered when planning for future missions.

2. Psychological Adaptation:

Psychological adaptation refers to the mental health and motivation of individuals and groups while separated from other humans. The mental component of mission planning will become an increasingly important aspect of future human space travel as human spaceflight extends past low-Earth orbit into deep space missions that are longer than the typical 6 months at the International Space Station (ISS). Deep space missions will require teams that are comprised of people who have different cultural and social backgrounds, and the stress of being away from Earth for extended periods of time cannegatively impact team performance and teamwork. Prolonged stress associated with being away from Earth can cause a decrease in performance, increase in anxiety (An), fear (Pe), and decrease in motivation (Mo). All three were previously identified as the main psychological variables used by Salotti as part of his model of cognitive endurance and emotional stability required for continued mission operation. Of all the risks faced in traveling to Mars, psychological risk may be the most dangerous. A round-trip journey to Mars will take approximately 2-3 years and provide prolonged isolation and confinement, monotonous daily routines, heavy workload and constant risk assessment over a communication delay that could potentially be up to 21 minutes per direction. Crews on this type of mission will not have access to regular supplies, crew rotations and/or continuous real-time contact with family members, and therefore, will be extremely vulnerable to increased levels of anxiety, depression, loneliness, disrupted sleep patterns, and interpersonal conflict.

Humans are highly social organisms; therefore, they need interpersonal interaction to sustain emotional stability, motivation and to accomplish complex cooperative tasks. The ability to maintain healthy interpersonal connections with the rest of the crew on a Mars mission, where communication delays with Earth can be up to 20 minutes per direction, will be a determining factor in the success of the mission. According to Szocik et al., (2018) relationship needs constitute the third tier of the hierarchy of fundamental human needs, with physiological and safety needs constituting the first two tiers. Relationship needs refer to the need for love, trust, communication and reciprocal care, which are severely challenged under the confines of an isolated and confining Mars mission environment.

As a result of the lack of spontaneous social contact, tactile comfort, and direct emotional feedback, astronauts may experience feelings of detachment, loneliness, and social stress, which can negatively affect cognitive function, sleep quality, and immune response.

One notable psychological threat is the possibility of developing a mass psychogenic illness, a form of collective behavioral disturbance caused by no external biological agent. Historical examples of mass psychogenic illnesses include the Salyut 5 incident (1976), in which a Soviet crew reported a persistent acrid smell on board the station, and although non-physical cause was found, the crew was prematurely returned to Earth due to their reports. Social dynamics are also adversely impacted: reduced group cohesion, strained interpersonal relationships, and repetitive interpersonal conflict are among the most documented outcomes. Additionally, sleep disorders are considered one of the largest operational risks according to NASA's Evidence Report on sleep loss, circadian desynchronization and workload.
Common sleep-related complaints experienced by astronauts include insomnia, fatigue, poor quality and fragmented sleep, and alterations in REM sleep patterns. Surveys indicate that more than half of all astronauts' report using sleep medications during their missions.
These incidents demonstrate how emotional and perceptual disturbances can spread throughout small, confined groups under duress and amplify anxiety and hinder collective decision-making.

3. Social and Governance Adaptation:

This category consists of inter-personal, institutional and organizational systems that govern the regulation of cooperation, conflict resolution, the legitimacy of activities, the division of labor, and the relationships between Mars and Earth (ReTM) throughout the early settlement phases. Since, without a functional societal structure, no settlement can sustain itself. Social fragmentation or the failure of governance systems, brought about by psychological strain, can lead to the disintegration of collective systems and is, thus, one of the most critical areas of adaptability.
Diplomacy is becoming increasingly important in space, as the "new space race" opens possibilities, but also risks. On the one side, there is enormous potential in space technologies such as reusable launchers, mega-constellations, off-worldliving spaces, and autonomous robots, to address problems on earth. On the other side, the dual-use character of many space technologies gives rise to fears of military conflicts in space, in particular when, once again, we find ourselves in a world of "great powers" competing with each other.
Thus, diplomacy in space represents a means of regulating risks and exploiting the opportunities offered by space.

Authors Cross and Pekkanen (2023) define space diplomacy as "the processes of dialogue between actors in existing or emerging frameworks, structures, institutions, or venues, with the goal of establishing cooperation or conflict regarding space related topics." Actors in space diplomacy employ a wide variety of formal and informal mechanisms of communication, persuasion, and negotiation to produce desired results. These mechanisms significantly impact how states and other stakeholders negotiate norms, convince others of their perspectives, or reach compromises on contentious issues. As the authors emphasize, however, space diplomacy is not only between governments, but also includes a wide array of non-governmental actors such as private companies, scientists, and astronauts, all of whom significantly contribute to the creation of the international policies governing space.

Over the course of history, numerous communities have developed in entirely new or completely altered environments. These historical examples provide insights on how societies aim to redefine their values, institutional structures, and interpersonal relationships in the context of unfamiliar environments. For example, the colonization of Australia is a known example of the emergence of a new society in response to penal exile. The First Fleet arrived in the vicinity of present-day Sydney in 1788 with severe challenges concerning health and high mortality. In its early stages, the settlement was there was low morale, excessive drinking, and lack of agricultural skills among both convicts and officers. Major reforms did not occur until the governor's administration aiming at reducing alcohol's consumption and promote religious practice, as well as creating sense of community. Over time, immigration from Great Britain increased, the penal system was gradually phased out, and the economy expanded rapidly due to the mid-19th century gold rush and Australia became a thriving and politically stable society. There are also examples of the transformation of national values following the collapse of a society include post-war Germany and Japan, in which demilitarization, democratization, and cultural transformation led to peaceful and politically disciplined societies, which were linked to international oversight, self-discipline, and structural reform.

These precedents do not directly relate to the exceptional circumstances of a remote space colony, characterized by isolation, confinement, and dependency upon life support systems; nonetheless, they illustrate that various societies have employed quite diverse approaches to creating functioning communities in conditions of pressure. Therefore, space colonies could potentially be guided by equally diverse philosophical, moral, or political models.

The above examples pose fundamental questions for mission planners as the selection of participants in the initial settlements, or what kind of cultural basis should a new society be founded on or if a non-militarized society can be prepared on Mars.

In addition to developing a stable society on Mars, the risk of deviant behavior and crime that can arise both during the journey to Mars and in the early phase of colonization needs to be thoroughly analyzed. Preventing crime is part of a larger effort to create a set of shared values, social norms, and systems of collective control inside a community.

There are several reasons why this topic is important. Firstly, all the space missions completed to date have included highly selective crews, typically drawn from military or paramilitary ranks, and highly disciplined and hierarchical organizations. In contrast, the colonization plans of individuals such as Elon Musk, Robert Zubrin, and Robert Wagner call for mass transportation to Mars involving thousands of reusable launch vehicles, hundreds of passengers per trip, and a million colonists in just a few generations. It is unrealistic to expect the same degree of discipline observed among professional crews in the ISS era from such a large and socially heterogeneous population. Secondly, the journey to Mars will be many months long, and will involve forced confinement in cramped living quarters, along with isolation, stress, disrupted sleep patterns, decreased levels of physical activity. All these factors will likely increase interpersonal tensions and aggressive behaviours; prior studies commissioned by NASA, including the Safe Passage report, have identified psychological disorders as one of the primary risks associated with extended duration missions, and the potential consequences of such disorders for the safety of the crew.

Thirdly, there is a legal aspect to consider; if a Martian colony does develop crimes, then it is necessary to develop new criminal statutes, mechanisms of law enforcement, potential sanctions, and competent institutions. Current international space law addresses these issues only minimally.

Finally, as space becomes increasingly important in the lives of people on earth, the ability of states and other actors to engage in effective diplomacy will determine whether space continues to be a cooperative and peaceful domain or if space becomes a source of conflict and competition.

4. Resource and Cognitive Management:

Resource management in space requires the development of sophisticated technology, as well as a fundamentally new cognitive adaptation from the crew members. Because future missions, especially those to Mars, will take place in closed, extremely constrained systems, in which astronauts cannot depend on Earth-based support, the ability to understand, predict, and manage the systems that allow them to survive is necessary for the crew. Resource management is a form of mental discipline: it entails learning to understand and interpret the behavior of life support systems, identifying the earliest warning signs of a malfunction, and making rational decisions in conditions of scarcity and uncertainty.

All environmental elements inside a space habitat must be constantly regulated and of these environmental elements influences the daily cognitive experience of astronauts, who must learn to accept that resources are limited. Astronauts must monitor and balance atmospheric composition; consume water precisely and continually recycle it; provide lighting to support circadian rhythms; limit noise to acceptable levels; prevent contamination of equipment and health by dust and contaminants; and protect themselves from radiation using protective measures and operational awareness.

Resource management is essential for the achievement of autonomy from Earth in the Martian context in which communication delays and requires rapid decision-making.

4. *Demographic Dimension:*

Finally, human adaptation must also be considered in relation to population dynamics. The demographic dimension concerns the long-term viability of a human community on Mars. While short missions can rely on small crews and periodic resupply from Earth, a permanent human presence requires a completely different scale of population, organization, and social stability. A settlement cannot depend indefinitely on cargo deliveries: with current technology, transporting large quantities of resources every year is economically and logistically unsustainable. For this reason, demographic growth becomes a strategic component of the colony's survival. A Mars settlement must reach a minimum population size capable of sustaining essential activities across multiple domains—technical maintenance, food production, habitat construction, healthcare, education, and governance. Below a few dozen people, Earth can still send consumables and specialized equipment; however, as the population grows, the volume of required imports increases proportionally, quickly becoming economically and logistically prohibitive. Sustainable development therefore depends on minimizing external inputs and establishing local production capacities, supported by an adequate number of skilled individuals. From the perspective of population exogeography, demographic growth on Mars is shaped by two processes. The first is migration from Earth, which in the early phases represents the only way to expand the settlement. Space migration differs radically from terrestrial patterns: it is constrained by extreme distances, high travel costs, long transit times, and environmental hazards, meaning that early migrants will be few, highly selected, and likely to remain permanently on Mars. The second process is natural reproduction, which becomes essential once interplanetary transport is no longer sufficient or reliable. Reproduction in low gravity, high radiation, and isolated social conditions introduces biological, ethical, and psychological challenges, but it ultimately represents the only mechanism capable of securing long-term demographic stability. In this sense, a Mars-born generation—not only physically adapted to the environment but also culturally shaped by it—becomes a cornerstone of demographic sustainability. Population geography applied to Mars also raises questions of genetic diversity, life expectancy, and founder effects. Small populations are vulnerable to random demographic shocks, loss of skills, and reduced adaptive capacity. Research suggests that even if the minimum number for survival is around one hundred individuals, this is only a starting point: a thriving, resilient community requires a larger and more diversified population, capable of maintaining multiple industries, distributing labour efficiently, and absorbing unforeseen events such as accidents, illnesses, or social tensions. In this sense, the demographic dimension is not simply a matter of numbers but a process of adaptive social expansion. It involves balancing growth with available resources, ensuring that living conditions remain healthy, and creating the conditions for long-term cultural, economic, and biological continuity.

These adaptation processes are interdependent: physiological stress affects psychology; psychological fragmentation undermines governance; governance failures compromise resource systems; resource scarcity amplifies physiological and psychological vulnerability.

2.3 Comparison of analog models of human adaptation

2.3.1 The role of ground-based analogues and limitations of the ISS

Ground-based analogues have played a significant role since the Apollo era for planning human space flight and planetary exploration. They enable scientists to examine human adaptation to certain environmental stresses, as well as the way humans interact with technology and how they work in terms of operational processes in environments that represent many of the stresses that astronauts will face in their journey to Mars. However, there are many challenges associated with keeping astronauts healthy, safe, and performing at their best as the duration of the missions increases.

While the International Space Station (ISS) has provided valuable insights into the effects of microgravity on the human body, it represents a limited model of deep space travel. Scientists conducting research on the ISS are limited by the number of astronauts on board, the length of time they spend on the station, the cost of operating the ISS, and the lack of control over the type of research conducted on board. In addition, the ISS does not simulate many of the conditions associated with a mission to another planet, such as communications delays, living on a planet with limited resources, working autonomously for extended periods of time, and living on the surface of a planet. Therefore, ISS research tends to underestimate many of the psychological, social, and operational stresses associated with long-duration missions. Thus, ground-based analogues serve as a complement to research being conducted on the ISS.

2.3.2 Why a comparative model must be used

According to Cromwell et al. (2021): "A single perfect ground analog that simulates all the characteristics and effects of spaceflight does not exist". A comparative model is required as each analogue only replicates a subset of the stressors associated with a trip to Mars to identify the common mechanisms of human resiliency and vulnerability that occur across them. This cross-environment synthesis enables the development of a system-wide model of adaptation to Mars, as recommended by Hoying et al. (2021) that analogues should be utilized as components of a broader optimization framework that links stressors, behavioral responses and operational performance.

Therefore, comparative approaches serve two primary scientific purposes:

- Decomposition: breaking down the Martian environment into separate, researchable components.
- Integration: developing a comprehensive model of human adaptation by combining data from various analogue platforms.

These principles together create a methodological link between laboratory-based experimentation and the actual conditions that astronauts will experience on a long-duration mission to Mars.

2.3.3 Defining "Terrestrial Analogue"

Terrestrial analogue can be defined as a natural or man-made environment on Earth that produces, under controlled or partially controlled conditions, one or more of the same stressors, constraints or operational characteristics that are found in human spaceflight and planetary exploration. The defining criteria for analogues are based on functional similarity rather than geographic similarity to Mars. An analogue must produce one or more of the mechanisms or conditions that most significantly impact the health, performance, and operational efficiency of humans in long-duration missions (ESA Behavioural Health Review, 2019).

Their utility is derived from the fact that analogues can induce stressors that could not be implemented safely or economically in spaceflight applications, and that analogues allow for larger sample sizes, longer observational periods and more extensive methodologies (Cromwell et al., 2021).

Also, it is worth noting that these are fundamentally distinct from mission simulations, even though the two types may overlap in application; analogue environments are determined by their internal characteristics: isolation at polar stations, hypoxia at high altitudes, confinement in underwater habitats, alterations in human physiology due to bed rest, and hostile environmental conditions in volcanic and desert regions. These characteristics are present regardless of the imposed mission scenario and provide researchers with naturally occurring stressors like those encountered in Mars. While, mission simulations, are scenario driven and scripturally defined. They recreate the operational structure of a mission including communication delay, resource allocation, psychological burden, hierarchical structures within a crew, and emergency response plans. Examples of mission simulation include Mars500, CHAPEA, HERA, and other controlled habitat studies in which the "Mars-ness" of the environment is defined by the design of the protocols, not the physical attributes of the environment (Mars500 Overview, 2011; ESA Behavioural Health Review, 2019).

Although NASA is a major player in analog research, analog research is inherently international and interdisciplinary in nature. Many analogue programs are operated by ESA, Roscosmos/IBMP, DLR, JAXA, CNES and a multitude of independent research organizations. The variety of analogue programs demonstrates that analogues are a methodology category and not an institution category: an analogue's definition is not based upon the agency that develops it, but the relevance of the stressors that it recreates.

2.3.4 The comparative approach

The comparative approach is built around the principle that no single terrestrial analogue can accurately represent the entire complexity of the Martian environment.

An initial step in developing this systematic comparison involves determining the stressor cluster each analogue environment represents and evaluating the relevance of each cluster to the anticipated Martian conditions. Using NASA's hazard classification system for crew health and performance, stressors generally fall into the following clusters:

- Isolation and Confinement
- Partial Gravity or Reduced Mechanical Loading
- Environmental Extremes
- Limited Autonomy and Communication Delays
- Resource Scarcity and Habitat Constraints

Once the clusters have been identified, the comparative method does not seek to find perfect matches between analogues and Mars but seeks to discover recurring patterns of human adaptation across analogue environments that model different aspects of the mission profile. This enables researchers to identify cross-cutting physiological, psychological and/or operational-resource sustainability mechanisms that appear to recur despite differences in local conditions (Cromwell et al., 2021; ESA Antarctic Review).

However, while terrestrial analogues provide a strong empirical tool for studying physiological, psychological, social and environmental adaptation, not all aspects of human adaptation to Mars can be studied through analogue-based experimentation. Specifically, governance adaptation exists at a different analytical level and cannot be realistically replicated through analogue environments that attempt to physically or environmentally simulate the conditions associated with governance. Therefore, governance was investigated in this study through a comparative analysis of terrestrial treaties, institutional frameworks, and public-private governance models that were developed for other extreme and remote domains and not through analogue environments.

The integration of each terrestrial analog requires a qualitative and integrative methodology to assess patterns of adaptation that are common across the analogs, and to analyze the mechanisms of human resilience and vulnerability to those stressors.

Application of the comparative framework to analog selection:

Stressor	High-Fidelity Analogs	Mid-Fidelity Analogs	Adaptation Evidence
Reduced gravity	AGBRESA, :envihab	Mars500	Muscle/bone loss; HRV adaptation
Isolation & confinement	Mars500, Concordia	Antarctica missions	Mood, stress, autonomy, cohesion, sleep
Environmental extremes	Concordia, Antarctica	:envihab	Hypoxia effects; immune changes; circadian disruption
Autonomy & delayed comms	Mars500	CHAPEA	Decision-making, operational independence
Habitat constraints	CHAPEA, :envihab, ISRU	Mars500	Architecture-performance link; resource stress
Surface operations	Antarctica, CHAPEA, ISRU	Mars500 EVA	Task performance under extreme conditions

(Table 1: Summary of key Mars mission stressors, corresponding analog environments, and documented human adaptation outcomes, distinguishing between high- and mid-fidelity analogs.)

Each terrestrial analog can be seen as modeling a unique subset of the overall stressors associated with a Mars Mission; therefore, the comparative approach will integrate the use of multiple platforms, each providing a unique part of the total human adaptation picture.

2.3.5 Physiological response to the space environment

The purpose of physiological terrestrial analogs is to simulate certain physiological responses that occur in humans when exposed to the space environment through certain specific responses, as opposed to the complete mission profile. Two of the most well studied terrestrial analogs are head down bed rest (HDBR) and dry immersion (DI). Both HDBR and DI are designed to simulate the lack of mechanical load associated with microgravity and induce physiological adaptations like those observed in space flight.[44]

The AGBRESA (Artificial Gravity Bed Rest with European Space Agency):

There is a significant amount of literature supporting the use of bed rest as a reliable method for studying the effects of prolonged microgravity exposure on the human body. In addition, due to its extensive use by multiple space agencies around the world, a high degree of methodological standardization has occurred in bed rest studies at the international level. Several common procedures have been established regarding the selection of subjects, the environmental conditions of the bed rest facility, the diet, clinical monitoring, and the collection and processing of blood and urine specimens. Also, several common physiological measurements are taken in all bed rest studies, many of which are the same measurements used to assess the health of astronauts prior to launch, during space flight, and after landing.

Testing/Measures	Pre Phase Testing													
Standard Measures	BR-14	BR-13	BR-12	BR-11	BR-10	BR-9	BR-8	BR-7	BR-6	BR-5	BR-4	BR-3	BR-2	BR-1
Nutrition/Hematology/Immunology					15									15
Exercise testing								30						
Sensorimotor testing						90								
Cardiovascular testing					60									
Bone Density scan					60									
Psychology testing			30						30					
Reconditioning														
Investigator Measures														
Questionnaires	5	5	5	5	5	5		5	5	5	5	5	5	
Metabolic Rate					30									
Strength Testing					60									
Aerobic Capacity testing											60			
Anaerobic Power testing								45						
Exercise Training														
Resistance Training	90		90		90			90		90		90		
Aerobic Interval Training		90	30	90	30				90	30	90	30		
Aerobic Continuous Training	30	20		20				30	20		20			
Testing Time (hrs)	2.1	1.9	2.6	1.9	5.8	1.6	0.0	3.3	2.4	2.1	2.9	2.1	0.1	0.3

Testing/Measures	BR - Week 1							BR - Week 2							BR - Week 3							BR - Week 4								
Standard Measures	BR 1	BR 2	BR 3	BR 4	BR 5	BR 6	BR 7	BR 8	BR 9	BR 10	BR 11	BR 12	BR 13	BR 14	BR 15	BR 16	BR 17	BR 18	BR 19	BR 20	BR 21	BR 22	BR 23	BR 24	BR 25	BR 26	BR 27	BR 28	BR 29	BR 30
Nutrition/Hematology/Immunology							15														15									
Exercise testing																														
Sensorimotor testing																														
Cardiovascular testing																														
Bone Density scan																														
Psychology testing			30							30							30							30						
Reconditioning																														
Investigator Measures																														
Questionnaires	5	5	5	5	5	5		5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Metabolic Rate	30							30						30								30						30		
Strength Testing							30														30									
Aerobic Capacity testing									60														60							
Anaerobic Power testing								45														45								
Exercise Training																														
Resistance Training	40		35		40			40		40		35			40		35		40			40		40		35			40	
Aerobic Interval Training		32		15		35			32		15		35			32		15		35			32		15		35			32
Aerobic Continuous Training	30		30		30			30		30		30			30		30		30			30		30		30			30	
Testing Time (hrs)	1.8	0.6	1.7	0.3	1.3	0.7	0.8	2.5	1.6	1.8	0.3	1.2	0.7	0.6	1.3	0.6	1.7	0.3	1.3	0.7	0.8	2.5	1.6	1.8	0.3	1.2	0.7	0.6	1.3	0.6

Testing/Measures	Post Phase Testing								Total Time (hrs)
Standard Measures	BR+0	BR+1	BR+2	BR+3	BR+4	BR+5	BR+6	BR+7	
Nutrition/Hematology/Immunology	15								1.3
Exercise testing	30								1.0
Sensorimotor testing	90								3.0
Cardiovascular testing		60							2.0
Bone Density scan			60						2.0
Psychology testing					30				3.5
Reconditioning				60	60	60	60		4.0
Investigator Measures									
Questionnaires	5		5		5		5		3.8
Metabolic Rate		30							3.5
Strength Testing		60				60			4.0
Aerobic Capacity testing	60				60				5.0
Anaerobic Power testing	45			45					3.8
Exercise Training									
Resistance Training									17.3
Aerobic Interval Training									14.0
Aerobic Continuous Training									8.8
Testing Time (hrs)	4.1	2.5	1.1	1.8	2.6	2.0	1.1	0.0	76.9

Standard Conditions	Standard Measures
• Bed Rest Duration: 60-days long duration; 30-days short duration	• Sensorimotor: Posture Assessment; Treadmill Locomotion
• 6° Head-down Tilt	• Cardiovascular: Tilt Test; Aerobic Capacity
• Study Integration	• Exercise/Muscle: Isokinetic Testing; Vertical Jump
• Standardized Diet	• Nutrition Assessment
• Subject Selection Criteria	• Hematology Tests
• Biological Sample Handling Guidelines	• Immunology Tests
• Data Management Guidelines	• Psychology: Positive & Negative Affect Scale; General Health Questionnaire

(Fig. 7: An example of an integrated testing schedule following the international bed rest guidelines developed by the International Academy of Astronautics study group. Cromwell et al. 2021)

The: envihab bed rest[45] environment provides an excellent example of a large-scale bed rest environment that provides both an isolated bed rest unit and the ability to precisely regulate several environmental factors such as temperature, humidity, barometric pressure, oxygen

[44] Cromwell, R. L., Huff, J. L., Simonsen, L. C., & Patel, Z. S. (2021). Earth-based research analogs to investigate space-based health risks. New Space, 9(4), 204-216.
[45] von der Wiesche, M., Stern, C., Nitsche, A., Trammer, M., Mulder, E., & Jordan, J. (2018). The: envihab-Linking biomedical research and technological innovation for Astronaut health.

levels, and CO2 levels. These environmental control features are useful in simulating space flight related environmental extremes in addition to simulating the lack of mechanical load associated with bed rest. The facility includes additional research tools beyond bed rest capability, including controlled atmospheric chambers, medical imaging equipment and a short arm centrifuge for simulating artificial gravity. The modularity of this facility enables investigators to study a variety of physiological adaptations countermeasures.

The AGBRESA study[46] was a randomized controlled bed rest study (RCT) whose purpose was to analyze how humans physiologically and psychologically de-condition under prolonged microgravity-analogue conditions, as well as to evaluate Artificial Gravity (AG) as a potential countermeasure. It was conducted as two independent experimental campaigns, each lasting 60 days of 6° head down tilt (HDT) bed rest at the: envihab research facility in Cologne, Germany. It had two objectives: first was to determine the multi-system human adaptation and de-conditioning caused by prolonged simulated microgravity and second was to investigate if daily artificial gravity, generated by short-radius centrifugation, could inhibit the effects of de-conditioning in various physiological and psychological domains.
It was conducted was by NASA, ESA, and DLR to harmonize methodologies for simulating space-flight analogs so that the data collected in the analog environment could be compared directly with space-flight data. There were 24 healthy adult participants (eighteen males and six females) with an average age of about 33 years. Each participant was screened for medical conditions and deemed suitable for participation in long-duration bed rest studies according to internationally accepted research and ethical standards. Participants were randomly assigned to one of three experimental groups, each consisting of 8 participants: 1) a control group of participants who were exposed to 60 days of strict head-own tilt bed (HDT) bed rest without any counter-measures; 2) a continuous artificial gravity group (cAG) who received one continuous thirty minute AG session per day; 3) and an intermittent artificial gravity group (iAG) who received 6, 5 minute AG sessions per day, separated by short periods of rest. This grouping permitted a controlled comparison of artificial gravity exposure and no countermeasure, as well as comparisons between the differing temporal structures of AG exposure, to address the hypothesis that the frequency of gravitational transitions affects adaptive and regulatory responses. Artificial Gravity was provided using a supine short-radius

[46] Clément, G. R., Crucian, B. E., Downs, M., Krieger, S., Laurie, S. S., Lee, S. M., ... & Zwart, S. R. (2022). International standard measures during the AGBRESA bed rest study. Acta Astronautica, 200, 163-175.

centrifugation configuration, which is compatible with space flight constraints and has been used in previous space-flight analog research studies. The centrifugation protocol was designed to create a gravity gradient along the length of the participants' bodies to produce approximately about Earth-like gravity (1Gz) at the middle of the body, weaker gravity (0.3 Gz) at head level, and stronger gravity (2Gz) at foot level. They were subjected to centrifugation once per day during the entire 60-day HDT period. Prior to and immediately following each centrifugation session, the participants remained in the supine position to maintain the bed-rest condition. However, the direction of rotation of the centrifuge changed daily to avoid vestibular adaptation effects and to limit motion sickness. So, the total daily AG exposure time was the same for both cAG and iAG groups (30 minutes per day) to allow the study to determine the impact of the structure of exposure rather than the total amount of gravitational exposure. It was employed the International Standard Measures (ISM) framework established by the International Academy of Astronautics, in cooperation with space agencies around the world, to enhance methodological consistency and the ability to compare results with other studies. The ISM framework consists of a standardized set of measurements that will facilitate systematic comparison among studies of bed rest, dry immersion, isolation, and space flight. Utilizing the ISM framework, the AGBRESA study implemented a multi-domain measurement strategy that assessed the musculoskeletal, cardiovascular, sensorimotor, immune, metabolic, psychological, and ocular domains. The same measurement protocols, timelines, and assumptions were used across all measurements to increase the external validity of the measurements and to permit direct comparisons with other analog environments and space-flight datasets.

The study had three distinct phases. Baseline data collection (BDC) was the first phase and included an ambulatory pre-HDT phase where all the baseline physiological and psychological measurements were made. This was followed by the 60-day phase, except during centrifugation sessions for the AG groups and the last phase was the post-HDT recovery phase (R+), which measured the immediate and short-term recovery.

Physiological effects of prolonged HDT in the control condition:

Participants in the control group, who were exposed to 60 days of strict HDT bed rest without any countermeasures, exhibited a consistent pattern of de-conditioning across multiple physiological systems:

- At the musculoskeletal level it resulted in with significant loss of bone mineral density, reduction in muscle strength in the knee and ankle muscles. Overall, it exhibited a substantial loss of structural and functional capacity with serious consequences for post-mission mobility, injury risk, and rehabilitation needs.
- The cardiovascular de-conditioning, from an operational standpoint, would limit participants' capabilities in surface operations, extravehicular activities, and emergency response actions during spaceflight or planetary exploration missions.
- Orthostatic intolerance was another significant result with inability to remain in an upright position for the full duration of the test.
- Sensorimotor assessments indicated significant impairments in postural stability and balance control having significant implications for locomotion, surface navigation, and manual task execution in reduced-gravity environments.
- Ocular assessments demonstrated structural changes like the ocular changes found in other microgravity-analog studies. While there were no reports of acute vision loss, the structural changes have relevance to spaceflight-associated neuro-ocular syndrome (SANS).

However, the daily exposure to artificial gravity produced domain-specific mitigation effects of de-conditioning. The greatest and most consistent benefits of artificial gravity exposure occurred in bone health. Both the continuous and intermittent artificial gravity protocols significantly attenuated bone mineral density loss.

Artificial gravity exposure also appeared to attenuate the decline in aerobic performance even if the effects were small and did not completely restore pre-HDT cardio-respiratory performance. Therefore, passive centrifugation alone appears to be a limited cardiovascular stimulus in comparison to active exercise-based countermeasures.

Additionally, artificial gravity appeared to buffer against de-conditioning in several biochemical and immunological domains. However, artificial gravity did not appear to protect against muscle strength loss in the major muscle groups, specifically the knee and ankle muscles. Furthermore, artificial gravity did not seem to completely prevent the development of orthostatic intolerance, while sensorimotor and balance impairments were seen in both AG and control groups. Finally, structural changes in the eyes, specifically increases in retinal thickness, were seen in both AG and control groups.

The results highlight the necessity for longer or more frequent AG exposure, higher head-level G-loads, and inclusion of active exercise during centrifugation to maximize the efficacy of AG.

While head-down tilt bed rest cannot reproduce all the risks associated with interplanetary travel (e.g., space radiation), it is currently the most reliable terrestrial model to reproduce many of the physiological effects of long-duration microgravity.

The Mars500 project:

Mars500[47] was a 20-month confined habitat experiment of a 520-day mission to Mars. It represented a full mission simulation of a trip to Mars, including the outbound journey to Mars, time spent in Martian orbit, a simulated Martian Surface Phase, and the return journey back to Earth.

The Mars500 experiment was performed in a specially constructed and equipped laboratory at the Institute of Biomedical Problems (IBMP) of the Russian Academy of Sciences in Moscow. The laboratory was a sealed and self-sustaining habitat. It simulated the environment found in a real interplanetary spacecraft with respect to the operational, environmental and logistical conditions experienced during a Mars mission.

Methodologically, Mars500 can be considered as a high-fidelity analog of a Mars mission for studying the physiological and psychological effects of prolonged confinement and isolation, and the impact of prolonged stress on physiological functions. The habitat was designed to simulate the conditions of an interplanetary spacecraft, so that the effects of prolonged confinement and isolation could be studied independently of the effects of microgravity.

The primary focus of the Mars500 study was not to study the effects of microgravity on the physiological and behavioral functions of humans. Rather, it focused on the effects of prolonged isolation and confinement on the physiological and behavioral functions of humans, and how they adapt and decondition physiologically and behaviorally over time, as would occur on a long-duration mission to Mars.

Six adult males were recruited from three countries (Russia, Europe and China) to participate in the Mars500 study. They were representative of the diverse populations expected to be involved in future interplanetary missions. Each participant underwent a comprehensive assessment of their medical history, physiological health and psychological state before the isolation phase began, to establish that they were fit and suitable for the prolonged confinement required for the study.

[47] Ushakov, I. B., Vladimirovich, M. B., Bubeev, Y. A. E., Gushin, V. I., Vasil'eva, G. Y. E., Vinokhodova, A. G. E., & Shved, D. M. (2014). Main findings of psychophysiological studies in the Mars 500 experiment. *Herald of the Russian Academy of Sciences*, *84*(2), 106-114.

Because of the logistics, operational and ethical constraints of conducting an experiment lasting 520 days, it was not possible to include a control group outside the sealed habitat. Therefore, the study used a within subject longitudinal design, where each participant acted as their own control. Several physiological assessments were made of the participants before the confinement phase, and again after various intervals throughout the 520 days of confinement. During the confinement phase, the participants lived under normal gravity in the sealed habitat. The habitat was maintained at a constant temperature and humidity, and had limited lighting and restricted living area, similar to that of a spacecraft. The participants were fed a standardized diet and worked a standard schedule to maintain consistency with typical spacecraft missions. The access to information about events outside the habitat was limited and delayed, like what may happen during an interplanetary mission.

The 520-day confinement period was divided into several distinct phases of simulated operation. For example, the participants were subjected to simulated Mars orbit insertion, crew separation, and simulated Mars surface activities, each of which increased the participants' operational workload and psychological burden. The phases of operation enabled investigators to study the participants' physiological responses to prolonged confinement, as well as to specific stresses imposed by the operational phases of a mission.

Measurements of physiological variables were made at regular intervals (typically 35 to 70 days apart) throughout the 520-day confinement period. The use of this longitudinal measurement strategy enabled investigators to identify progressive, nonlinear, and phase-dependent changes in physiological variables over the course of the confinement period. Unlike other studies of bed rest or artificial gravity, the Mars500 study did not include artificial gravity as a countermeasure. Rather, the study focused on exercise-based countermeasures as the primary way to mitigate physiological deconditioning during the long-term confinement of a Mars mission.

The countermeasure framework consisted of a variety of exercise modes, including treadmill running (both motorized and non-motorized), cycle ergometry, elastic band-based resistance exercises, whole-body vibration, and resistance exercises. The countermeasure framework also included periods of no structured exercise, which provided an internal reference point for evaluating the effectiveness of the different exercise countermeasures.

Physiological effects of long-term confinement:

The most consistent finding related to the progressive decreases in the participants’ lower limb muscle strength. The degree of strength loss experienced by some participants was comparable to that previously reported in bed rest studies and, in functional terms, equivalent to several decades of terrestrial aging. These findings demonstrate that reduced daily physical activity and confinement are sufficient to cause meaningful deconditioning of the musculoskeletal system and led to a reduction in the participants’ overall functional performance, which affected their ability to produce and maintain forces during mission-relevant tasks, such as prolonged surface excursions, manual handling of equipment, and emergency responses under time constraints. Furthermore, performance degradation occurred progressively rather than acutely, indicating the cumulative nature of confinement-induced deconditioning over long-duration missions.

While Mars500 did not replicate the microgravity-induced unloading of the cardiovascular system, the study did reveal directional effects of reduced cardiovascular and aerobic regulatory functions over time. The participants displayed signs of reduced aerobic efficiency, possibly due reduced spontaneous movements and confinement-related lifestyle constraints. Although the magnitude of cardiovascular deconditioning was less severe than that previously observed in bed rest and spaceflight studies, the present findings suggest that gravity alone is insufficient to protect against the effects of prolonged confinement and chronic stress on cardiovascular function.

In addition, there were changes in body composition and metabolic regulation characterized by small losses in total body mass, but larger changes in muscle mass and quality, and changes in metabolic efficiency. These findings suggested that the participants adapted to the reduced physical demands of confinement, and that the changes in body composition and metabolic regulation were influenced by the participants’ exercise compliance and motivation. Prolonged confinement resulted in chronic changes in neuroendocrine and stress-related functions, indicative of the chronic psychological and operational demands of the simulated mission. Prolonged confinement also resulted in progressive disruptions to the participants’ sleep-wake cycles and circadian regulation. Despite the structured schedules and attempts to impose a strict artificial light-dark cycle, the participants showed increasing variability in their sleep timing and duration, particularly in the latter stages of the mission.

Modest, yet statistically significant changes in immune-related variables were detected over the course of the confinement period.

The exercise countermeasures implemented were partially effective in preventing the physiological decline that occurred during the confinement period.
All the participants who were assigned to a period of no structured exercise, experienced a more rapid rate of decline in physiological function than those who continued to engage in structured exercise. These findings clearly show that physical activity plays a crucial role in maintaining physiological function during periods of prolonged confinement.
However, even when the participants engaged in optimized structured exercise programs, the effects of prolonged confinement, lack of physical activity and chronic stress were still evident. Overall, the findings from the Mars500 study support the notion that confinement and operational context are independent factors contributing to physiological changes, separate from the effects of microgravity.

2.3.6 Psychological and behavioural adaptation

Mars500:

Unlike physiological analogues, isolation and confinement analogues are specifically designed to investigate behavioural health and performance at both the individual and team level. Although the MARS500 mission has been examined from several different perspective, there is also a psychological one. Therefore, the psychological framework used in the MARS500 mission studied functional adaptation, resilience and personal growth, and therefore integrated subjectively reported self-assessment tools and objectively measured psychophysiological indicators. Longitudinal within-subject designs were employed to investigate the psychological adaptations to the confinement, with each crew member providing their own reference point.
Therefore, for the collection of psychological data was utilized a multiple methods assessment strategy, incorporating standardized psychometric questionnaires along with psychophysiological testing.
A distinguishing feature of the psychological protocol of the MARS500 project was the incorporation of psychophysiological indicators (i.e., autonomic responses during controlled stress tasks) to complement the subjective reporting. Therefore, researchers were able to:

- Detect inconsistencies between perceived and actual stress regulation.
- Measure adaptive efficiency (high performance with minimal physiological cost).

- Evaluate voluntary emotional control as an indicator of resilience.

The project demonstrated measurable but non-clinical changes in mood and affective regulation over the duration of the prolonged confinement. Crew members experienced a reduction in positive affect and a degree of emotional flattening during the mid-mission phases of the project when the crew experienced monotony and little external stimulation. Crew members' emotional responses to external stimuli were found to be decreasing in intensity and increasing in uniformity during the duration of the mission, indicating a form of emotional adaptation and not deterioration. These results are consistent with habituation to sensory deprivation and prolonged environmental predictability and did not progress to depression, affective instability or other forms of clinically significant psychopathology. During the entire period of confinement, crew members demonstrated stable or enhanced stress resistance, as measured through both psychological and psychophysiological indicators. These findings provide support to the conclusion that MARS500 represents a model of successful long-term psychological adaptation, rather than a model of gradual psychological disintegration. One of the primary psychological shifts observed during and after the mission was the increase in the internal locus of control[48] in most of the crew members, indicating an increased perception that the outcome of events was caused by the actions of the person, rather than by chance or by external forces. This is important to the context of deep space exploration, where the crew will be required to make decisions and act with a high level of autonomy and with potential delayed external support. Positive stress-related personal growth was reported by crew members following the completion of the mission. The growth was greatest in areas related to social awareness and interpersonal understanding, emotional maturity and self-reflection, and perspective taking. From the behavioral level, the mission was associated with changes in the quality of sleep and circadian rhythms. However, these changes were considered adaptive, and there was no indication of chronic insomnia or other clinically significant sleep disorders. There were also no evidence of major psychiatric disorders, severe anxiety states or cognitive collapse of the crew members, since the psychological stress experienced was always within manageable limits. The absence of severe psychiatric disorders supports the conclusion that long-duration confinement is psychologically taxing, but that it is manageable if the crew

[48] Solcova, I., & Vinokhodova, A. G. (2015). Locus of control, stress resistance, and personal growth of participants in the Mars-500 experiment. Human physiology, 41(7), 761-766.

is properly selected, trained and supported with structured routines and meaningful task engagement.

Human exposure to Isolated, Confined and Extreme (ICE) environments:

The prolonged human exposure to ICE environments is still relatively rare, however systematic research into ICE has been ongoing for over 60 years. It was the emergence of human spaceflight beginning in the 1950s and 1960s, the establishment of permanent research stations in Antarctica, and the development of undersea habitats that initiated a long-standing scientific interest in how people function and maintain their health in prolonged isolation and extreme environments. Subsequently, a large volume of research has resulted from numerous experimental and operational platforms.

Research stations in Antarctica are one of the best-known ICE analogs for studying the psychological adaptations that will be required to sustain long-duration space missions. They are unique because they represent not just physical isolation, but a combination of environmental hostility, operational irreversibility, and prolonged social confinement, all of which are likely to contribute to the psychological stressors that are expected to occur during deep-space exploration.[49]

"Antarctica—the harshest, most inaccessible, and least populated region of the Earth. In Antarctica, as in space, there is a complex interaction of the human–environment– technology system." (Demidov, N. E., & Lukin, V. V. 2017.)

Therefore, it shares many of the same interactions between the human, environmental and technological systems as space missions. The environmental hostility and remoteness of Antarctica, along with its extremes of temperature, make it similar to space in terms of perceived lethality and hostility. Additionally, the extreme photoperiods present in Antarctica, which consist of either prolonged periods of darkness during the winter months or continuous daylight during the summer months, will disrupt normal circadian rhythms.

Once the research team arrives at a research station and the winter begins, there are few options for evacuation or resupply until the end of the winter season, which creates an atmosphere of enforced autonomy and prolonged separation from any external support. Therefore, research

[49]Demidov, N. E., & Lukin, V. V. (2017). Antarctica as a testing ground for manned missions to the Moon and Mars. *Solar System Research*, *51*(2), 104-120.

stations in Antarctica provide a very realistic setting for researchers to study how individuals and teams adapt to the psychological stresses associated with prolonged isolation when there is no opportunity to escape.

The psychological stressors associated with life in Antarctica arise from chronic exposure to environmental monotony, sensory deprivation, and social restrictions. Individuals live in small, stable groups with limited opportunities for novelty or privacy and thus the demand placed on the ability to regulate emotions and manage interpersonal relationships is continuous. However, research demonstrates that the psychological effects of living in Antarctica are typically adaptive and not pathological. Moreover, environmental extremeness exacerbates these challenges; extreme cold, prolonged periods of darkness, and the ever-present threat of environmental disasters increase the stress placed on the individual and compound the sense of isolation and vulnerability.

Within the larger context of Antarctic research, Concordia Station has served as a site for a near two decade-long series of biomedical research studies supported by the European Space Agency (ESA). As a high-fidelity analog for long-duration space missions, Concordia Station has provided a location for researchers to study how humans adapt to prolonged exposure to ICE conditions. Located at Dome C on the eastern part of the Antarctic Plateau, commonly referred to as "White Mars,"[50] Concordia Station is situated at an elevation of approximately 3200 meters above sea level. The lower atmospheric pressure at this elevation results in chronic hypobaric hypoxic exposure for individuals residing at the station, which adds another physiological and psychological stressor.

Concordia Station has been continuously occupied since 2004 and usually hosts winter-over crews consisting of 10-16 individuals who are divided between technical personnel necessary for the continued operation of the station and scientists conducting research at the station.

Concordia Station is one of the most hostile environments in which humans reside. Because the station is completely cut off during the Antarctic winter, there is no possible way to evacuate or resupply the station for several months. Temperatures at the station are often below -50°C and sometimes reach as low as -80°C. The overall goal of the biomedical research program conducted at Concordia Station is to understand how prolonged exposure to ICE environments influences human adaptation and to apply the knowledge gained to future lunar

[50] Van Ombergen, A., Rossiter, A., & Ngo-Anh, T. J. (2021). 'White Mars'–nearly two decades of biomedical research at the Antarctic Concordia station. *Experimental physiology*, *106*(1), 6-17.

and Mars missions. The studies[51] reviewed here were selected from projects by the European Space Agency (ESA) at Concordia Station between 2003 and 2013; out of the 36 ESA-funded biomedical studies that were identified, 18 scientific publications were included in the review. These studies covered five main categories of research: psychology, neuroscience, sleep physiology, cardiovascular physiology, and the immune system. Each study was selected in a consistent and reliable way; ESA included a trained medical doctor in each winter crew that coordinated the experiments, supervised measurements, and made sure the same procedures were followed across different studies and seasons.

The studies involved a small number of individuals, typically 12-16 individuals, which reflects the maximum size of the permanent crew at Concordia. Most of the studies utilized a longitudinal design that extended throughout the entire winter-over period of 12-13 months, with data being collected before deployment, during different phases of the mission (early, middle, and late winter), and sometimes after the mission ended. The authors acknowledge that due to the operational and logistical constraints imposed by the environment, there were inherent structural limitations to the studies, including limited group sizes, mostly male participants, limited time for testing, and reduced flexibility in how experiments could be carried out.

Each study demonstrated changes in sleep duration, timing, fragmentation, and circadian alignment, especially during the polar night. Blue-enriched artificial light interventions successfully improved circadian entrainment, alertness, and overall well-being and suggested that lighting design would be an important operational countermeasure for mitigating circadian disruptions during long-duration space missions.

Cardiovascular studies assessed that low oxygen by itself, if people remain physically active, does not increase the risk of dangerous blood clots. This is an important result for the design of spacecraft and living spaces with reduced air pressure.

In total, the reviewed studies clearly demonstrated that human adaptation to ICE environments is robust but not neutral. Long-term exposure to ICE environments produces measurable psychological, sleep-related, immune, and physiological changes that are generally subclinical but operationally significant. Social stress appears to accumulate progressively during winter-over missions, whereas cohesive group cultures and mature coping mechanisms facilitate better adaptation. A midwinter "psychological hibernation" phenomenon, characterized by emotional

[51] Van Ombergen, A., Rossiter, A., & Ngo-Anh, T. J. (2021). ‘White Mars’–nearly two decades of biomedical research at the Antarctic Concordia station. Experimental physiology, 106(1), 6-17.

flattening and social withdrawal, emerges as a common and adaptive response rather than a pathological state. Cognitive performance remains generally intact, though complex, high-skill tasks appear vulnerable to training decay. At the end, sleep and circadian disruption appear to be among the most affected areas, but, together, these findings suggest that human adaptation in ICE environments is resilient yet susceptible to cumulative stressors.

2.3.7 Operational adaptation and resource sustainability

CHAPEA and Mars Dune Alpha as operational analogues:

Mars represents a challenging environment also in the context of accumulation of many minor operational inefficiencies, errors, or behavioral maladaptation's that can become overwhelming during a prolonged mission. Since future expeditions will need to operate autonomously for long durations with little-to-no direct support from Earth and Mars crews will have to make local decisions concerning maintenance, scheduling, medical care, and resource allocation under conditions of uncertainty and delayed communication with Earth. Therefore, human performance on Mars cannot be measured using traditional physiological or psychological models but instead must be viewed as an emergent property of interactions among humans, technology, architecture, and operational systems.

The Crew Health and Performance Exploration Analog (CHAPEA) program[52] was specifically designed to explore this aspect of human adaptation. It is designed to simulate the operational realities of long-duration surface missions to Mars via high-fidelity analog environments that combine physical confinement, isolation, workload, and mission complexity.
Each mission involves four crew members who reside in a purpose-designed habitat, Mars Dune Alpha[53], at NASA's Johnson Space Center for extended periods of time. This habitat is designed to simulate realistic daily operations of a Mars mission, and includes simulated extravehicular activities (EVA), scientific experiments, maintenance procedures, and crew self-management. From these missions, several data across different domains are collected

[52] National Aeronautics and Space Administration. (n.d.). *About CHAPEA*. https://www.nasa.gov/humans-in-space/chapea/about-chapea/
[53] Yashar, M., Glasgow, C., Mehlomakulu, B., Ballard, J., Salazar, J. O., Mauer, S., & Covey, S. (2022). Mars dune alpha: A 3D-printed habitat by ICON/BIG for NASA's Crew Health and Performance Exploration Analog (CHAPEA). In *Earth and Space 2022* (pp. 976-984).

focusing on capturing how operational constraints shape the collective behavior and system-level performance of a crew, rather than simply observing the responses of individual crew members to isolation. The analog missions include several stressors that were selected to represent Mars-relevant conditions as much as possible, and include limitations on resources, strict operational schedules, equipment malfunctions, communication delays, and sustained task demands.

Within the context of the CHAPEA program, Mars Dune Alpha is not viewed as a passive shelter, but as an active operational system that influences the behavior of the crew. Mars Dune Alpha was designed to contain constraints like those expected on Mars, including a fixed internal volume, a fixed layout, few opportunities to modify its structure, and a high degree of dependency on its internal life support and utility systems. These design characteristics enable researchers to assess how architectural features influence the daily operations of the crew, the cognitive workload experienced by the crew, the priorities of the crew regarding tasks, and the social interactions of the crew. The internal configuration of Mars Dune Alpha is organized along a functional and psychological gradient, with a progression from private spaces to common operational spaces. This spatial configuration is intended to facilitate both individual recovery and collective activity, and to demonstrate how spatial constraints influence stress management, conflict resolution, and social cohesion.

Resource sustainability within the habitat exists not only because of the technical efficiency of the life support and utility systems, but because of the habits formed by the crew, the routines established by the crew, and the decision-making processes used by the crew. Daily practices concerning food preparation, waste management, maintenance, and scheduling become critical to the long-term sustainability of the habitat. Mars Dune Alpha also serves as a testbed for incorporating Earth-supplied hardware into a structure whose design concept is aligned with in-situ construction principles. Airlocks, medical pass-throughs, mechanical and electrical systems, and modular interior components are included in the habitat to assess the inter-operability, maintainability, and tolerance to failure of the systems and components.

While it is is not pressurized to the same degree as a spacecraft, it enables a meaningful assessment of how interfaces, access points, and modular systems can support long-term operation of a habitat with minimal external intervention. The analog environment clearly demonstrates the significance of standard interfaces, replaceable components, and design-for-repair principles in a context where there are limited opportunities for resupply, and outside help is either delayed or unavailable. From an operational standpoint, this reinforces the notion that resource sustainability is indistinguishable from system maintainability.

This perspective supports the broader viewpoint that future Mars habitats must be conceptualized as integrated operational systems rather than simply as protective shells.

The first analog mission began on June 25, 2023, and ended on July 6, 2024. A second mission began on October 19, 2025. Taken together, these two missions will provide longitudinal data on how crews adapt operationally over time within a constrained environment.
Voyagers of Mars: The First CHAPEA Crew's Yearlong Journey (Loggins, 2024), the official NASA mission report, states that future Mars crews must be able to repair and maintain equipment, grow their own food, and sustain their health while dealing with communication delays between Earth and Mars. This framing is consistent with the operational sustainability framework used in this study, which views human performance as being dependent upon the combined technical competence and self-reliance, rather than continuous oversight from Earth. The crew not only completed mission-critical tasks but developed informal social routines that helped to maintain their social cohesion over a long period of time, they celebrated holidays and birthdays, cut each other's hair, and found ways to laugh and find humor in the face of prolonged isolation. These examples illustrate how the development of informal social routines helps to support psychological sustainability and morale in a closed and resource-constrained system. Mission Commander Kelly Haston indicated that teamwork and adaptability were the most important aspects of the CHAPEA mission. She stated that the crew relied on shared training and trust among crew members to navigate the many challenges they faced every day, and that she saw each day present both obstacles and opportunities for learning (Loggins, A. 2024). Her comments reinforce previous studies of isolated, confined, and extreme (ICE) analog environments, where teams develop the adaptive capacity necessary to overcome the challenges they face through shared responsibility and distributed expertise. Medical Officer Nathan Jones offered additional insight into the implications of communication latency for the crew. He noted that decisions about when to communicate with mission control had to be carefully considered due to the approximately one-hour round trip communication delay (Loggins, A. 2024); illustrating the breadth of autonomy on Mars extends far beyond decision making authority to include strategic information management, prioritization, and timing.
Science Officer Anca Selariu described the mission as a continuous cognitive and existential learning experience; the isolation fostered reflection on human values, creativity, and cultural identity, and a reevaluation of the dependency on digital connections (Loggins, A. 2024).
Flight Engineer Ross Brockwell noted that anticipating failures and developing contingency plans allowed the crew to develop creative solutions to problems, including the use of a 3D

printer to manufacture tools and adapters as needed (Loggins, A. 2024). The qualitative evidence[54] generated by the crew complements the experimental results obtained in analog research and demonstrate how the autonomy, resilience, and sustainability of a Mars crew are implemented in their daily lives in a closed and resource-constrained environment.

In-Situ Resource Utilization (ISRU) and operational sustainability:

Large-scale additive manufacturing will be an important component for human habitation on the Moon and Mars; as well as the use of additive manufacturing to process resources found locally on the planets. The goal of these approaches is to minimize the amount of material launched from Earth and transported to the Moon or Mars for construction purposes. As a result, the reliance on Earth-launched construction materials will significantly decrease the mass, cost, and logistical requirements. Thus, In-Situ Resource Utilization (ISRU)[55] becomes a critical capability for sustainable exploration on the Moon and Mars. NASA performs analog missions for ISRU through collaborations with international and institutional partners, i.e., the Pacific International Space Center for Exploration Systems and the Canadian Space Agency. NASA's ISRU analog missions involve validating the hardware necessary to identify, characterize and separate water and carbon dioxide from planetary materials as those found on the Moon (regolith) and Mars (volcanic). Similar types of technology may be used to utilize resources found in various planetary environments, i.e., the lunar polar region and surface areas on Mars. As defined by Sanders, G. B., & Kleinhenz, J. E. (2022) ISRU includes any hardware or operational process that uses and/or transforms in-situ resources (natural materials, waste, etc.) into commodities for robotic and human exploration and space commerce. So, when viewed through a lens of scalability, the relevance of ISRU is very clear. Every kilogram of material that needs to be transported from Earth results in additional mission mass, cost, and frequency of launches. Therefore, reducing transported mass is the key to increasing the feasibility of sustaining long term presence.

---

[54] Loggins, A. (2024). *Voyagers of Mars: The first CHAPEA crew's yearlong journey*. National Aeronautics and Space Administration. https://www.nasa.gov/missions/voyagers-of-mars-the-first-chapea-crews-yearlong-journey/

[55] Reagan, M., Janoiko, B., Johnson, J., Chappell, Ph. D, S., & Abercromby, A. (2012, January). NASA's analog missions: Driving exploration through innovative testing. In *AIAA SPACE 2012 conference & exposition* (p. 5238).; Sanders, G. B., & Kleinhenz, J. E. (2022, September). NASA envisioned future priorities for in situ resource utilization. In International Astronautical Congress (IAC).

Much of the development effort has been dedicated to extracting usable materials from the atmospheres and soils of planetary bodies, specifically Mars. Laboratory testing has given way to demonstration of integrated subsystems. Analog missions have provided early field-testing of oxygen extraction, including those at Mauna Kea. More recent studies have shown the possibility of creating oxygen and methane using integrated systems in simulated Martian environments. These studies have clearly shown the potential for producing consumables locally instead of having to transport them. One of the major milestones of the development effort was the successful demonstration of producing oxygen in situ, using the Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE)[56], which was part of the Mars 2020 Perseverance rover. During its operational period, MOXIE successfully produced 122 grams of oxygen with a purity level of over 98%. Although the quantity was minuscule relative to what would be needed to sustain human life missions, the significance of the demonstration was that it showed oxygen could be produced technologically in a reliable manner under actual Martian environmental conditions, and that it could be repeatedly done.

From a scalability perspective, the most important result of the experiment is that it demonstrated that atmospheric processing could function in a reliable and repeatable fashion in situ. Therefore, ISRU moved from being a conceptual or laboratory based strategy to becoming an operationally proven capability. The MOXIE experiment was designed to run continuously for one full Martian year in order to test the operational stability and system robustness of the system over a variety of environmental conditions. Long duration operational validation is crucial if ISRU experiments are going to expand to large scale production systems capable of supporting crewed missions. Ultimately, this represents the ability to convert local resources into consumables will be a critical factor in establishing sustainable long-duration human presence on Mars.

2.3.8 Governance adaptation: institutional and legal models

The new "New Space" Era has led to an exponential growth of space activities, placing significant pressure on existing regimes governing those activities.

[56] National Aeronautics and Space Administration. (2020). NASA’s oxygen-generating experiment MOXIE completes Mars mission. https://www.nasa.gov/missions/mars-2020-perseverance/perseverance-rover/nasas-oxygen-generating-experiment-moxie-completes-mars-mission/

Existing methods for conducting space activities have been largely deemed unsustainable for the future due to a growing number of congested orbital paths, poor post-mission disposal, and the potential increase in active spacecraft over the next 10 years.
These trends reveal fundamental structural limitations within international space law, as the legal regime that governs outer space was created during the Cold War, when the primary purpose of space activities was carried out by governments for scientific, strategic, or symbolic purposes. As such, international space law established broad principles of stability and restraint, rather than specific, detailed regulatory mechanisms for intensive commercial activity.
Academic debates regarding the concept of space law date back to at least 1926, many years prior to the technical capabilities to engage in space activities (Pozza M. 2024). A regulatory structure surrounding the governance of space consists of both binding and non-binding instruments, working in tandem to provide a layered regulatory environment. Binding instruments include the core UN space treaties, national regulations, and international standards, whereas non-binding instruments include voluntary guidelines, best practice, and aspirational norms. Although the four core UN space treaties establish the foundational principles for space law, they are high-level, not universally ratified by all actors engaging in space activities, and do not effectively address modern day sustainability issues. Following the establishment of these core treaties, international governance evolved toward less formalized structures, including multilateral agreements and voluntary guidelines, intended to support treaty-based law by providing more detailed operational guidance. National regulatory regimes serve to implement international principles into operational directives, but there is great variability in the interpretations and enforcement of those directives. This variation leads to space operators selecting the jurisdiction with the most favorable operating conditions, also known as flags of convenience, which can undermine the achievement of collective sustainability goals. Commercial actors generally prefer non-binding forms of governance because strict regulation can be seen as costly and limiting to innovation. The difference between public regulatory objectives and private operational incentives is at the center of the existing governance disputes. Unlike traditional hierarchical systems, space governance operates as a positive feedback loop of continuous engagement among multiple actors. The space community includes space operators, international coordination entities, national regulatory agencies, standards organizations, and industry associations that together create governance outputs through continuous feedback loops.

The Antarctic Treaty as a precedent for Space Law:

The 1959 Antarctic Treaty was an early precursor to International Space Law and a model for how nations can work together for the good of humanity when there is great geopolitical tension between nations. In fact, the 1959 Antarctic Treaty was the first to set aside a region of the earth as a scientific reserve. One of the main accomplishments of the Treaty was the formal recognition of the right of free scientific investigation. Parties agreed to facilitate research and share the results of scientific observation, thus institutionalizing cooperation in a difficult-to-reach area due to extreme conditions and the difficulties of logistics:
"Article I: Antarctica shall be used for peaceful purposes only;"
"Article II: Freedom of scientific investigation in Antarctica and cooperation toward that end...shall continue;"
"Article III: Scientific observations and results from Antarctica shall be exchanged and made freely available."
(Antarctic Treaty Secretariat, n.d.)"

The goals were very similar to what was at stake for the world's leaders during the Space Race. The Sputnik shock prompted the creation of the National Aeronautics and Space Administration (NASA) by the U.S. Congress. President Eisenhower proposed using the principles of the 1959 Antarctic Treaty as a model for creating an independent agency responsible for regulating all space-related activities in the United States. After that the United Nations created the UN Office of Outer Space Affairs (UNOOSA) to encourage international cooperation in space and created COPUOS in 1959 to oversee future treaties and agreements related to the use of outer space for peaceful purposes.

Under the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS), five major international treaties established the foundation of international space law. The five treaties are: the 1967 Outer Space Treaty (OST); the 1968 Rescue Agreement; the 1972 Liability Convention; the 1976 Registration Convention; and the 1979 Moon Treaty. Together, they create the fundamental legal framework for international cooperation and responsibility in outer space.

The Outer Space Treaty:

The Outer Space Treaty is the most significant treaty in the history of international space law and has been the most important single legal document in the field of space law since its entry into force in 1967. More than a hundred countries have ratified the Treaty. Article I of the Treaty provides the general principle that the exploration and use of outer space, including the moon and other celestial bodies, shall be done for the benefit and in the interest of all of humanity. By establishing outer space as a shared domain, rather than simply another extension of sovereign territory, Article I reflects the efforts of the drafters to create a new framework for international relations in space. The political context of its drafting must be considered, since only two states at the time, the United States and the Soviet Union, had achieved the technological capability to carry out space-related activities. Other states supported the OST because they believed that if these two superpowers were allowed to exploit outer space to gain strategic or military advantage, the consequences could be disastrous. Under Article VI, private entities are permitted to participate in space-related activities provided that those activities are authorized and supervised by states. This provision helped shape the role of the private sector in space activities by permitting commercial operators to compete with governments and international organizations in space activities, although within a state-centered responsibility framework.

However, the four subsequent treaties were designed to implement and clarify the principles of the OST by dealing with various emerging problems resulting from technological advancements. The 1968 Rescue Agreement requires states to aid astronauts in distress and to report to both the launching state and the UN Secretary-General when such distress occurs. The Liability Convention of 1972 developed the regime of responsibility further by defining key legal terms ("damage," "launching," and "space object") and by establishing the rules for liability for damage caused by space objects. Non-spacefaring states were especially attracted to this convention because it provided a legal safeguard against harm caused by the activities of others over which they had little control. The Registration Convention of 1976 was designed to require states to register objects placed into orbit around the Earth or beyond, to enhance transparency, traceability, and accountability in space activities. Finally, the Moon Treaty represents the most ambitious and controversial component of the UN space law framework. The Treaty is applicable not only to the Moon but to all celestial bodies in our solar system. The central principle is that extraterrestrial territories and resources constitute the "common heritage of mankind" and that their utilization should be regulated through collective action of the international community and to prevent unilateral appropriations and unfair exploitation of extraterrestrial resources, there is a strong prohibition of property rights in extraterrestrial territories. However, this position resulted in being marginalized politically; in fact, none of the major spacefaring states, including the United States, members of the European Space Agency, Russia, China, Japan, or India, has ratified it. Therefore, the Moon Treaty is commonly viewed as a failure; despite this, it is the only international treaty that has dealt with the question of property rights in outer space and continues to influence contemporary discussions of the use of extraterrestrial resources, governance and equity in outer space.

International space law is effective to varying degrees; while the core treaties of international space law establish legally binding commitments for states parties to those treaties, the practical effects of these commitments are limited because of the decentralized system. So, states may choose to disregard certain provisions of international treaties, interpret them selectively, or disagree about the precise legal implications of provisions. Furthermore, the lack of centralized enforcement mechanisms makes it difficult to achieve consistent application of the principles of international space law. Consequently, implementation of international space law depends on the voluntary cooperation of individual states and the willingness of those states to comply with the provisions of the relevant treaties.
Against this background, the regulation of private property rights in outer space has emerged as perhaps the most contentious and unresolved issue in international space law. Thus, the Outer Space Treaty prohibits national appropriation of celestial bodies but does not address the question of private ownership or appropriation by non-state actors. The resulting uncertainty has contributed to continued confusion in the international legal community regarding the question of whether private entities acting with the authorization of states can own or appropriate extraterrestrial resources. This ambiguity has given rise to competing views within the international legal community. On the one hand, private entities are merely extensions of the states, therefore, any private appropriation would amount to indirect national appropriation. On the other hand, is that the lack of clarity regarding private ownership constitutes a legal loophole and that private entities can utilize and possibly appropriate extraterrestrial resources, so long as states do not claim sovereignty over the territory itself. Examples of actual claims to ownership of extraterrestrial property illustrate the continuing uncertainty regarding property rights in outer space. In 2000, a man named Gregory Nemitz registered ownership of the near-Earth asteroid 433 Eros, claiming it as part of his Eros Project and after the landing of NASA's NEAR Shoemaker on the asteroid, Nemitz demanded a parking fee, asserting that the probe was on his property (Iliopoulos & Esteban, 2020). NASA denied the claim, stating that there

was no legal basis under international space law for such a claim. The Nemitz claim was ultimately rejected, but the case illustrated that there were no clear legal guidelines for making private property claims in space. While another relevant case is NASA having had asserted ownership of the Moon rocks returned to Earth during the Apollo missions, and this claim has generally been accepted by the international community. This de facto recognition, not codified in international law, demonstrates that certain types of claims to ownership have been implicitly accepted in practice and contribute to the inconsistencies in the interpretation of the legal norms of outer space.

National responses, The U.S. SPACE Act of 2015:

The growing legal uncertainty associated with private activities in space resulted in the United States Senate holding hearings to identify legal reform options that would facilitate the development of a commercial space industry. There was wide-ranging agreement on the preservation of the fundamental principles of the Outer Space Treaty while implementing some minor regulatory changes. These efforts ultimately resulted in the adoption of the U.S. Commercial Space Launch Competitiveness Act of 2015, also referred to as the SPACE Act. The SPACE Act granted U.S. citizens the authority to engage in the commercial exploration and recovery of space resources, including water and minerals, subject to the exception of biological life. At the same time, the Act affirmed that the United States did not assert sovereignty over celestial bodies. Although this clarification provided some clarity, the legislation triggered considerable debate about whether the Act was compatible with international space law. Some supporters of the SPACE Act argued that the right to recover space resources was consistent with existing state practice, as well as prior interpretations of the Outer Space Treaty made by the U.S. Government as extracting space resources did not equate to territorial appropriation and therefore did not contravene the Outer Space Treaty. Others advocated for a more measured position, indicating that although the Act did not explicitly contradict international law, it failed to address the larger legal uncertainties surrounding space mining. Another, more critical viewpoint posited that the SPACE Act represented an indirect exercise of sovereignty, as it allowed private entities to appropriate in areas in space that were prohibited from being appropriated by nations under the Outer Space Treaty.

The Artemis Accords, an example of adaptive governance models:

The Artemis Accords demonstrate another way of approaching the problem of legal ambiguity and regulatory adaptation, which characterize present day space governance. The Artemis Accords are a set of non-binding political agreements adopted in 2020 to implement existing principles of international space law into modern exploration practices, especially on the lunar surface. Although the Accords reaffirmed adherence to the Outer Space Treaty (OST) and interpreted certain issues, specifically space resource use and the prevention of harmful interference, differently than the OST, the Accords clearly indicate no intention to create legally binding obligations. Instead, the Accords were developed as soft law instruments and implemented as a combination of bilateral agreements and operational arrangements, rather than through multilateral treaty mechanisms. Consequently, the legal relevance of the Accords rests in their normative and interpretative functions rather than their enforceability as formal law. At a time when the OST contains many ambiguities and omissions, the Accords provide a functional framework for participating countries to develop shared understanding of how to apply the OST to operational practices without renegotiating the terms of the treaty. The governance model represented by the Artemis Accords represents a paradigmatic shift in space lawmaking from a focus on developing universal, binding multilateral treaties to more flexible and targeted instruments.

Substantially, the Accords operationalize many of the principles that are contained in the OST, including peaceful uses, transparency, interoperability, emergency aid, registration of space objects, and mitigating orbital debris. However, the Accords also contain new governance concepts that exceed the scope of the existing treaty framework. The Accords address the issue of space resource use by stating that space resource use is permissible in accordance with the OST and does not constitute national appropriation. The Accords' formulation of this concept is designed to provide legal certainty for commercial actors while affirmatively maintaining the non-appropriation principle.

One of the most innovative aspects of the Artemis Accords is the concept of safety zones[57]. Safety zones are based upon Article IX of the Outer Space Treaty, which requires states to perform all activities with due regard for the interests of other states and to enter consultations with other states in situations where there is a potential for harm caused by an activity of one state to the interest of another. It is a mechanism for coordinating and avoiding conflicts arising

[57] Gilbert, A. Q. (2023). Implementing safety zones for lunar activities under the Artemis Accords. *Journal of Space Safety Engineering*, *10*(1), 103-111.

from activities that are proximate to one by providing a framework for communication, coordination and cooperation among interested parties. To ensure consistency with the non-appropriation principle, safety zones are explicitly defined as being temporary, proportionate, and dependent upon the nature of the activity that is taking place.

Despite their explicit definition, safety zones continue to generate controversy from a legal and political perspective. Critics argue that, even though safety zones are non-binding in terms of their legal status, they may serve as de facto exclusion zones for other actors, especially in high value locations on the moon such as the lunar south pole. Additionally, critics express concern regarding the lack of a requirement for non-signatories to recognize or comply with safety zones, and the possibility of unequal access, norm fragmentation, and the establishment of privileged governance arrangements. Proponents of safety zones argue that they are an essential adaptation of existing legal principles to meet the requirements of actual operations and that their flexible form permits continuous revision and eventually multilateralization rather than the creation of a legal precedent.

An important distinction exists between the governance model established by the Artemis Accords and previous multilateral arrangements, such as the International Space Station Intergovernmental Agreement. Unlike the Intergovernmental Agreement, which allocated rights and obligations to signatory countries through a centralized, binding legal framework, the Accords established a set of standards of conduct that are operationalized through contracts and political processes. Therefore, the governance model established by the Accords represents a decentralized system in which norms arise from practice, coordination and contractual implementation, rather than through regulation based on a common treaty.

However, the adaptive governance model established by the Accords also generates serious concerns regarding inclusion and legitimacy. The Accords were initiated by a single country and are available primarily to countries that are willing to adhere to the Accords' interpretive framework. As a result, the Accords potentially exclude key stakeholders from the process of developing norms. The example of China's exclusion from the Accords, resulting from U.S. legislative restrictions, demonstrates how domestic politics can influence a country's ability to participate in global governance initiatives. Similarly, smaller and less technologically advanced countries may experience pressure to agree to predetermined understandings of space law to maintain access to opportunities for future exploration.

Rather than moving towards a single, universally applicable governance regime for space, the field of space law may evolve into a multi-polar or bipolar regime characterized by overlapping and mutually inconsistent sets of norms, each articulating different meanings of foundational principles such as resource utilization and operational control.

From an analog-based perspective, both the international space law and the Antarctic Treaty System are useful models for future Mars governance, not because they provide institutional models to replicate, but because they govern human activity in environments characterized by extreme environmental conditions, lack of sovereignty, scientific priority, and international oversight. Both regimes are also plagued by persistent legal and institutional ambiguity stemming from ambiguous definitions, weak enforcement mechanisms, and changing interpretations of basic principles. Therefore, the purpose of using analogs is not replication, but diagnosis: identifying which governance mechanisms have demonstrated resiliency, which have generated continued ambiguity, and where structural gaps exist.

Therefore, the Artemis Accords should be viewed as an adaptive response to regulatory stagnation, commercial pressures and technological acceleration, and not as a definitive resolution to the governance challenges of the New Space Era. The Artemis Accords demonstrate that contemporary space governance is increasingly shaped by soft-law instruments that emphasize operational feasibility and political convergence over formal legal universality. While the Accords may improve short-term coordination and reduce uncertainty for investors, they increase longer-term risks of fragmentation, exclusion, and undermining of multilateral oversight.

CHAPTER 3: DISCUSSION BEYOND SURVIVAL: DEMOGRAPHIC ADAPTATION IN MARS SETTLEMENTS

3.1 From migration to permanent settlement

Multi-planetary vision of SpaceX[58] significantly contributes in changing the way we understand space migration. It goes well beyond the notion of temporary exploration and provides a basis for the establishment of permanent settlements.[59] Thus, a human migration to Mars is seen as a one-way trip with a focus on establishing a stable, long-lasting society. In this

[58] Musk, E. (2018). Making life multi-planetary. *New Space*, *6*(1), 2-11.

[59] Young, D., & Docherty, N. (2025). An anticipatory regime of multiplanetary life: on SpaceX, Martian colonisation and terrestrial ruin. *Science as Culture*, *34*(2), 168-193.

respect, the traditional space mission logic, where among the goals there is the returning to Earth, is completely abandoned; instead, Mars will serve as a populated territory with an increasing population developing its own systems of production, governance and social organization. The redefinition of migration as a permanent move has several important demographic consequences; a migration intended to last for generations, unlike a migration that is intended to be temporary, requires the creation of social and organizational structures that will facilitate the continuation of life over time. Therefore, a permanent settlement will have achieved demographic mass necessary when it reaches a level that will enable the development of systemic resilience, a diverse set of skills, and social reproduction and intergenerational transmission. However, below a certain demographic threshold, the newly established settlement will continue to be vulnerable to external disturbances, dependent upon continuous supply lines from Earth, and unable to regenerate itself.

Human settlement on Mars cannot be seen as an extension of terrestrial migration processes. The structure of space travel comprehending distance, low gravity, lengthy travel times, delayed communication capabilities, and the inability to rapidly return to Earth, severely limit the ability to reverse the direction of the movement. The environmental and human adaptations previously discussed are, therefore, the structural background to this transition. They represent the need to gradually achieve local autonomy and to organize the human presence collectively in the transition from one type of environment to another. Once past the initial threshold of survival in the extreme Martian environment, the key question transitions from individual endurance to collective continuity. Thus, this chapter places itself at this conceptual turning point, indicating the transition from survival to demographic adaptation. Migration is studied under the lens of a demographic process which is irreversible, isolated and requiring stability across generations. It focuses on the structural conditions that allow a human population to exist, reproduce and evolve in an exogeographic environment, converting a temporary presence into a permanent settlement.

3.1.2 Climate adaptation on Mars

As a reference for analysing human settlements on Mars, adaptation strategies used on Earth concerning climate change issues provide a way to understand how people have built resiliency in extreme situations. Terrestrial climates are shaped by the interaction among many different components from atmospheric to terrestrial, to oceanic and biological that govern temperature, precipitation, and long-term variations in the climate system, all of which impact ecosystems, societies, and economies. Consequently, climate change has increased the level of environmental stress on Earth, and has caused an increase in the frequency of extreme weather events and ecological and socio-economic instability. The combination of increasing global population density and increasing global connections between production and consumption systems increases the likelihood that disturbances in one domain, such as agriculture, water availability, energy systems, transportation, and public health will spread to other domains, creating a chain reaction of effects. For these reasons, terrestrial climate adaptation has historically been accomplished using a two-pronged approach; adapting to climate change by adjusting existing infrastructure, institutions, and societal practices to accommodate the changing environmental conditions (e.g in-situ adaptation), and/or by moving populations to areas with less severe environmental conditions (e.g relocation). The act of migrating and rearranging the location of settlements thus represent the major mechanisms that enable societies to reduce demographic pressure and build long-term resiliency.[60]

This adaptive strategy, however, is not transferable to the Martian environment. Indeed, in contrast to Earth's environment, Mars represents a permanently hostile environment for human life, with no climatic fluctuations occurring within the bounds of survivability for unsheltered humans. Therefore, seasonal or multi-generation migrations cannot serve as viable adaptation options on Mars and so, it must be based upon the establishment of permanent settlements, utilizing the continued mediation of environmental factors through the selection of suitable habitation zones and the creation of structures capable of maintaining consistent interior conditions over extended periods. Climate adaptation on Mars represents both a risk, as previously discussed in other sections of this report, but also serves as a demographic constraint. Since relocation cannot serve as an effective adaptation mechanism, the ability of settlements to maintain demographic stability will depend upon their ability to manage reproduction and maintain social cohesion under the constant stress of environmental pressures. While several principles derived from terrestrial adaptation remain conceptually relevant, it is necessary to transform them to apply to the Martian context; terrestrial ecosystem-based management approaches, which seek to enhance the capacity of natural systems to buffer against climatic stress, suggest that Martian settlements will function as managed, closed or semi-closed ecosystems in order to maintain ecological balance, rather than simply allowing it to occur naturally. Similarly, the development of highly controlled climate-smart agricultural

[60] Eslamzade, Jeyran. United Nations Department of Economic and Social Affairs Population Division.

systems on Mars, that are intended to support food production in a permanently constrained environmental regime, is analogous to the adaptation of terrestrial agriculture through the use of climate-resilient crops and soils. Furthermore, developments in terrestrial early warning systems show how important ongoing observation and forecasting skills are to reducing climatic risks.[61] Long-term habitation will rely on the implementation of sensor networks and predictive platforms that can foresee hazards and trigger automated safety protocols in the Martian environment, where hazards such as dust storms are both persistent and potentially system-threatening. Finally, terrestrial experience also demonstrates the importance of governance and resilient infrastructure in managing environmental transformations.[62] Lastly, experience on earth also shows how crucial governance and robust infrastructure are to handling environmental changes. Addressing environmental problems and health hazards on Earth requires coordinated decision-making, ongoing monitoring, and flexible policy-making. Governance and robust infrastructure are crucial on Mars; communities must be able to guard against contamination, chemical imbalances, and system failures within the habitat. The need for modular and distributed systems for Martian settlements that can support demographic stability and adapt to technological or environmental failures is further supported by the proven vulnerability of rigid, monocentric infrastructure to extreme events on Earth.

Collectively, these comparative insights demonstrate a fundamental transformation in adaptive logic: whereas terrestrial climate adaptation has historically relied upon mobility, migration, and the reorganization of settlements, climate adaptation on Mars must be achieved through at first the selection of settlement zones and the design of habitats with the primary mechanisms for mediating climatic constraints.

3.2 Comparative models of Martian settlement

The challenge of establishing a sustained human presence on Mars has inspired multiple conceptual models of settlement, each emphasizing different strategies to maximize safety, self-sufficiency, and sustainability in the hostile Martian environment. Mars offers no breathable atmosphere, intense radiation, extreme cold, and a vast distance from Earth, factors that force engineers and planners to carefully weigh trade-offs in habitat design, location, and

---

[61] Susan Gawlowicz, "Early Warning System Would Predict Space Storms on Mars: RIT Professor Develops Monitoring System for Mars and Earth," Rochester Institute of Technology News, March 29, 2010.
[62] Wang, F., Harindintwali, J. D., Wei, K., Shan, Y., Mi, Z., Costello, M. J., ... & Tiedje, J. M. (2023). Climate change: Strategies for mitigation and adaptation. *The Innovation Geoscience*, *1*(1), 100015-1.

infrastructure. This section discusses four major models proposed for Mars human settlement:

1) a polar-subsurface model, situating habitats near the ice-rich poles and largely underground;

2) equatorial-surface model, building at lower latitudes on the open surface;

3) concentrated vs. distributed urban models, contrasting a single centralized colony with a network of smaller outposts;

4) resource-driven settlement model, in which the location and growth of the colony are determined by the availability of key resources.

Each model is examined in terms of its rationale, feasibility, technical implementation, and social implications, drawing on current research and design studies. It is important to note that these models are not mutually exclusive, a real Mars settlement plan may combine elements of each, separating them provides a clear framework to understand the distinct challenges and advantages associated with different approaches.

3.2.1 Polar-Subsurface Model

Concept and rationale:

The polar-subsurface model envisions a Mars base located in high latitude regions and largely situated beneath the surface, for example inside natural cavities or human-dug tunnels. The primary appeal of a polar location is the abundant water ice known to reside in the Martian polar caps and permafrost. Water is a critical resource for life support (drinking water, oxygen via electrolysis, and agriculture) and can be cracked into hydrogen for fuel; establishing a settlement next to a large in-situ supply of ice could drastically reduce the need to haul water from Earth. Additionally, building the habitat in the subsurface, such as within a lava tube or under meters of regolith/ice, provides natural protection from many of Mars' hazards. A 2009 study by the International Space University (ISU) found that among various cave types on Mars, lava tubes offer the most feasible option for a permanent settlement due to their size, structural stability, thermal moderation, and accessibility for both robots and humans. These extensive subsurface voids could accommodate entire habitat modules and shield inhabitants from radiation and micrometeorites, which are serious concerns on the surface. In fact, a substantial rock overhead can attenuate cosmic radiation by roughly three orders of magnitude compared to the dose on an exposed surface. The Martian atmosphere is far too thin to offer much radiation protection, so the subsurface model's inherent shielding is a compelling advantage; ISU's analysis noted that a lava tube with a few meters of overlying rock would nearly eliminate the crew's radiation exposure, as well as guard against meteorite impacts and dust storms. In short, the polar-subsurface strategy is driven by the rationale of tapping into polar water resources and using the planet itself as a shelter. The promise of plentiful ice for life support and fuel production, combined with the safety of an underground haven, makes this model attractive as a pathway to an initial permanent settlement on Mars.

Feasibility and technical factors:

Implementing a polar-subsurface settlement presents unique technical challenges alongside its benefits. A major task is identifying a suitable subsurface space near the poles. Lava tubes are primarily expected in volcanic regions (e.g. equatorial areas like Tharsis or Elysium), but high-resolution orbital imagery has revealed possible skylight entrances to subsurface voids at various latitudes. Site selection must balance access to ice with the presence of a stable cavity; ISU recommends choosing a lava tube site based on multiple criteria including proximity to water ice, available solar or geothermal energy, mineral resources for industry, safe landing zones, and regions of scientific interest. If a natural cave near the pole is unavailable, an alternative is to excavate tunnels or bury habitat modules under the polar regolith or ice sheet. In either case, significant precursor missions would be required to survey and prepare the location. Robotic explorers (rovers, drones, perhaps specialized "cave crawlers") should reconnoiter the candidate lava tube or dig site in advance, assessing its geometry, stability, and ease of entrance for large habitat components. Robotic preparation might also include clearing or enlarging an entrance and stockpiling ice/regolith for construction.

Once a suitable subsurface void is secured, habitat deployment could involve emplacing inflatable or modular structures inside the cavity and then sealing the entrance. The lava tube's interior would need to be partitioned or lined with an air-tight material to hold a breathable atmosphere. An advantage is that the lava tube's rock walls provide built-in radiation and micrometeoroid shielding, reducing the amount of shielding material that engineers must add.

Mars underground also has a much more stable thermal environment: temperatures several meters below the surface remain nearly constant over day-night cycles, mitigating the stress of

Mars' extreme temperature swings. This simplifies thermal control of the habitat and reduces energy needed for heating in the frigid polar night. The polar environment itself, however, imposes other technical demands. Near the poles, sunlight can be absent for many months each winter, meaning a heavy reliance on non-solar power sources. Settlement designers almost universally consider nuclear power essential in this scenario. A compact fission reactor could provide continuous electricity and heat through the long dark period when solar panels are useless. Energy from the reactor could be used not only for habitat life support and heating, but also to melt subsurface ice for water and to run chemical plants that turn polar water and atmospheric CO_2 into oxygen and methane fuel. In fact, by leveraging in-situ resources at the poles, a Mars base could produce its return propellant on-site; Mars mission plans have noted that hydrogen feedstock for the Sabatier reaction[63] might be delivered from Earth initially or sourced by processing the plentiful ice "on the Martian poles".

Beyond power and resource extraction, other technical factors include communications and mobility. Polar locations have less direct line-of-sight to Earth for communication, at times the curvature of Mars or seasonal orientation could block signals, so a settlement might require relay satellites in Mars orbit to maintain year-round contact with Earth and with any equatorial assets like orbiters. For mobility, the crew would use pressurized rovers or unpressurized vehicles for excursions around the base or to nearby science sites. In polar terrain, those rovers must handle icy, possibly crevassed surfaces and extreme cold that can affect batteries and machinery. Technologies proven in Antarctic operations could inform Mars rover designs. Notably, life support systems in a subsurface polar habitat must be extremely robust and capable of operating in reduced gravity with minimal maintenance. Redundancy and reliability are paramount, as highlighted in deep-space life support studies: because emergency resupply or quick return is not feasible on Mars, the life support system must have higher reliability and more autonomy than the ISS systems, requiring a dedicated development effort and long testing to reach the needed fail-safe performance. This applies to all Mars settlement models but is especially critical when the crew might be "overwintering" in isolation at the pole.

[63] The Sabatier reaction is an exothermic, catalytic reaction that converts hydrogen (H_2) and carbon dioxide (CO_2) into methane (CH_4)) and water (H_2O). The reaction generally takes place at temperatures ranging from 300 – 400°C on a Nickel based catalyst. It has applications for converting atmospheric CO_2 into methane and H_2O for use as fuel and life support resources in both terrestrial and space exploration related energy systems.

(Fig. 8: This photograph was taken during Professor Alfonso Giordano's course Exogeography: Astropolitics and Space Economy at LUISS University (Guest Lecture by Samanta Snidaro & Andrea Fino, SAND & BIRCH STUDIO, October 29, 2025). The image shows a physical model by SAND & BIRCH STUDIO, illustrating the polar-subsurface settlement for Mars: a cross-sectional representation of a habitat embedded beneath the surface, potentially within a lava tube or excavated cavity.)

Social structure and governance:

A polar-subsurface settlement would profoundly shape the living experience and social dynamics of its inhabitants. On one hand, safety and habitability would be enhanced compared to an exposed surface outpost; the crew would have significantly lower radiation exposure reducing long-term health risks, and they would be spared from dust storms and extreme temperature swings while inside the caves or tunnels. The additional shielding means that habitat designers could potentially incorporate larger common volumes or thinner-walled inflatables, since the protection comes from the cave, not the habitat hull itself. This could allow more spacious living quarters, helping alleviate the claustrophobia and stress of a small crew confined together. Indeed, planners have suggested that a lava tube base might eventually house larger numbers of people or bigger agricultural areas than a comparably mass-intensive surface base, precisely because the cave provides a ready-made "mega-structure" to build into. The psychological benefit of room to move, and possibly the ability to simulate an Earth-like environment inside.

The polar underground model also introduces social challenges. The crew will be living in perpetual darkness for months during the Martian winter if they are deep under ice or if the polar night covers the region. Lack of natural sunlight can disrupt circadian rhythms and negatively impact mood and mental health, like seasonal affective disorder on Earth, but potentially more acute, unless mitigated by full-spectrum lighting systems and carefully managed daily schedules. During the summer, conversely, polar regions receive continuous sunlight; if any part of operations involves venturing outside or near entrances, the 24-hour daylight could also require behavioral adaptation. Overall, maintaining a healthy day-night cycle for the crew will rely entirely on artificial cues in the subsurface habitat. Another social consideration is the extreme isolation. Real-time communication will be limited to their small group and delayed messages from Earth, exacerbating feelings of confinement. Crew selection and training must emphasize psychological resilience and coping strategies for a monotonous environment. In a polar-subsurface base, these needs might be met by providing recreational facilities inside the lava tube and ensuring crew have private quarters despite the shared cave setting.

A subsurface colony would likely be tight-knit and highly cooperative. Survival in a cave habitat depends on everyone following safety protocols in fact a single mistake like breaching the pressure seal or contaminating the water supply could endanger the entire group. This necessity could foster a strong sense of community and interdependence, but it also means individual freedoms are inherently limited by safety requirements. Space policy analysts have argued that any extraterrestrial settlement will demand stricter regulations on daily life than we are accustomed to on Earth, simply to keep people alive. For example, one cannot freely exit the habitat without a suit, and certain areas or actions[64] will be under strict control. In a small polar base, this may translate to a quasi-military style routine at first, with clear roles and hierarchy during critical operations. The risk of authoritarian dynamics has been noted: without external oversight or escape options, a Mars settlement's leadership could, even unwittingly, slide into tyrannical oversight in the name of safety. To counter this, crew training might include shared decision-making exercises and conflict resolution mechanisms.

An additional human factor is planetary protection ethics, if the base is near Martian water ice, there could be concern about contaminating a potential niche for Martian life. International guidelines currently designate "special regions" (areas likely to have liquid water) as off-limits

[64] e.g. like airlock operations and EVA timing

to crude contamination. A polar-subsurface base would have to implement stringent biosecurity protocols to avoid forward contamination of the ice for instance, by treating waste and avoiding release of Earth microbes.

The polar-subsurface model offers outstanding feasibility for long-term habitability by leveraging Mars' natural shelters and resources. It maximizes radiation safety and resource independence at the cost of geographic isolation, power complexity, and psychological challenges due to darkness and confinement. Early studies conclude that an initial permanent Mars settlement could indeed be made possible by such an architecture, as it "realize the benefits of cave habitats while reducing risks to crewmembers". This model may well represent the "living off the land" approach for Mars: hiding in Mars' underground near the coveted polar ice, humankind's first off-world settlers could survive and eventually thrive shielded from the Red Planet's harsh surface environment.

3.2.2 Equatorial-Surface Model

Concept and rationale:

The equatorial-surface model takes a nearly approach: establish the Mars settlement in a relatively low-latitude, open surface environment, typically on a flat plain or crater near the Martian equator. This concept builds on the fact that most Mars missions to date have targeted equatorial regions because of milder conditions and easier access. An equatorial site offers more moderate temperatures and day/night cycles than the poles, as well as maximum exposure to sunlight for solar energy. Unlike the polar night, equatorial locations have roughly 12 hours of daylight throughout the year[65]. This abundance of sunlight is a key rationale: a surface base can power itself partly with photovoltaic arrays, which is attractive for initial missions trying to minimize nuclear fuel. Furthermore, equatorial regions avoid the CO_2 frost and extreme cold that grip the poles in winter. Daytime summer temperatures at the Martian equator can climb above 0 °C, a great contrast to the frigid −120 °C or lower typical of polar nights. Although nights are still cold, −70 °C or below, and the atmosphere is thin, the thermal environment is less extreme overall, easing engineering constraints on habitats and machinery. The equatorial model is also favored for logistical reasons: launching and landing trajectories from Earth naturally favor lower latitudes on Mars. It takes less energy to reach an equatorial orbit and

[65] Mars' axial tilt is similar to Earth's, there are seasons but a site near 0° latitude will always get near 12-hour days.

land near the equator than to perform large plane changes to reach high latitudes. In practice, this means heavier payloads can be delivered to an equatorial base. Additionally, an equatorial settlement can maintain continuous communication with Earth using standard direct-link or orbital relay strategies, without the need for special polar relays, except for periodic solar conjunction phases. These practical advantages underlie NASA's historical Design Reference Missions, which often assume an outpost in the Mars midlatitude or tropical zone.

The surface aspect of this model implies that habitats and infrastructure are constructed on the ground under the Martian sky, rather than deeply buried. Early Mars base proposals, from the 1980s NASA Mars Reference Mission to more recent concepts like Mars One and SpaceX's envisioned Mars City, commonly depict a cluster of pressurized modules landed on a flat surface, connected by tunnels or corridors, and covered with some regolith berms or shields for radiation protection. The rationale here is one of initial simplicity and direct exploration: building on the surface allows the crew to immediately access the surroundings for scientific work and to use the terrain for construction. There is also a psychological rationale, humans in fact are evolutionarily adapted to open skies and natural daylight. Living on the surface could provide natural light through windows or translucent habitat materials, which might improve crew well-being compared to a completely subterranean life. Indeed, astronauts have often commented on the morale boost of seeing Earth or stars from a spacecraft; on Mars, viewing the alien but real landscape through a window or camera feed could be similarly valuable. Another reason to choose an equatorial surface site is science yield. Many of Mars's most intriguing geological and potentially biotic sites as ancient lakebeds, clay-rich outcrops, volcanic terrains, are in lower latitudes. A base in these regions doubles as a science station enabling extensive field exploration. Synthetically the equatorial–surface model is driven by the idea of a straightforward outpost in a friendlier part of Mars, leveraging solar power and direct engagement with the Martian surface environment.

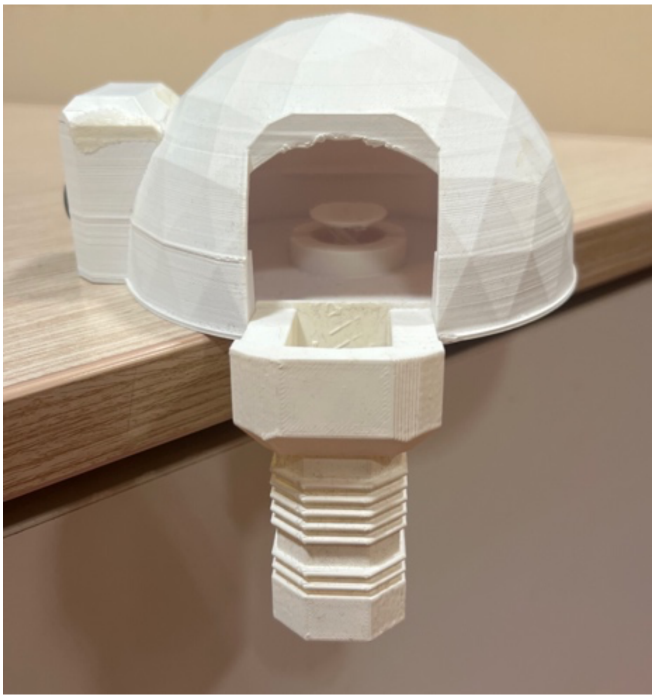
Technical feasibility and design:

Although "on the surface" sounds simple, a Mars equatorial base requires ingenious engineering to cope with the dangers of radiation, thin air, and dust. Without the natural cave roof of the subsurface model, a surface habitat must bring its own shielding or utilize local materials for protection. Radiation from cosmic rays and solar storms is a grave concern, over the recommended annual limit for astronauts. Any long-duration habitat must reduce that exposure. One common solution is to bury the habitat modules under regolith. Studies indicate that about 2–3 meters of Martian soil are needed to significantly attenuate cosmic rays to safe levels. The equatorial-surface model therefore often includes robotic excavators or 3D printers that, upon landing, immediately start piling regolith on top of the habitat. In one design, bags of unprocessed regolith are stacked around an inflatable dome to provide additional shielding. Another advanced concept from NASA proposes using a robotic system like the multi-legged ATHLETE rover with a freeform additive construction tool to sinter or bind Martian regolith into a solid "shell" over an inflatable habitat, essentially printing a radiation shield in situ. This shell, possibly made of a Martian concrete could protect the crew from both radiation and micrometeorites. The habitat structures themselves would likely be multi-layered inflatables or prefabricated units with integral radiation protection. For instance, lightweight polymer materials are much more effective at blocking galactic cosmic rays than aluminum; a 15 cm polyethylene layer can cut radiation in half. Designers take advantage of this by incorporating hydrogen-rich materials in the habitat hull and positioning consumables (water and food) around living areas for extra shielding (Arnhof, 2016).

Beyond radiation, the low atmospheric pressure on Mars means habitats must be strong pressure vessels. Most surface base concepts use cylindrical or spherical modules, like those of the International Space Station but modified for Mars gravity, or deployable inflatables that attain a habitable volume once pressurized. These would be landed via entry, descent, and landing systems at the chosen site. NASA's reference architecture, for example, pre-deploys a habitat and return vehicle on Mars before crew departure; the crew then lands nearby and moves into the ready habitat. Site layout is an important technical consideration. To mitigate the risk of a catastrophic accident, the landing zone for crew and cargo vehicles should be kept at a safe distance from the main habitat. Analyses of Mars mission risks have concluded that having the ascent/landing vehicle too close poses an "unnecessary safety risk to the entire outpost", since a crash or explosion could wipe out the base (Cohen, 2015). A design study called Strategies for Mars recommended placing the primary landing zone at least 5 km from the habitat site, with rovers used to ferry the crew. Locating a Mars base involves trade-offs: it should be far from landing risk, but not so far as to make transport inefficient (5–10 km is a typical compromise). The site should also be flat and smooth to ensure safe landings and to ease construction of the habitat and solar arrays.

Power infrastructure for an equatorial-surface base could initially rely on solar energy with storage, but given Mars' limitations, likely augmented by nuclear power. Mars receives about

50% of the solar irradiance that Earth does due to its greater distance from the Sun, and frequent dust storms can further reduce sunlight by obscuring the sky. This means solar panels on Mars produce significantly less power than the same area on Earth, and energy must be stored for the cold nights. A possible approach is a hybrid: solar panels provide power during the day for secondary systems or to charge batteries, while a small nuclear reactor runs at night and as an energy backup. Energy is needed not only for life support and habitat heating, but also for ISRU processes if utilized. Life support systems for a surface base would leverage experience from ISS but must be more autonomous and efficient. The habitat would include a closed-loop or semi-closed Environmental Control and Life Support System (ECLSS) to recycle air and water. Given the distance from Earth, spares and maintenance are a worry, reliability is crucial, and designers try to use as much redundancy and simplicity as possible to avoid frequent part replacements (Metzger, 2015). For food, early crews will bring the majority of their rations, but surface bases typically also include a greenhouse or plant growth unit to supplement diet and regenerate air. In fact, providing a greenhouse has engineering and psychological upsides. Plants can recycle CO_2 into oxygen and help with humidity control, but they also offer fresh produce and a morale boost. The Mars Surface Habitat concept by Arnhof (2016) assumed a greenhouse would supply roughly half of the crew's food needs, requiring on the order of 130 m^2 of crop area for a crew of five.



(Fig. 9: This photograph was taken during Professor Alfonso Giordano's course Exogeography: Astropolitics and Space Economy at LUISS University (Guest Lecture by Samanta Snidaro & Andrea Fino, SAND & BIRCH STUDIO, October 29, 2025). The image depicts a physical model by SAND & BIRCH STUDIO, representing the equatorial-surface module: a dome-shaped habitat positioned directly on the surface.)

Social structure and governance:

Living in an equatorial-surface settlement would, in many ways, resemble life on a remote research outpost, think of Antarctic bases or the International Space Station, but on a dusty red desert. The crew's daily life would be defined by EVA (spacewalk) planning, habitat maintenance, and scientific exploration of the surrounding terrain. Mars' natural environment would be more immediately present to them than for a subsurface crew.This connection to the diurnal cycle and the outside world may improve psychological well-being. However, stepping outside is still an event that requires a spacesuit and careful timing.

Socially, a small equatorial base with an initial crew of 4-6 individuals would function like a tight unit, but as the base grows with successive missions, it could evolve into a more complex community. The equatorial model naturally lends itself to incremental expansion: each new mission can land additional habitat modules and attach them, forming a larger base over time (Cohen, 2015). As this concentrated base expands, it begins to require organizational structure: allocation of work roles, maintenance of common facilities, and local governance. Early crews likely operate under their launching nation or agency's authority. Yet as the settlement becomes semi-permanent, questions arise: how are disputes resolved? What laws apply for international crews? How are resources owned or shared? These are not solved yet, and experts argue that we need to pay more attention to these issues before human settlement.

One immediate social consideration is crew health and morale. The surface base crew will face isolation. The knowledge that they can step outside and directly interact with the Martian landscape can be empowering. This can provide a strong sense of purpose and motivation, which is crucial for long-duration missions. At the same time, confinement in a small module for long periods, especially during dust storms can strain interpersonal relations. Crowding and privacy issues will inevitably emerge as the habitat fills up. Studies of crews in analog missions suggest that even with as few as a dozen people, subgroups can form and conflicts may arise, especially when resources are scarce (International Space University, 2009). Mission planners are aware of these risks; thus, the habitat design usually allocates personal quarters for each person and some communal areas that can be scheduled or used in shifts to give crew members a break from each other. Having meaningful work as science, maintenance and construction is also a solution against social friction. Rotation of duties and regular communication with Earth can help keep mentally stimulated and feeling supported by Mission Control and loved ones.

The equatorial–surface model offers a pragmatic and initially simpler path to establishing a foothold on Mars. It takes advantage of regions with better solar energy and easier access, and it aligns with how we have conducted Mars exploration so far. Technically, it demands innovative use of local materials for shielding and robust systems to handle Mars' dust and radiation. Socially, it allows crews to be pioneers in direct contact with Mars' environment, which can be both inspiring and stressful. Over time, an equatorial base could grow into the first true Mars settlement if it proves to be sustainable.

3.2.3 Concentrated vs. Distributed Urban Models

As a Mars settlement progresses beyond the initial outpost stage, a crucial question arises: Should humanity concentrate its presence in one prime location or spread out across multiple sites on Mars? This section examines the two visions of Martian urban development:

1) A concentrated model, where a single, central city or base grows and densifies;

2) A distributed model, where multiple smaller settlements are established in different locations and form a network.

These are not mutually exclusive strategies, but they represent distinct planning philosophies with different technical and social implications. For clarity, we discuss each model independently in terms of its rationale and characteristics and then consider the trade-offs between them.

1) **Concentrated Settlement Model: The single Mars City**

Concept and rationale:

The concentrated model envisions a primary Mars settlement that serves as the main hub of human activity. Essentially, a Martian city that grows by accretion.

In the early years, this might simply be the initial base expanded with additional habitat modules, laboratories, greenhouses, and other infrastructure all in one contiguous complex.

Over decades, it could develop into a sizable town with hundreds or thousands of inhabitants in interconnected living quarters. The rationale for concentrating settlement in one location is grounded in efficiency and critical mass. By focusing resources on a single site, settlers can build up extensive infrastructure like power plants, life support systems and fabrication facilities that will benefit from economies of scale. A single growing colony also allows specialization among the population, and a self-sufficient social ecosystem can emerge. In a small, scattered outpost, every person must cover many roles; in a larger community, roles can differentiate, which is how sustainable societies form. Logistics and supply are simpler in a concentrated model as well, rockets from Earth have one destination to land, and internal distribution of goods on Mars is confined to a local area. This reduces the overhead of moving materials between distant outposts. Historical analogs can be found in the way early settlements on Earth often clustered around a single harbor or oasis initially, to pool resources before spreading inward.

Technical feasibility and design:

From a technical perspective, a concentrated Mars city can become a showcase of advanced engineering. All vital systems can be co-located and integrated: for example, a large life-support facility recycling water and air for the whole settlement, large agricultural domes or hydroponic farms supplying food, centralized warehouses for spare parts, and perhaps a single spaceport or launch pad serving all transport needs. The concentrated model would also benefit from continuous improvement of one site: each mission can bring upgrades and expand capacity at that site (e.g. more solar panels, more habitats, improved radiation shielding over time, etc.), bringing the colony closer to Earth-like livability. An example of this incremental growth is seen in scenario studies where successive launch windows deliver extra habitat modules and redundant systems to the same base. By the third or fourth delivery, the base might have multiple habitation units clustered together and additional return vehicles for safety (Cohen, 2015).

Governance and social structure:

Some scholars argue that sustaining freedom in a Mars settlement will require actively encouraging democratic norms and transparency from the start, to counteract the inherently controlling environment (Cockell, 2009). Socially, a concentrated Mars settlement could eventually offer a richer life experience than tiny, isolated outposts. With more people comes more potential for friendship, cultural activities, and even family life. A study discusses the need for industrial development and local resource use to fulfill the basic needs of a colony of hundreds, implying that such a colony would be well on its way to supporting not just survival, but a semblance of normal living (Salotti et al., 2015). One major disaster at the site: a large meteoroid impact, a massive habitat fire, or a serious epidemic could threaten the entire population. Risk analyses acknowledge this, which is why redundancy and emergency strategies are layered into design. For instance, NASA's Mars Design Reference Architecture (DRA) incorporated an Abort to Surface scenario: if the orbital return vehicle failed, the crew might have to remain on Mars for an extra mission cycle, meaning the surface base needed backup systems to support a double duration stay. This kind of robust design is even more critical when the surface base is the only settlement, it must be prepared to be self-sustaining and to recover from failures because there is nowhere else to go. Some have suggested that a large Mars settlement should eventually construct hardened "safe havens" like underground bunkers or a heavily shielded module where the population could huddle in case of a major solar storm or habitat leak (Arnhof, 2016).

Therefore, the concentrated settlement model aims for a thriving central colony that can develop into a self-sufficient Martian city. Its strengths lie in unified development, a growing and diverse community, and efficient use of resources. It embodies the classic science-fiction image of a Mars city under domes. Its weaknesses are the vulnerability of centralization and the sociopolitical pitfalls of a single isolated society. If executed thoughtfully, a concentrated Mars settlement could be humanity's beachhead that eventually enables expansion across Mars, it's the seed from which a civilization might sprout.

2) Distributed Settlement Model

Concept and rationale:

In contrast with the single city model, the distributed model proposes that humans on Mars establish multiple smaller settlements in different locations, connected through transportation and communication networks but largely independent in their immediate operations. Instead of one Martian city, there might be a network of villages or outposts. The rationale for distribution is primarily risk mitigation and resource optimization; by not putting all human assets in one place, the species increases its odds of survival. This concept mirrors how early exploration on Earth often led to a string of outposts: multiple bases in Antarctica today, each belonging to or focusing on different groups and research. Mars is a vast planet with varied terrain and resource locales; a distributed approach seeks to "cover more ground" and exploit that diversity.

Technical feasibility and design:

Implementing a distributed model is demanding. Each settlement must have a minimum level of infrastructure to support life, essentially duplicating life support, power, habitation, and landing facilities at each site. This initially seems inefficient compared to a single base. However, as the scale of Mars activity grows, having multiple hubs can reduce some logistics costs: for example, if propellant is being made at the pole, a crew launching from an equatorial base might detour to the polar station to refuel instead of bringing all fuel from Earth (Arnhof, 2016). The ISU "Mars Cave" study, for example, proposed setting up remote power generation along the route to a cave site, so that electric rovers could recharge on long journeys into the subsurface. This idea of distributed support units illustrates a benefit: secondary outposts can extend the range and capabilities of astronauts beyond what a single base could do.

The distributed model's feasibility improves as technology advances. If we have robust autonomous construction robots, we could send them to multiple locations simultaneously to build habitats before crews arrive. Each outpost could start as a largely robotic mining or science station that humans visit or rotate through and later become permanently inhabited as capacity grows. Communications infrastructure would be crucial, a Mars-wide communications network implemented through orbiters, GPS-like satellites and surface relays would need to be in place so that distant outposts stay connected (International Space University, 2009). The ISU report notes the idea of an ad hoc surface network linking all exploration units. This implies that as soon as multiple locations are occupied, Mars might deploy its own telecommunications system, effectively an internet of Mars, to coordinate activities. Transportation is another backbone: in a distributed scenario, travel could be by pressurized rover caravans for regional distances or by rocket hops for longer distances possibly using reusable rockets taking off from one base and landing at another.

Governance and social structure:

A distributed collection of settlements would likely start with each outpost having a small crew not unlike the size of current Antarctic winter-over analog teams. Each outpost could be sponsored or operated by different countries or organizations, especially if the motivations differ one might be a commercial mining camp, another a governmental research base, another a private venture. This introduces questions of coordination and governance across distances. On Mars, given the difficulty of travel and communication delays, it is plausible that outposts will operate autonomously day-to-day, cooperating by mutual agreements rather than by any imposed government in the initial years. They would, of course, share information and possibly aid each other in emergencies. If one base has a medical doctor and another base's crew suffers an injury, a rescue mission might be mounted if distance permits. The ethics of mutual aid and inter-settlement relationships will be a novel frontier. For the individuals living in small outposts, social life is extremely intimate and isolated, again. Agencies might mitigate this by rotating crews between settlements: after a year at a polar station, a person might transfer to the main equatorial base for a break or a larger community experience, similar to how researchers rotate between isolated field camps and main stations in Antarctica. Such rotations would be complex on Mars due to travel, but as the network matures it might be feasible periodically.

The distributed settlement model paints a picture of Mars inhabited by multiple pockets of humanity, each optimized for its locale and specialty, collectively covering more of the planet's opportunities and guarding against a single point of failure. It aligns with a long-term vision of Mars not as one city but as a world with towns and stations spread out; perhaps the seed of a future Mars-wide civilization. Its success relies heavily on robust transport and communication to link the outposts, and on a spirit of cooperation to ensure that they help rather than hinder one another's survival. While initially more complex to set up than a single base, a distributed approach could prove more resilient in the face of catastrophe and more scalable as humanity's ambitions on Mars grow. In practice, we may see a hybrid: starting with a concentrated base and then expanding to a distributed network once the first settlement is secure. That way, Mars exploration can benefit from both the focus of a central hub and the breadth of multiple footholds.

3.2.4 Resource-Driven Settlement Model

Concept and rationale:

Underlying all the above settlement strategies is the fundamental challenge of supply: how to provide the consumables, materials, and energy that a Mars colony needs. The resource-driven settlement model takes this challenge as the primary organizing principle, positing that the locations, design, and evolution of Martian settlements will or should be determined chiefly by the availability of resources and the ability to utilize them in situ. In essence, this model asserts that "resources rule", wherever Mars offers accessible water, minerals, or other vital commodities will become the focal points of settlement, and the technologies to extract and use those resources will shape the colony's character.

The rationale for a resource-driven approach is compelling. Mars is far too distant to indefinitely supply a growing colony from Earth; the cost in fuel and time to send large quantities of food, water, building materials, or propellant is prohibitive. If a settlement is to become lasting and self-sufficient, it must gradually wean itself off Earth resupply by tapping Mars' own store of raw materials. In the near term, doing so also dramatically lowers mission costs. A resource-driven model would elevate such experiments to full-scale production facilities forming the backbone of the settlement.

The primary resources of interest for human settlement include:

- **Water**: found as ice or hydrated minerals.
- **Gases**: CO_2 from the atmosphere for making oxygen or fuels, nitrogen for buffering breathable air, argon for industrial use.
- **Regolith and Minerals**: which contain silicon, iron, aluminum, magnesium, etc., useful for construction and manufacturing;
- **Sunlight/Energy**: an environmental resource to harness.

Mars also has traces of other elements like sulfur, phosphorus, chlorine in perchlorates that can be useful for agriculture or industry if processed. The resource-driven approach dictates that settlements will be sited where these resources are richest or easiest to obtain. For instance, a water-driven settlement might be set up beside a known ice deposit in mid-latitude ground or at the edge of a polar ice cap. A mineral-driven settlement might focus on a region like Valles Marineris, where layered sedimentary deposits could yield sulfates and clays for extraction of water and metals, or ancient hydrothermal regions.

Technical feasibility and design:

The technical heart of a resource-driven model is the suite of ISRU hardware that turns raw Martian material into useful products. Water extraction is pivotal. If the base is near visible ice, engineers might simply mine the ice: heat it or crush it and sublimate it, then condense the water vapor. If water is in hydrated minerals, it may require heating many tons of soil to release a small fraction of water. Either way, energy is a limiting factor this is why a resource-driven model tightly couples with the energy infrastructure. For construction, Mars offers basically two materials in abundance: regolith and rock. These can be used to make bricks, concrete, or radiation shielding as discussed earlier. A resource-focused strategy would see the base quickly deploy regolith-moving equipment, essentially treating the soil as both a hazard and a material to be processed. Concepts for Martian concrete involve mixing regolith with polymers or using sulfur from Martian soil as a binding agent (Arnhof, 2016).

This vision aligns with researchers' term "building toward self-sufficiency" (Johnson et al., 2013). The immediate goal is to reduce reliance on Earth for essentials, and the longer goal is to enable not only sustainability but eventually commercial viability: the ability to export something of value or to support a larger economy on Mars.

Social and economic dimensions:

Focusing on resources will also shape the culture and economy of the Mars settlement. In early phases, the outpost might feel like a frontier mining town or an oil rig, the crew are not just scientists and explorers, but effectively pioneers and workers running extraction equipment day in and day out. Over time, as basic needs become secured via ISRU, the economic model of the settlement might evolve. If the settlement can produce more than it needs (e.g. a surplus of fuel or oxygen), it might trade these with incoming missions for other goods, effectively becoming a supply deposit. The Outer Space Treaty allows resource use but prohibits national appropriation of territory, which creates a gray area for property rights: if a company mines Mars water, do they own that water? Recent dialogues as the Artemis Accords lean toward treating space resources as harvestable with prior notice, but the law is still evolving.

The resource-driven model thus feeds into the narrative of Martian self-sufficiency and even independence. When a colony can produce most of what it needs its reliance on Earth diminishes and it gains political weight. Future debates about Mars governance may hinge on this: a largely self-sufficient Mars settlement might seek greater autonomy. In conclusion, the resource-driven settlement model is about harnessing Mars to the fullest so that humanity can truly settle rather than just camp there. It underpins the feasibility of all other models: whether at the pole or equator, concentrated or distributed, a settlement that uses local resources will outperform one that depends wholly on Earth. If the polar-subsurface and equatorial-surface models are two different starting points, and the concentrated vs distributed models are possible layouts of Martian society, the resource-driven model is the strategy that will ultimately allow any of those settlements to flourish. The words of one ISRU project summary resonate here: "by harnessing space resources, explorers would not have to bring everything from Earth… thereby either reducing the total mass launched or increasing what can be accomplished" (Sanders & Larson, 2012).

Each of the four models: polar-subsurface, equatorial–-surface, concentrated urban, and distributed outposts, driven throughout by resource utilization offers a distinct lens on the path to living on Mars. The polar-subsurface model prioritizes safety and resource access at the cost of isolation and darkness, potentially serving as a secure beachhead. The equatorial-surface model emphasizes operational ease and early mission optimization, placing humans in a relatively benign environment to explore and gradually build up, though it requires clever engineering to manage radiation and dust. The concentrated model imagines a single growing Mars city, leveraging human community and economies of scale, whereas the distributed model envisions resilience and comprehensive exploration through multiple settlements. Finally, the resource-driven model underlies all approaches by ensuring that whichever path we take, we move steadily toward independence from Earth by utilizing Martian materials. In practice, a real Mars settlement strategy will likely blend these models: for example, an initial equatorial surface outpost that evolves into a concentrated base, which then spawns distributed resource camps as it incorporates more ISRU: an approach hinted at in various NASA strategic plans (Sanders & Larson, 2012).

Ultimately, the success of human settlement on Mars will hinge not on rigidly following one model, but on remaining flexible and adaptive, much like the pioneers of Earth had to do. Mars will throw challenges: dust storms, geological surprises and equipment failures, and settlers may find themselves switching strategies. The models serve as guideposts to inform those decisions. They remind us why we choose a polar crater versus an equatorial plain, or why we send one big habitat versus several small ones and what trade-offs come with each choice.

3.3 Demographic scenarios and population growth on Mars

Mars'surface has been for long time an interst among researchers, writers, dreamers, and entrepreneurs[66]. Today, human settlement that, once were purely science fiction is now expected as a real objective, thanks to the discovery of its potential for habitability, of elements necessary for survival such as numerous recoverable materials, and of the possibility of expanding humanity beyond Earth. These possibilities are primarily due to the combined efforts of both government agencies, such as NASA and the European Space Agency, along with private actors, mainly in the United States with SpaceX, Lockheed Martin, and Blue Origin, who plan to be prepared to send humans to Mars by 2032. Likewise, countries beyond the Western world, China and the United Arab Emirates, have also expressed their desire to establish an outpost on Mars. Therefore, as the prospect of establishing a sustainable Martian community is becoming increasingly urgent, so too is the need for strategic planning for the development of a Martian society. While research related to the engineering and scientific requirements of developing human habitats on Mars exists, there is also an increasing need relative to how a Martian society will economically and politically organize itself. Technical and biological factors are critical in ensuring survival in such extreme environment, but it is also important, for a sustainable settlement the quality of social organization, governance, resource allocation and the ability of the settlement to anticipate and control both internal and external conflicts.

Studies conducted regarding the application of human factors to Martian settlements have demonstrated that significant events such as natural disaster, pandemic and, or disruptions to trade with Earth do not result in purely technical outcomes, but rather create potentially devastating indirect social and economic consequences for the settlements' social structures, institutions and overall population cohesion (Salotti et al. 2015). In particular, it demonstrates that many risks are existential not necessarily due to their immediate severity, but due to their potential to create escalating effects within the social and organizational structure of the settlement and ultimately the capacity for coordinated action.

Thus, the survival, but also development of a human community in an exogeographical context depends crucially on its socio-political organization (Giordano, 2025).

[66] Smith, T. L. (2025). Martian diversity: A government for pluralistic communities on Mars. *Space Policy*, 101687.

Firsly, a crucial inital dependance from Earth is reffered to food. The production on Mars of the latter is typically envisioned as limited to supporting supplies for small crews for short or medium terms. However, Cannon and Britt's 2019 study proposes a far more expansive objective: producing sufficient food on Mars to sustain a civilian colony of approximately one million people permanently in 100 years. The model assumes growth due to both immigration and birth, estimates per-capita caloric requirements, and simulates land use based on a diet consisting of staple food crops, insect-based products, and cellular agriculture (cultivated lab-based meats and derivatives). Therefore, according to their study, achieving food self-sufficiency should be feasible on Mars in about a century provided that reasonable inputs are used; however, prior to this time, massive amounts of food will need to be imported from Earth.

Another factor, and not the only, that may ensure the Mars' community independence and long-term stability is reproduction. In this phase, it is important to stress the differences between endurance and regeneration notions. So, endurance represents the ability of a settlement to continue to function under stress. On the other hand, regeneration refers to the ability to reproduce which will help the community in adapting to environmental changes both man-made and naturally occurring through generations. Therefore, if the species wants to remain for centuries to come, reproduction will allow to adapt to the new uncertainties that may occur while living on Mars. A community on Mars that is reproducing at a high enough rate will be less dependent on immigration from Earth to keep the population at a sustainable level.

3.3.1 How much population is needed? Demographic thresholds between survival and settlement

The assessment of human settlement on Mars does not stop at simply identifying the critical human factors for survival in an extreme environment. To achieve a sustainable human settlement on Mars it is needed both the overcoming of physical constraints but also establishing a demographic base that will insure the long-term autonomous operation of the settlement and socio-technical continuity. Demographic adaptation will therefore play a strategic role and ultimately will be a determining factor in establishing a transition from a survival mode to a regenerative mode, in which the settlement has the capability to self-reproduce over time socially, biologically, and institutionally. As the feasibility of continuous resupply of the settlement from Earth becomes increasingly impractical due to cost, distance and the logistical vulnerabilities associated with it, demographic growth will become a structural necessity and no longer a secondary outcome.

A demographic simulation model[67] was developed to assess the length of time it would take for a Martian settlement to reach a minimum population level that could independently support industrial activity (Salotti et. Al, 2011). The model assumes that after the initial settlers arrive on Mars there will be little to no immigration from Earth, and that the population will grow primarily through demographic processes based on births and deaths.

Initial settlement and demographic constraints:

Through the adoption of this mathematical model, the study[68], evaluates an initial population of approximately 110 settlers, which was chosen as a suitable number of people for a first permanent mission to guarantee the survival of a Martian colony, given a particular organization and lifestyle. It also identifies different categories of the functional population groups: active workers who maintain life support systems and operate industry; children who contribute to the demographics of the settlement but require investments over long periods of time; assistants who perform educational and caregiving functions; and the elderly who require community support. These groups must be in balance for the settlement to remain viable. For example, if the number of children or elderly grows too large then too many of the adult population will be engaged in assisting the children or elderly and there will be fewer adults available to work in vital areas. This type of imbalance can very rapidly undermine the survival of the colony by weakening its ability to support life sustaining functions and crucial services. For this reason, the model includes clear support requirements to address this problem; because younger children need more caregivers than older ones, a growing population may put more strain on caregivers, which could reduce the colony's ability to be proactive, until the younger children themselves take the caregivers' place. Therefore, one of the parameters of the model is the proportion of adults who can be assigned to assistive roles, relative to the adult population overall; this is a structural constraint that restricts the rate of population growth before the system becomes unstable.

---

[67] Salotti, J. M., Da Fonseca, T., Lainé, A., & Moisset, C. (2011, October). Impact of human factors on the growing rate of a martian population. In *Impact of Human Factors on the Growing Rate of a Martian Population* (pp. 1-5)
[68] Ibidem

Births are not exclusevely based on biological factors, but fertility is influenced by both biological and cultural constraints, as well as the availability of resources in this context. Biological factors include the percentage of the population that is infertile, as well as the minimum and maximum reproductive ages. The average number of children desired based on social norms and the cultural resistance to higher fertility are the two parameters used to model cultural factors. Therefore, this mechanism illustrates how reproduction, which appears to be an individual decision, becomes a collective, system-wide decision in a closed and resource-constrained environment. Consequently, for a birth to occur, the couple must be biologically fertile, the culture must permit or promote more children, and the colony must have enough adults to offer assistance without going over the assistance threshold. The simulation results indicate that sustainable growth is only possible within a narrow range of fertility levels; on one hand, if fertility is too low, the population will gradually decline toward extinction, on the other hand, if fertility is too high, the number of children will grow faster than the colony's ability to provide education and support for the children, resulting in a shortage of active workers. The most stable outcomes will occur when women have an average of four to five children and the policies implemented to support families also preserve a sufficient number of active workers. When women have four to five children on average and policies that support families maintain a sufficient number of active workers, the most stable results will be achieved. However, the study also takes into account the dynamics of aging and death; this adds another long-term constraint because deaths happen randomly around an average lifespan and people who are getting older require assistance. There will be fewer active workers available if life expectancy rises without a corresponding increase in productive capacity because the colony will have to shoulder more of the burden of caring for the elderly. Longer lifespans are sometimes seen as desirable, but in small, isolated communities, they can cause structural issues because they increase dependency beyond what the settlement can generate, endangering the colony's ability to survive. Therefore, a colony's long-term viability depends on both the number of new arrivals and the population's age distribution over time.

Autonomy threshold:

The primary goal of the simulation is to determine the population threshold required for the colony to achieve autonomy. The study defines this threshold as approximately 50,000 people, a population at which the colony can sustain necessary industries, specialized labor, and institutional complexities without continuous support from Earth. Simulation runs terminate either when the colony reaches the autonomy threshold or after 1,000 years; but, under favorable conditions (e.g., low cultural resistance to having children, moderate assistance burden, etc.), the colony can attain the goal number in less than 300 years with an average fertility rate of approximately 4.6 children per woman. Instead, under less favorable conditions (e.g., strong cultural resistance to having children, low fertility rates, etc.), population growth is slowed or reversed, and the colony fails to reach the autonomy threshold and potentially collapses. It is also noted that, despite having the same parameters, outcomes can vary significantly due to random events and initial population composition, which illustrate the inherent uncertainty in the long-term demographic evolution of a Martian colony.

Results:

The demographic simulations show how human factors have a significant impact on the growth of a Martian colony. A low number of children per woman and significant cultural restrictions on family size will lead to either long-term population decline or slow population growth, and when the percentage of the population that is fertile decreases, population growth will be difficult to maintain. Furthermore, the results of the simulations highlight the importance of resource utilization by humans. An excessive number of children or elderly individuals increases the need for assistance, reduces the number of active workers available for productive functions, and when the need for assistance exceeds a critical threshold, population growth slows or the colony is unable to reach the autonomy threshold. Lastly, the study emphasizes that these results should not be interpreted as predictions but rather as the outcomes of a simple model that was designed to illustrate the effect of fertility, cultural factors, and the constraints placed on assistance in determining long-term demographic evolution.

3.3.2 Long-Term Maintenance of a Martian Population

Although the preceding sections have examined the number of individuals required to transition from a mere existence to an autonomous state of living on Mars, maintaining a stable population over the long term, will require a different analytical tool. The ability to maintain a stable population on Mars is not merely dependent upon the growth rate of the population, but the inter-relationship between the birthrate of individuals on Mars, social organization, political institutions, technology and scale effects.

There is not a single demographic solution, but several models[69] exist that emphasize the unique mechanisms by which a Martian settlement may sustain itself over time. Therefore, these models should be viewed as not predictive, but rather as analytical frameworks that are applicable at different levels, timescales and objectives of the settlement.

Political-institutional continuity and governance stability:

A degree of continuity that pertains to political-institutional stability over time is highlighted in Jacob Haqq-Misra's analysis of the difficulties associated with maintaining a human settlement on Mars[70]. The study evaluates the effects of sovereignty regimes, governance structures, and ethical commitments on the long-term viability of extraterrestrial settlements

At the core of Haqq-Misra's argument is an empirical assessment of the current international legal regime for outer space: “The Outer Space Treaty” of 1967 specifically prohibits the national appropriation of celestial bodies, thus precluding the use of traditional forms of territorial sovereignty on Mars. So, it is discussed that the combination of the prohibition against national appropriation of celestial bodies, and the competing national interests, make the formation of a centralized planetary authority both politically unfeasible and normatively undesirable (Smith, 2025; Szocik et al., 2020). Therefore, the political-institutional continuity on Mars cannot rely on Earth-based sovereignty models. To fill this void, there is the proposal of the establishment of a “Martian Secretariat”[71], an administrative coordinating body intended to harmonize national space policy, resolve conflicts and facilitate cooperation among the various stakeholders involved in the Martian settlement. The Secretariat would not be the sole authority on Martian territory or its inhabitants, but would coordinate among stakeholders through consent-based mechanisms to promote political pluralism and avoid the potential for fragmentation and conflict (Szocik et al., 2020). From a demographic perspective, long-term demographic stability is directly impacted by the governance model presented by Haqq-Misra. Access to essential resources, including pressurized habitats, oxygen production systems, and energy supplies, may be restricted by unregulated competition among settlements, unrestrained territorial expansion, or monopolization of vital infrastructure. Therefore, the study asserts that

[69] Szocik, K., Wójtowicz, T., & Braddock, M. (2020). The Martian: Possible scenarios for a future human society on Mars. *Space Policy*, *54*, 101388.
[70] Haqq-Misra, J. (2025). A model for economic freedom on Mars. *Space Policy*, *71*, 101652.
[71] Proposed by Bruhns and Haqq-Misra, cited in Szocik, K., Wójtowicz, T., & Braddock, M. (2020). The Martian: Possible scenarios for a future human society on Mars. *Space Policy*, *54*, 101388.

political institutions must proactively regulate expansion to avoid the risk of system collapse and social inequality, linking governance stability to regulated demographic growth.

The ethical notion of "deep altruism" is a noteworthy aspect of the research. It is predicated on the idea that the original generation of investors and settlers will come to terms with the possibility that they will never personally profit from their contributions, rather than on a desire for financial gain; rather, their efforts are focused on the welfare of future generations, who will inherit the institutional, social, and economic foundations built during the early phases of the settlement (Szocik et al., 2020). It is an important ethical concept because it is presented as a prerequisite for political continuity in an environment where short-term self-interest could prevail in decision making. Indeed, economic sustainability plays a critical role within this governance logic. The study emphasizes that a strong local economy that can sustain the population without assistance from Earth is necessary for political autonomy, and that a settlement's continued reliance on Earth-based supply chains would make it more susceptible to outside influences and compromise its capacity for self-governance. In other words, there is a connection between economic sustainability and governance continuity.

In relation to how can population growth be managed, political-institutional continuity emerges not as a result of demographic success, but as an independent and necessary condition for sustainable human presence on Mars. Without governance mechanisms that enable management of expansion, resolution of conflicts and enforcement of intergenerational responsibility, demographic growth alone risks replicating the inequalities and instabilities experienced on Earth in an even more fragile Martian extraterrestrial context (Szocik et al., 2020).

Establishing humanity as a multiplanetary species

Elon Musk's model[72] aims to build a self-sustaining Martian city that is not merely an industrial or scientific hub, but rather one that can sustain itself over time without structural reliance on Earth. In order to lower the likelihood of catastrophic events on Earth and guarantee the long-term survival of the human species, with the ultimate goal to establish humanity as a multi-planetary species. From a demographic point of view, it presents a an approach that is very different from the minimum-threshold approaches used previously by (Salotti et al., 2011). The

[72] Musk, E. (2018). Making Life Multi-Planetary. New Space, Vol. 6, N. 1, pp. 2–11.

condition for a Martian society to become genuinely autonomous is not the attainment of a minimal demographic equilibrium, but rather the surpassing of a civilization-level threshold estimated at around one million inhabitants. At this scale, the settlement would be able to sustain a complex division of labor, autonomous institutional structures, and a diversified economy, thus decreasing the vulnerability to demographic and, or productive shocks (Szocik et al., 2020). In order to reach the needed population size, the study outlined a logistics strategy for a massive migration from Earth to Mars, and not through endogenously generated population growth. The initial transportation system referred to as the Interplanetary Transportation System (ITS), is conceptualized as a permanent Earth-Mars transportation infrastructure, which operates on regular cycles, with each vehicle designed to transport approximately 100 persons, and potentially 200 or more passengers per trip to decrease the per-capita costs. The long-term goal is to deploy a true Martian colonial fleet consisting of more than 1,000 reusable spacecraft, which are launched in coordinated waves during the most favorable launch windows (Szocik et al., 2020). Also, assuming a capacity of 100 individuals per vehicle, the transfer of 1 million inhabitants to Mars would require approximately 10,000 round-trip voyages; the settlement process would take place through several migratory waves because optimal Earth-Mars orbital alignment occurs every 26 months. Finally, based on these assumptions, Musk estimates that the needed population size could be reached in a range of 40-100 years, corresponding to 20-50 launch windows.

From the demographic analysis perspective, the assumption made here is that Mars is treated as an open demographic system for a relatively long period of time, in contrast to previous models, which assumed that migration flows are closed almost immediately after the establishment of the settlement, and the majority of the population increases through natural reproduction. A key factor of the study is the drastic reduction in the costs of transportation from Earth to Mars. It is believed by the authorst[73] hat the cost of travel must be reduced to approximately $200,000 per person, similar to the average price of a home in the United States, and in the long run, further reductions of travel costs to under $100,000 per person are anticipated. This level of economic accessibility is significant because it allows for mass colonization of Mars with a heterogeneous population in terms of skills, social background, and age. Musk expects that Mars will experience a chronic labor shortage during the early and

[73] Musk, E. (2017). Making humans a multi-planetary species. *New Space*, *5*(2), 46-61; Szocik, K., Wójtowicz, T., & Braddock, M. (2020). The Martian: Possible scenarios for a future human society on Mars. *Space Policy*, *54*, 101388.

intermediate phases of the settlement, resulting in a demographic structure in which labor demand will act as a strong attractor and stabilizer of the population. This economic model assumes that all aspects of the community life must be rebuilt from scratch, including heavy industry and energy infrastructure, agriculture, and everyday services. Therefore, the demographic continuity of the Martian population is not maintained through targeted reproductive policies, but rather through the constant inclusion of the population in the productive system, and it is reinforced the relationship between the economic growth and the social stability. In addition to the physical and economic dimensions of life on Mars, the study includes the material and social conditions of the daily lives of the inhabitants, with the settlement envisioned as a system of modular housing units including dome-shaped structures built using local materials such as Martian regolith for communal, agricultural, and recreational areas, and underground habitats, possibly in lava tubes, to protect the inhabitants from cosmic and solar radiation (Musk, 2018; Szocik et al., 2020; Giordano, 2025). Concerning large-scale food production, it will be technologically feasible in the long run through a combination of hydroponics, cellular cultivation, and alternative protein sources such as insects and synthetic biomass. Researches suggest that there would be enough food produced for a population of 1 million inhabitants to sustain itself for a terrestrial century, provided continuous technological innovation (Musk, 2018; Szocik et al., 2020). Another important aspect is social and cultural life, it is emphasized that the journey to Mars and life must be psychically sustainable, and even attractive, providing spaces for leisure, socialization, and cultural expression. This aspect acquires an indirect demographic relevance, since the voluntary permanence and population stability depend not only on biological survival, but also on the perceived quality of life.

At small scales, population continuity is inherently fragile; even slight variations in fertility, mortality, or age structure of the population can lead to significant impacts on the viability of the settlement. In these cases, reproduction cannot be treated as a spontaneously occurring process or solely as an individual event; otherwise, the burden placed on the workforce, which is required to ensure the survival of life support systems and critical infrastructures, could compromise the viability of the settlement. Thus, the demographic continuity is primarily ensured by the capability of regulating demographic dynamics in accordance with the functional capacity of the colony, leading to the conflict between biological regeneration and the urgent need for survival. However, as the settlements grow in size, the nature of the problem undergoes significant changes. The demographic sustainability of the population becomes increasingly linked to the political and institutional arrangements in addition to demographic fine tuning. An unregulated demographic growth, lacking the mechanisms for controlling the access to basic resources, decision making, and resolving conflicts, can generate new vulnerabilities rather than provide resilience. In this stage, the demographic sustainability is ensured by the capability of the governance structures to prevent demographic growth from weakening the preconditions for the existence of collective life, especially in an environment where essential resources, such as oxygen, energy, and pressurized space, are structurally limited. Finally, at large scales, demographic continuity can emerge as a result of complexity and redundancy. If a settlement attains a sufficient size of the population, the system becomes less responsive to individual demographic fluctuations. Therefore, skill loss, temporary imbalances in age structure, or localized failures can be absorbed without threatening the general viability of the settlement. In this case, the long-term sustainability is based on the specialization, diversification, and coexistence of multiple social and economic functions. However, this type of resilience requires that the transition towards a large-scale settlement has already occurred, and does not eliminate the vulnerabilities related to the early stages of development. In summary, the issue of demographic continuity on Mars is multi-domensional. As the settlement develops into an enduring, interconnected community, it first arises as a functional necessity to balance reproduction with the labor needed for life support, then it develops into a governance requirement to manage limited engineered resources, and finally it becomes a product of systemic complexity.

3.4 Governance, ethics, and sustainability

3.4.1 Who regulates these processes? Levels of governance and demographic impact

In addition to defining how large the Martian population needs to be, and understanding how the population could sustain itself over time, it is important to consider how the process will be regulated. This aspect is not the exclusive responsibility of one single governing body, rather it arises from a multi-polar and layered system of norms, practices and actors. As such, international treaties, national laws, and corporate regulations for space development, will interact in a non-hierarchical way and create a complex regulatory system that affects who, how many, and how people will live on Mars.

The regulatory framework can be understood through three primary levels, which all have different influences on the demographic process, yet are all connected. Firstly, at the international level, the so-called "Space Law 1.0[74]" has been represented by the Outer Space Treaty since 1967, which currently represents the most important part of international space law. Many authors argue on the context in which the treaty was created; during the era of states space exploration and temporary missions it lacked for a structural base to govern permanently settled areas and sustainable populations (Ferreira-Snyman, 2021; Neef, R. 2021.). The lack of clarity on certain issues create an area of regulatory uncertainty that indirectly affects demographic processes. And since, long-term stability of extraterrestrial settlements cannot be guaranteed by a colony that is structurally dependent on Earth, it is necessary in order to prioritizes autonomy and self-determination that it must gradually develop self-directed institutional frameworks to autonomously manage resources, settle disputes, and adjust to environmental constraints. Political organization and spatial planning become crucial tools for ensuring the community's long-term survival in harsh environments like Mars (Giordano, 2025). Secondly, the national legislations and mission agreements of states, which are referred to as "Space Law 2.0[75]", represent the second level of regulation. The United States, Luxembourg, the United Arab Emirates and Japan have implemented national laws that legitimize the extraction and possession of space resources by private actors (Su, J., & Li, J., 2025). At the same time, projects such as the US-led Artemis Accords and the International Lunar Research Station (ILRS) project promoted by China and Russia[76], establish operational standards, cooperative principles and security measures, such as safe zones around vital infrastructure. These agreements result in a regulatory fragmentation of the Martian scenario and consequently in settlements that may be subjected to different legal frameworks causing direct effects on demographic composition, migration patterns and access to vital resources. Thirdly, is the level of corporate governance and private self-regulation, which are often referred to as "Space Law 3.0[77]". Many studies show how the inability to exert effective political control from Earth can lead to a situation of de facto corporate governance, whereby companies that manage the infrastructure, also take on regulatory and disciplinary functions[78]. Indeed, SpaceX has indicated that Mars should be a free planet, with no external authority and disputes solved through self-governing principles established after settlement. However, these

[74] Neef, R. (2021). Artemis accords: A new path forward for space lawmaking?. *Adel. L. Rev.*, *42*, 569.
[75] Ibidem.
[76] Ferreira-Snyman, A. (2021). Challenges to the prohibition on sovereignty in outer space-A new frontier for space governance. *Potchefstroom Electronic Law Journal/Potchefstroomse Elektroniese Regsblad*, *24*(1).; Neef, R. (2021). Artemis accords: A new path forward for space lawmaking?. *Adel. L. Rev.*, *42*, 569
[77] Neef, R. (2021). Artemis accords: A new path forward for space lawmaking?. *Adel. L. Rev.*, *42*, 569.
[78] Smith, T. L. (2025). Martian diversity: A government for pluralistic communities on Mars. *Space Policy*, 101687.

types of statements raise serious questions about the democratic legitimacy and the protection of basic rights in situations in which the population is dependent on life support systems and therefore very susceptible to resource control (Smith, 2025). Thus, establishing a Martian criminal code[79] is seen as a practical necessity in order to prevent neglect, sabotage and behavior that is incompatible with the survival of the community, in an environment in which individual action can have lethal collective consequences. The regulation of property rights and resource governance represent an additional source of legal vulnerability. On the one hand, the recognition of property rights is generally regarded as being essential for long-term planning and investment. However, the lack of a common legal framework risks leading to the repetition of terrestrial geopolitical conflicts and the fragmentation of governance among settlements (Ferreira-Snyman, 2021). To counteract this risk, several authors suggest supra-settlement coordination mechanisms (for example, the Martian Secretariat), which would aim to coordinate the legal norms of the various settlements and settle disputes in a situation in which enforcement from Earth is practically impossible. From a demographic perspective, legal stability serves as a stabilizing factor in the support of settlement permanence and intergenerational continuity. As such, law on Mars functions not only as an instrument of order, but also as a core element of demographic sustainability in a closed and irreversable human system.

3.4.2 Settlement scenarios and structural constraints:

There are a variety of colonies that could be conceptualized for Mars. For example, settlement can be thought of in relation to Mars imagined as a future refuge for humanity, providing an alternative habitat in response to the degradation of the environment, or overpopulation or a systemic collapse on Earth (Wójtowicz, & Szocik 2021). In this sense, restricted or imposed access to Mars cannot be completely excluded, resulting in a settlement composed of individuals who relocate involuntarily. However, there are many ways that settlers on Mars may organize themselves, depending on these dynamics. They could create a military base, a base to work, a city for the wealthy, or even, hybrid configurations in which settlers from different social strata coexist under unequal conditions[80]. In such cases, constraints concern

[79] Smith, T. L. (2025). Martian diversity: A government for pluralistic communities on Mars. *Space Policy*, 101687; The Martian: Possible Scenarios for a Future Human Society on Mars Konrad Szocik a, *, Tomasz Wojtowicz b, Martin Braddock c

[80] Wójtowicz, T., & Szocik, K. (2021). Democracy or what? Political system on the planet Mars after its colonization. *Technological Forecasting and Social Change*, *166*, 120619.

spatial and institutional segregation that may divide the colony into privileged zones and areas inhabited by lower-status groups, with clear implications for social cohesion and demographic continuity.

Therefore, if one considers Mars as a selective refuge, it is very plausible that the first phase of a Martian settlement would be accessible primarily to individuals with substantial economic resources. As long as the journey to Mars is private and technologically complicated, the price tag for the average person will certainly be much too high. For this reason, Mars represents a "dream destination" for humanity (Wójtowicz, & Szocik 2021). It is difficult to imagine a situation where there will be an equal distribution of migrants to Mars in the first phase. Interplanetary transportation will be limited, and building large enough and independent infrastructure to sustainably provide for human needs (e.g food, water, energy and support) will be a huge challenge. Thus, strict entrance requirements may be needed at first since there is no room for errors. In the long term nature of a Martian settlement technological development is crucial and there may be serious consideration for a large scale settlement effort. As time passes and advances are made in space technology, the barriers to entering a Martian settlement will decrease, and more people will be able to participate.

Certaintly, One of the primary functions of governance concerns the management of vital resources (Smith, 2025). On Mars, differently from Earth, these resources are not present in nature but have to be artificially created and sustained through complex life support systems. Due to the necessity of control of such resource for survival and due to the ability to access them that is directly dependent upon their availability, there is an intrinsic risk of authoritarianism in governance, whether or not the intent behind it is ideological. This has been repeatedly emphasized in the literature, and the focus has generally been placed on the risk of authoritarianism stemming from the systemic concentration of control of life sustaining technologies (Smith, 2025; Szocik et al., 2020). As a way to minimize this risk, several authors have proposed models of governance in which the essential resource management systems are diffusely owned. For example, Haqq-Misra's economic sovereignty model[81] suggests that settlers should be co-owners of the essential systems through mechanisms such as full reserve banking and shared capital structures. Through such mechanisms, the monopolization of essential systems by either corporations or governments can be prevented, and the risk of authoritarian power concentrations can be minimized . Such mechanisms are important from a

[81] Haqq-Misra, J. (2025). A model for economic freedom on Mars. *Space Policy*, *71*, 101652

demografical point of view because they ensure stable access to essential resources across generations.

In addition to the discussed economic and technological constraints, biomedical constraints represent another significant barrier to mass colonization. The chronic effects of the physical hazards of the space environment (e.g. reduced gravity, radiation), will lead to long term physiologic consequences. Therefore, radical forms of human enhancement[82], possibly including genetic modification, may be necessary to enable human survival and reproductive viability on Mars. However, these forms of enhancement will add additional layers of inequality and raise additional ethical dilemmas. Indeed, mandatory enhancement raises fundamental questions regarding personal rights. While participation in enhancement technologies may be justifiable as a therapeutic intervention or for protection purposes, mandatory participation in enhancement technologies raises significant ethical dilemmas. Additionally, the Martian environment may require the development of a new set of moral guidelines, where otherwise unacceptable invasive medical procedures may be deemed acceptable due to survival requirements. Biomedical constraints are, therefore, fundamentally linked to political decision making, and will shape the eligibility criteria for settlement, and influence the demographic structure of the colony across generations.

Although voluntary colonization[83] is often seen as the predominant paradigm for establishing human settlements on Mars, involuntary settlement scenarios are possible. One example of involuntary settlement is the military expansion into space, where personnel may be required to stay in extraterrestrial facilities for extended periods of time. Under such circumstances, governance structures are likely to be characterized by the hierarchical and authoritarian features associated with military organizations. While some restrictions on personal freedoms may be tolerated in a purely military context, long-term militarization of a Martian settlement would create significant difficulties if civilian populations were to be included. Civilian settlers may object to such regimes as incompatible with civilian life, and especially so if militarization became the dominant characteristic of social organization. Other forms of involuntary

[82] Szocik, K., Wójtowicz, T., & Braddock, M. (2020). The Martian: Possible scenarios for a future human society on Mars. *Space Policy*, *54*, 101388.
[83] Wójtowicz, T., & Szocik, K. (2021). Democracy or what? Political system on the planet Mars after its colonization. *Technological Forecasting and Social Change*, *166*, 120619.

settlement, such as economically or scientifically driven missions, would likely have a less marked effect on political structures, although they would also restrict individual autonomy.

3.4.3 Governance models proposed in the literature and demographic implications

There is not a single governance model, instead literature on proposal for governance on Mars is populated by various models rooted in analogies to historical institutions, democratic theory, and the exceptional conditions of permanent life away from Earth. Rather than indicators of theoretical fragmentation, this diversity reflects a sign of consensus that no existing terrestrial political system can be transferred directly to a Martian context without producing demographic, social, and ethical tensions. The legal and political framework is a blank space: space law experts note that it's unclear which terrestrial legal solutions will work on Mars, and planners cannot yet predict how Martian society and politics will evolve (Tronchetti, 2013). So, these proposals may be understood not as mutually exclusive ideologies, but as context-dependent responses to the same structural constraints; future settlements are expected to be small in their initial stages, internationally sourced, and composed predominantly of highly skilled technical personnel operating in an extreme and closed environment. So, under such conditions, political systems are assessed primarily in terms of their capacity to ensure effective decision-making and demographic continuity.

The ongoing debate on Mars governance tends to gravitate to some form of direct democracy as the most intuitive and normatively appealing form. Advocates such as Elon Musk have drawn attention to the idea that direct democratic mechanisms may make better sense on the Red Planet than representative systems, particularly because they allow laws to be more easily repealed than enacted[84]. Musk's proposal would employ a a qualified majority for creating new rules, but require even less of a blocking minority to revoke them, to reduce the risk of persistent maladaptive legislation in a high-risk environment. In addition, the support for democratic governance is futher bolstered by the expected nationalities of early settlers. Futhermore, selection scrutiny processes, like that employed for Mars One project, suggests that the overwhelming majority of potential colonists come from Western polities where democracy, rule of law, and separation of powers are internalized norms. From this perspective, direct democracy actors may be especially able to maximise political legitimacy and protect a

[84] Wójtowicz, T., & Szocik, K. (2021). Democracy or what? Political system on the planet Mars after its colonization. *Technological Forecasting and Social Change*, *166*, 120619.

broad individual rights in an environment where voluntary participation and shared risk are the order of the day. Still, the literature highlights that the suitability of direct democracy is very much contingent on the social, economic and cultural make up of the population; voting behaviour, values priorities and even understanding of rights itself are learnt on Earth, and there is no guarantee that democratic majorities will consistently favor long-term collective interests (Wójtowicz, & Szocik, 2021). In primarily economic settlements focused on space mining or resource exploitation, democratized decision making may lead to a strong incentive for short term maximization resulting in more flexible rules to exploit all resources ecologically sustainably, leading to very short term viability at the cost of the settlement as a whole in the long term. In this way, there may be maximal freedom, but also this may lead to risks of policy paralysis, majoritarian dominance, and insufficient restraint on critical survival decisions; for these reasons, technocratic rule is proposed by many studies as a necessity of a functional form to begin with on Mars. Technocracy[85] is defined as a political system where a decision making authority is in the hands of technically trained experts and is exercised on the base of specialised knowledge. This model is not based on ideological opposition to democracy, but on the recognition that early colonies will have a professional population predominantly comprised of engineers, scientists and system operators. Life-support systems, infrastructure, and environmental risk can only be maintained through rapid, fact-based decisions which are incompatible with slow-moving or politicized instances. Accordingly, technocracy takes form as an arrangement that minimizes ideological conflict and prioritizes operational efficiency in contexts where errors can have immediate severe consequences.

An additional study, points out a common interpretive structure for these debates; starting from the expected demographic composition, so highly diverse, internationally sourced, and operating under extreme constraints, it is proposed that survival on Mars requires a revised form of liberalism (Smith, 2025). In this reading, individual freedoms on Mars cannot be the priority, but they must be adapted to the material constraints of the context, which is closed and hostile, and where any individual actions will have direct consequences for collective survival. It is not suggested that personal values would be left out from public decision-making, but actively incorporated to define both rights and their legitimate limits. Governance is to be

[85] Wójtowicz, T., & Szocik, K. (2021). Democracy or what? Political system on the planet Mars after its colonization. *Technological Forecasting and Social Change*, *166*, 120619.

seen as the mechanism through which pluralism is preserved while enabling decisive collective action in survival-critical domains.

Therefore, the plurality of governance models proposed in the literature may be anknowledged as converging responses to the same structural limitation, rather than competing institutional proposals. In the study is exposed a preference for parliamentary arrangements in which representative bodies co-exist with randomly selected citizen chambers and expert advisory councils is an attempt to retain desired political participation, while also couching the technical restrictions imposed on the polity in the political institutions that lead to political decisions (Wójtowicz & Szocik, 2021). Additionally, this line of reasoning is emphasized by an appeal to the need for a codified Martian constitution. It is argued that formalized legal structures are necessary to regulate authority, rights, and responsibilities across generations in a setting where enforcement from Earth is impractical and demographic continuity depends on long-term predictability (Wójtowicz & Szocik, 2021). Thus, classical liberalism as it is on Earth cannot be direcltly applied in such different context and the extreme interdependence imposed by the environment requires governance systems capable of legitimately constraining individual behavior in order to preserve collective viability (Smith, 2025). This point of view is futher supported with the focus shifts from internal governance to relations between settlements. Proposals to selectively adapt elements of the Law of the Sea and the Antarctic Treaty System to achieve both cooperation and the preservation of scientific practices and regulated economic activity without recentreting Earth's model on Mars (Smith, 2025). There are even more radical proposals such as the call for liberation from Earthly political and economic control. Framed in contexts of moral transformation, such proposals also expose the risks of severing institutional support too abruptly in an environment where inter-settlement cooperation is essential for survival[86]. And, ideas on shared value systems and penal norms are not optional cultural features, but foundational mechanisms for maintaining order during transit and settlement (Szocik et al., 2020; Smith, 2025).

Following Smith's reasoning[87], Mars governance should take the form of a value-informed liberal order, preserving pluralism and protecting individuals from arbitrary power, while accepting carefully circumscribed limits on autonomy; without such limits, neither

[86] Haqq-Misra J.'s proposal cited in Smith, T. L. (2025). Martian diversity: A government for pluralistic communities on Mars. Space Policy, 101687.
[87] Smith, T. L. (2025). Martian diversity: A government for pluralistic communities on Mars. Space Policy, 101687.

unrestrained sovereignty nor unchecked freedom can sustain demographic continuity or collective survival at a planetary scale.

Alongside these proposals, it has been addressed in the literature as well corporate governance, particularly within the context of a potential private space enterprise driven approach. Corporations like SpaceX or Blue Origin are driving current interplanetary missions and it is generally recognized that private actors are likely to exercise substantial de facto authority during the initial phases of settlemen (Wójtowicz & Szocik, 2021). However, corporate governance is not seen as a political model in the literature, but instead as a temporary and possibly negative transitionary measure.

The future demographics of any Martian colony are also affected by the idea of corporate governance. Profit-maximizing systems may put short-term productivity ahead of social reproduction, intergenerational stability, and equitable access to resources, endangering long-term demographic stability and social legitimacy. With respect to the Martian environment, which is hostile and completely dependent on engineered systems for oxygen, water, food, habitat, and medical care, the ability to control the infrastructure of these engineered systems means that one has the ability to control actually the very essence of life. Haqq-Misra's analysis of economic freedom on a sovereign Mars provides an example of how the concentration of economic power is identified as a threat to long-term political and social stability (Haqq-Misra, 2025). Institutions with total control over vital resources gain authority comparable to that of a sovereign nation, the capacity to influence population size, access, and longevity, citing historical critiques of fractional reserve banking and monopolistic capital accumulation. Therefore, demographic regulation under corporate governance regimes would occur indirectly through economic mechanisms, rather than being determined through explicit political decision-making: an employment contract, productivity criteria, or cost-efficiency criteria can serve as indirect mechanisms of population regulation, specifically where exit opportunities are structurally limited or non-existent. Indeed, in contrast to terrestrial labor systems, Martian colonists do not have the option of leaving an employer without losing their access to life support systems, making their economic dependence a source of demographic vulnerability. According to Smith, it is explicitly cautioned that when private entities control access to life support systems (e.g., oxygen, water, food, habitat), economic dependence can easily be transformed into coercive politics (Smith, 2025). Because the material conditions necessary for survival structurally limit the ability to dissent or leave, this dynamic threatens social cohesion as well as liberal principles. Persson[88] issues similar cautions, describing corporate dominance of vital resources as establishing quasi-feudal power dynamics incompatible with democratic accountability. Overall, this emphasizes the need for streghtening public institutions that are informed by values and the need to limit private power in environments where material dependence is absolute and the consequences of unbalanced politics are existential. By separating private ownership and profit maximization from access to the vital systems required for survival for diffused capital ownership aims to address this problem (Haqq-Misra, 2025). Additionally, it aims to prevent monopolistic control over survival-critical technologies and, by extension, demographic reproduction and continuity by requiring all citizens to be co-owners of essential systems. In order to preserve demographic autonomy and guarantee long-term population viability, the majority of the literature concurs that corporate authority needs to be subject to explicit institutional restraints, either through constitutional frameworks, diffused ownership models, or value-informed governance structures (Haqq-Misra, 2025; Smith, 2025).

The studies generally agree that the centralization of life critical resources is likely to generate coercive power, regardless of whether or not a particular political system formally includes provisions for democratic participation (Szocik et al., 2020; Smith, 2025). This can create a situation in which certain limits on individual freedoms are acceptable to the extent that they are deemed to be collectively necessary to survive in a given environment. However, this can blur the distinction between "emergency governance", based on such context, and "authoritarian rule," creating a situation in which it could be used as a justification for policies that are otherwise unacceptable under liberal conditions.

Furthermore, several authors have connected demographic regulation to this coercive potential. For instance, a discussion of why it is impossible to consider reproductive freedom as an unalienable right due to the material constraints of life on Mars, as every new person born will raise the carrying capacity of the community, necessitate greater resource allocations, and raise the community's overall risk (Smith, 2025). Overall, the governance models proposed show how the demographic stability of a Martian settlement depend principally by the outcome of institutional choices that regulate access, resources, reproduction, and rights. In this sense,

[88] Persson cited in Smith, T. L. (2025). Martian diversity: A government for pluralistic communities on Mars. Space Policy, 101687.

governance emerges as a structuring variable in the transition from a fragile human presence, functional to survival, to an intergenerational society capable of regenerating itself over time.

CHAPTER 4: CONCLUSION

4.1 Summary of key aspects

Demographic adaptation to Mars should be seen in terms of processes. The analysis assessed that Martian settlement signifies a transition from migration to permanent settlement under extreme constraints. Consequently, the shift to establishing human settlements on Mars changes many aspects of human adaptation which are interrelated by various dimensions.
The development of such analysis in this thesis was organized according to three successive conceptual phases, each representing the evolution of the relationship between humanity and an extreme extraterrestrial environment such as Mars.

The first phase concerns human emigration into space and the initial evaluation of Mars as a potential site for a human settlement. To study the suitability of Mars as a potential location for a human settlement, the geographical characteristics of Mars were evaluated both physically and environmentally. This research was necessary to determine the limits within which a human presence could exist. Therefore, it is acknowledged that Martian environment is very hostile to unprotected human life, primarily due to the lack of atmospheric gases, the high levels of ionizing radiation present, the unstable nature of liquid water, and the extreme variations in temperature. All these characteristics establish survival requirements for humans that are significantly more challenging than those on Earth. However, although studies suggest that there are some environmental constraints on a human presence on Mars, these are not totally insurmountable obstacles to human settlements; rather, they are "soft" feasibility conditions that could be lessened with the use of cutting-edge technologies. The presence of water, the availability of carbon dioxide that can be utilized for in situ resource exploitation, and the varied geological characteristics of the planet create the possibility of identifying more favourable locations for establishing a human presence, including lower altitude regions, natural underground formations, and geologically stable contexts, that represent the transition from simple exploration to settlement planning.

The theoretical framework for comprehending Mars as a potentially habitable space that is vulnerable to settlement processes rather than as an abstract astronomical object makes exogeography's pivotal role clear at this moment. The method emphasizes how human adaptation to space is a primarily geographic process rather than just a biological or technological one, and that identifying potential locations for human settlement, particularly in terms of soil stability, radiation protection, and water availability, is a necessary but insufficient condition for any permanence hypothesis. Once the theoretical possibility of a human settlement had been identified, the second phase of the analysis focused on human adaptation, using critical survival factors as a lens. During this phase, the thesis systematically examined the primary aspects of human adaptation: physiological, psychological, cognitive-resource management, social and institutional. The analysis clearly demonstrated that surviving on Mars is a human process first, regardless of whether it is a technical one. While the challenges associated with the extreme Martian environment are certainly significant, the primary challenges associated with surviving on Mars relate to sustaining performance, cooperation, motivation, and decision-making capacity over extended periods of time in conditions of isolation, uncertainty, and reliance on artificial systems. Simulated missions and comparisons with analogous Earth-based systems have reinforced this conclusion; research conducted in isolated, confined, and extreme environments has demonstrated that humans possess a considerable capacity for adaptation, however, this is not neutral: it causes measurable changes to the physiological, psychological, and social conditions of individuals. These findings suggest that many of the critical challenges associated with a Martian mission are not necessarily insurmountable but rather require purposeful strategic approaches to mitigate them through the design of habitats, the organization of work, advanced medical support, cognitive architectures for systems, and the conscious management of resources. Furthermore, studies have demonstrated that medical and engineering innovations can significantly decrease physiological and operational risks to humans, creating indirect benefits to the psychological dimension as well. Analogous terrestrial studies have supported the pursuit of targeted countermeasures to minimize the negative consequences of the effects of the Martian environment, such as the implementation of physical activity programs that are structured for the prevention of muscle loss, the control of exposure to artificial gravity, the regulation of the environment (light, atmosphere, routine), and the continuous monitoring of the psychophysical state of individuals. The development of advanced space medicine has evolved from being a component of an Earth-based model to becoming a self-contained care system, in which the use of artificial intelligence (AI) for the purposes of developing countermeasures based on analogues enables the transformation of the countermeasures developed during analogues into continuous operational systems[89]Predictive algorithms allow for the detection of early signs of physiological decline or psychological distress, enabling the provision of local clinical support and permitting the adjustment of exercise, workload, and therapeutic interventions in real-time. In addition, space architecture[90] operates as an integrated countermeasure for mental health and resource management. The architectural design of the habitat provides the user with choice architecture, constantly directing the user's behaviour, emotional state, and social interactions in conditions of isolation and operational irreversibility. The arrangement of spaces in the habitat, especially the ratio of private and public spaces, the reduction of social density, and the modulation of sensory inputs, can mitigate stress, conflict, and cognitive fatigue. Moreover, the architectural design includes elements that will make behavioural sustainability "the default," thereby minimizing waste, decision-making burdens, and distributive conflicts. Therefore, the habitat becomes an active countermeasure that provides a means to integrate psychological wellness, operational efficiency, and responsible resource utilization in deep space.

Another important outcome of this analysis is the recognition of a strong interdependence among the various dimensions of adaptation; for example, physiological constraints affect psychological wellness, housing conditions affect social cohesion, and resource management affects the cognitive and decision-making stability of individual and group members. However, unlike the other dimensions, governance cannot be simulated completely through environmental analogues and must therefore be addressed as a political, regulatory, and institutional issue. As is the case on Earth, the governance of cooperation, conflict, authority, and responsibility becomes increasingly important on Mars, since decision-making errors or organizational failures can compromise the entire survival system. The third phase of the analysis begins once the immediate survival needs are at least partially met. At this point, the focus of the analysis shifts from the survival needs of potential Martian colonists to the continued human presence on Mars. Once again, this does not mean that the focus is on ensuring the continued survival of individuals or small groups, but rather that Mars is viewed

[89] Cornejo, J., Cornejo-Aguilar, J. A., Vargas, M., Helguero, C. G., Milanezi de Andrade, R., Torres-Montoya, S., ... & Russomano, T. (2022). Anatomical Engineering and 3D printing for surgery and medical devices: International review and future exponential innovations. *BioMed research international*, *2022*(1), 6797745.; Baghchehsara, A., Pate, S., Schlegelmilch, B., Rana, Z., Cinelli, I., Inamdar, K., & Ernst, F. Autonomous Operations for Spaceflight Mission Control: Challenges and Benefits.

[90] Abood, S. (2019). Martian environmental psychology: The choice architecture of a Mars mission and colony. In The human factor in a mission to Mars: An interdisciplinary approach (pp. 3-34). Cham: Springer International Publishing.

as a permanent destination for human beings, where the continued human presence on Mars depends upon the intentional creation of stable demographic, social, and regulatory conditions. Within this context, the section on climate adaptation served a specific methodological function: it did not address climate as a physical threat that has already been addressed in previous chapters, but rather reframed climate as a structural constraint on population and settlement. On Mars, unlike Earth, climate adaptation strategies that involve seasonal migration or territorial relocations are not feasible as viable mechanisms for enhancing resilience, given the permanently hostile nature of the Martian environment to unprotected human life. In addition, it is shown that across each of the settlement models studied, there are very different ways to achieve demographic regimes due to the way the logic of settlement is constructed (i.e., survival or growth). Settlements which are structured around the concept of survival will create protective environments, provide secure access to needed resources, and establish strong institutional controls. While these settlements may endure through extreme environmental stressors, they will rarely have the capacity to regenerate their population over the long term. In contrast, growth-oriented models allow greater population scalability and social complexity, yet introduce higher levels of environmental exposure and systemic risk, making demographic stability dependent on advanced governance and risk management. However, because they are often open systems (with less structural control), these settlements are exposed to greater risks from both the environment and within the societal structure, thus requiring advanced governance and risk management strategies to maintain demographic stability. One of the most significant findings of this study was that demographic viability is influenced by factors in addition to the total population of the settlement. Spatial organization, institutional framework, and the relationship between them influence the degree to which the settlement can achieve demographic viability. For example, centralized and extractive settlement models generally create a stable demographic regime by maintaining tight control over a relatively small population, whereas distributed and surface-oriented settlement models create opportunities for diversity and continuity among generations, but increase the difficulty associated with coordinating activities throughout the entire settlement. Regardless of the specific characteristics of a particular settlement, the question of demography is always linked to the distribution of power, the availability of resources, and collective decision-making processes.

Demography is now a strategic variable, as this theoretical change illustrated. A settlement's existence is not just about maintaining a certain population in a given area; it's also about maintaining the bare minimum of people needed to maintain the social reproduction of the settlement, develop the division of labor necessary to sustain it, pass on knowledge and skills to future generations, and ensure the continuous operation of a resilient social-ecological system, also known as systemic resilience. Additionally, the population growth is not a spontaneous or natural process. Since they have an impact on the system's overall operational capacity, demographic reproduction, population age distribution, and resource allocation are all ultimately implicit collective decisions in the case of a settlement founded in a closed and hostile environment.

Differences in the concept of endurance and regeneration were useful for analysing that the transition between these two stages is significantly influenced by the quality of governance.Who controls access to essential resources, who controls access to infrastructure, and who controls migration flows into the settlement, de facto exercises demographic power and influences who can live on Mars, under what conditions, and with what likelihood of establishing continuity. Finally, the literature surveyed concludes that no current governance model can be applied to Mars without modifications. Because of the extreme limitations of resources, isolation, and technological dependence, individual liberty cannot be conceived as an abstract right, but must be balanced against the need to preserve the collective survival of the settlement. Therefore, regulation of reproduction, resource management, and prevention of authoritarian forms of power must be recognized as important issues, particularly during the initial stages of settlement, when the population is small and the room for error is minimal. As such, governance on Mars is not merely a political issue, but a fundamental requirement to achieve demographic stability and to transition from a fragile human presence on Mars to a sustainable civilization.

4.2 Ethical challenges for future space missions

The possibility of humans living on Mars and going there on missions is a huge change in the history of space exploration. It's no longer just about arriving to the destination and returning back goal, but it is about making it possible for people to settle there permanently in an environment that, because of its physical and biological features, is not compatible with life as it developed on Earth. This change from short-term exploration to long-term settlement brings with it a number of duties that are not simply technical or scientific, but also moral, social, and institutional.

The focus is not merely whether it is technologically and medically feasible to sustain human life in an extreme environment, but under what conditions is it morally permissible to accept the extreme risk involved in surviving in such a harsh environment. Thus, while the technological and medical challenges of sending humans to Mars will ultimately determine feasibility, the ultimate question is to what degree is it morally acceptable to take extraordinary risk with an individual in order to attain a scientifically or strategically desired objective. Risk-benefit and cost-benefit evaluations are helpful in this context, but they are not enough to serve as the only foundation for decisions involving individuals taking extraordinary risks in order to achieve a scientific or strategic goal. These analyses make it clear what trade-offs are necessary for space exploration, but they do not address the ethical issues that arise when the danger becomes systemic and persists for an extended period of time. A permanent settlement differs from a short-term mission in more ways than one. In the latter case, survival is no longer a rare occurrence but rather a condition that must be guaranteed for a considerable amount of time[91].

There have been discussions regarding the potential for future generations of humans to adapt to the impending lunar and Martian colonies, defining them as "homo galacticus"[92], a future variant of human evolution. Some visionaries believe that there will be significant changes to human health and biology as a result of the new challenging environment. Mars poses several physical stresses to the human body including radiation, lower than normal gravity, and isolation, all of which are orders of magnitude higher than those posed to astronauts during previous missions. In this type of environment, the concept of "acceptable risk" loses its apparent neutrality and is necessarily linked to the mission objectives and the institutional priorities that direct them. Additionally, the length and purpose of missions to Mars affect the values of the crew members: what might be tolerated in the context of a symbolic and temporary mission to Mars may not be tolerated in the context of a mission of indefinite duration or of no return. Within this framework, the topic of human enhancement emerges as a forceful consideration. Pharmacological, technological, or biomedical interventions that are commonly viewed as highly controversial in ethical debates regarding Earth may become necessary tools for ensuring survival and functionability of astronauts in space. The distinction

[91] Spector, S. (2020). Delineating acceptable risk in the space tourism industry. *Tourism Recreation Research*, *45*(4), 500-510.
[92] Szocik, K., Shelhamer, M., Braddock, M., Cucinotta, F. A., Impey, C., Worden, P., ... & Munévar, G. (2021). Future space missions and human enhancement: Medical and ethical challenges. *Futures*, *133*, 102819.

between therapy and enhancement, which is already problematic on Earth, is likely to become even more ambiguous in the extreme context of space travel: what would be considered an enhancement of a healthy person on Earth, may become a minimal requirement for acceptable physiological functioning in deep space (Szocik et al., 2020).

Thus, Mars is not only a new geographic frontier, but it is also a true ethical laboratory. The combination of constant danger, isolation, and total reliance on artificial systems for sustaining life in space forces astronauts to rethink values that are often taken for granted on Earth; values such as the meaning of human life, the acceptable level of risk to life, the relationships between individual and collective responsibilities, forms of leadership, and the relationship between equality and authority are continuously being negotiated by astronauts in a way that is made more urgent by the fact that every decision made in space has irreversible consequences.

One of the areas, in which the moral tensions arising from the necessity of making difficult choices in space are most apparent, is in the realm of human reproduction. Children who are born on Mars may never be able to live on Earth, which implies that the individual freedom of children may be forever lost due to the decision of others made prior to their birth. Additionally, the effects of lower than normal gravitational pull, prolonged exposure to ionizing radiation, and a completely artificial environment on the process of human conception and the development of a fetus are not well understood. Therefore, the possibility of reproducing and giving birth to children on Mars raises questions that have never previously arisen in the course of human history. Regulating, delaying, or discouraging reproduction on Mars, or alternatively using advanced technologies, would all imply a profound redefinition of many of the basic concepts underlying families, parenthood, and intergenerational continuity. In the event that natural reproduction is deemed impractically risky or expensive for a Martian colony, then the latter may be forced to rely entirely on migration from Earth, which would challenge many of the assumptions of human society that are currently based on birth and the transfer of property from generation to generation; and the colony would also need to develop new social and regulatory models to replace those that exist in societies on Earth. Alternatively, the potential for using artificial wombs or genetically targeting specific traits would further extend the limits of what is currently considered acceptable in terms of human enhancement and would thus precede many of the debates that are currently underway on Earth. As a consequence of the nature of these risks, issues related to reproduction and childbirth may be considered to be secondary to other concerns in short-term missions. However, as a result of the need to ensure long-term survival in the context of a stable Martian colony, the need to adopt more radical approaches will become unavoidable. In this context, human enhancement will cease to be seen as an optional strategy and will become a pragmatic response to the persistent environmental challenges associated with living on Mars. However, this transformation will raise important questions concerning on what degree it is legitimate to interfere with the human body and mind and on what degree does functional improvement threaten the autonomy, identity, or social cohesion of individuals.

As discussed earlier, the history of human societies indicates that the limits on interfering with the human body have always been subject to revision. What is currently accepted as a normal practice today is the product of a lengthy and complex process of cultural and technological adaptation; prosthetic devices, implants, organ transplantation, and genetic therapy are increasingly being used as an integral component of modern medicine. In this regard, the enhancements designed for astronauts are considered as an extension of established practices to a significantly more extreme context. However, the idea of directly interfering with the moral capacities of humans through biomedical means is still problematic: such interference may lead to the sacrifice of certain fundamental aspects of humanity for uncertain benefits (Szocik et al., 2020).

In addition to the biological and ethical dimensions of human enhancement, there is a social dimension. Human communities are founded upon rules that attempt to balance cooperation and individual autonomy. On a Martian base, the relationship between these two competing goals may be intensified as a result of confinement, the scarcity of resources available, and the inability to abandon the system. While high levels of cooperation and mutual trust are required for survival on a Martian base, there is no guarantee that conflict, exploitation, or authoritarianism cannot occur as a result of the lack of real alternatives available to individuals. As a result, the design of Martian settlements cannot be limited to considerations related to technology, but must include, from the outset, a consideration of social cohesion, forms of governance, and mechanisms to prevent the abuse of power. Ultimately, human adaptation to Mars presents not only an engineering and medical challenge, but a challenge to the ability of human societies to redefine their fundamental values in extreme conditions, and to question the relationship between survival, human dignity, and the future of the species.
These considerations collectively demonstrate how human missions to Mars present a critical test of the ability of human societies to redefine their fundamental values in extreme conditions, and to question the relationship between survival, human dignity, and the future of the species.

Within this framework is the controversy surrounding the idea that Mars could serve as a "space refuge[93]" for humanity. According to some authors, settling on Mars would serve as existential insurance against worldwide calamities such as pandemics, asteroid strikes, and irreversible environmental collapses; therefore, it would be morally required of humanity to explore space in order to ensure the survival of the species (Szocik, et al, 2021). But this story has drawn harsh criticism. Several scholars have warned that the idea of an extraterrestrial refuge promotes a "disposable planet" logic and reduces the urgency of addressing the root causes of Earth's environmental and social crises; in other words, the expansion of human presence into space cannot serve as a justification for inaction regarding the protection of Earth, but rather should require an explicit balance between extraterrestrial ambitions and the preservation of the home planet.

The issue of sustainability, which comes out as a naturally cooperative and political issue, is a clear representation of this ethical conflict. Due to the transnational nature of orbits and the environmental externalities produced by space-related activities, the International Cooperation for Sustainable Space Development document highlights that no single nation-state or private entity can independently ensure the safety and sustainability of outer space (Noichim, 2005). In order to prevent raising systemic risk, international cooperation is therefore framed as a functional necessity rather than an ideal solution. It is predicated on procedures for coordinating launches, exchanging data, and creating common standards for debris mitigation. This approach is consistent with a multilevel governance model, in which the sustainability of space activities depends on the alignment of regulatory levels, and the balance between the civil, commercial, and military sectors. In the absence of such coordination, the policies developed by nations-states and private entities for space may become fragmented and contradictory, resulting in a diminished capacity for securing equity in access to resources and maintaining security. Within this context, space tourism emerges as one of the most immediate and contentious tests of the ethics of future missions to space. The distinction between suborbital, orbital, and beyond-Earth-orbit missions is not ethically neutral, as each category of missions implies different degrees of risk, reversibility, and the normalization of human presence in space. Short-duration, reversible suborbital missions continue to maintain a logic of symbolic exceptionality; in contrast, the shift to orbital missions, and the prospect of

[93] Szocik, K., Shelhamer, M., Braddock, M., Cucinotta, F. A., Impey, C., Worden, P., ... & Munévar, G. (2021). Future space missions and human enhancement: Medical and ethical challenges. *Futures*, *133*, 102819.

establishing permanent human settlements on Mars, contribute to a blurring of the lines between temporary exploration of space and settlement of space, leading to the emergence of new questions concerning the legitimacy of converting systematic exposure of individuals to extreme conditions into a routine, commercially-based activity.

In the "New Space" scenario[94], the growth of the influence of private actors, and the reductions in costs, have contributed to a rapid transformation of space into an emerging market. Although the estimates suggest that space tourism has an increasing potential for economic viability, the sustainability of space tourism from an ethical and political standpoint is uncertain. Research studies on Generation Z demonstrate a high interest in experiencing "astronaut-like" adventures and seeing the Earth from space. However, the research studies also identify significant barriers to participation in space tourism, including a perception of risk, costs, and the elite image of space, with women demonstrating a higher risk aversion than men (Giachino et al., 2023). The gap between the symbolic appeal of space tourism, and the willingness to accept risk associated with space tourism, demonstrates that space tourism is neither ethically neutral nor socially acceptable. Consequently, space tourism must be redefined in terms of the concept of "acceptable risk", as well as the development of governance models that address the transition from professional astronauts to civilian passengers, as well as the responsibility of civilian passengers to non-participating third parties, including the production of orbital debris, emissions, and environmental impacts from launches that are beyond the control of the individual passenger. As such, space tourism presents itself as a structural ethical problem that challenges the ability of contemporary societies to govern high-risk activities in a fair, responsible, and long-term oriented manner (Giachino et al., 2023).

4.3 Concluding remarks

This thesis has demonstrated that New Space is a distinct stage of the history of space exploration and that space can no longer be seen exclusively as a technical/scientific area. Instead, it is a complex political space where a multiplicity of political, economic, ecological and diplomatic forces are intertwined at a global level. Democratization, as conceived by Pekkanen, means that an expanding number of States and non-State actors participate in space

[94] Pekkanen, S. M. (2019). Governing the new space race.

governance: it does not signify the "end of the State," but rather, a more crowded field in which States retain their centrality as financiers, regulators and consumers of spatial capacity and where "new entrants" (with strategic and regulatory niches) have emerged (Pekkanen, 2019). The increased variety of actors contributes to the probability of disagreement about the most important principles (the status of "Global Commons", the delimitation of appropriation, property rights etc.) i.e. about issues that are fundamentally geopolitical (Pekkanen, 2019). As for commercialization, it is not simply defined as the industrial outsourcing. The "new" aspect lies in the autonomous initiative of companies targeting markets and activities outside Earth's orbit. The space industry is predicted to grow from approximately US$350 billion to $1 – 3 trillion during the 2040s (Pekkanen, 2019). In terms of the thesis, the politically significant element is not the figure per se, but its political impact: expectations of growth trigger national and corporate strategies, thereby increasing pressure on the rules, accountability and sustainability. Militarization is the multiplier of risk: Pekkanen points out that the challenge originates from the largely dual-use character of space technologies and establishes a link between debris density/clean-up capabilities and new security profiles, particularly focusing on jamming/lasers and the paradigmatic shift towards a "battle space awareness" logic (Pekkanen, 2019). This dynamic constitutes the foundation for the structural tension between cooperation and deterrence and explains why the governance of space cannot be viewed merely as a technical/legal issue. The transformation thus leads to two fundamental consequences that require moving to the next chapter. Firstly, the expansion of space activities increases the vulnerability of the space system itself, both environmentally and from a security perspective. With each launch, the increase in the number of launches, ground infrastructure and objects in orbit create cumulative negative externalities (emissions, local pollution, space debris), which are not evenly distributed, but follow along the geopolitical lines of privilege and marginality (Klinger, 2019). In other words, the distribution of damages (emissions, local pollution, expropriations, risk) follow logics of sacrifice zones and privilege, while the benefits (launch capacity, data, strategic rents) tend to be concentrated among the actors that have the greatest technological and regulatory capacity (Klinger, 2019). Secondly, the diversification of actors, States, agencies, military organizations, private companies, universities, and consortia, increases the difficulties in governing space using traditional instruments, based on binding treaties and hierarchical structures. As indicated by the multilevel governance approach, the current spatial system is characterized by a growing institutional fragmentation, which distributes the decisions and responsibilities across various levels and, generally speaking, entrusts them to informal or non-binding mechanisms (Del Canto Viterale, 2024). The increasing gap between the speed of technological innovations and the capacity of international institutions to generate shared and stable rules is therefore exacerbated in this context. Specifically, the increasing pressure on the rules for accessing and sustainable use of space caused by the anticipated economic growth results in a fragmented institutional response, creating a gap between the pace of innovation and multilateral coordination capacity (Del Canto Viterale, 2024; Pekkanen, 2019). Therefore, in view of the mentioned trends, space diplomacy appears as a central instrument for mediating competition and cooperation. Not only through large-scale international agreements, but through daily practices of technical, scientific and operational cooperation, which enable the system to operate effectively even under conditions of high geopolitical tensions, space diplomacy achieves the mediation of competition and cooperation. For example, the cooperation on board the International Space Station, which was maintained since the Russian invasion of Ukraine in 2022, because astronauts are the "quintessential space diplomats", illustrates the role of astronauts and experts as true diplomatic actors, cohesive teams with common expertise. This demonstrates how space diplomacy may guarantee micro-cooperation even if there is macro-political conflict, and that this resilience depends on practices and confidence built up over time and not only on normative documents (Cross & Pekkanen, 2023). Nevertheless, the resilience of space diplomacy does not eliminate the system's structural criticalities. The dual-use nature of space technologies, the increasing strategic relevance of Earth orbits and the economic pressure generated by the growth expectations of the sector, characterize space governance as an unstable equilibrium, in which cooperation, deterrence and exploitation coexist in a permanent state of tension (Pekkanen, 2019). Consequently, in the absence of a supra-national authority and in a scenario where the traditional treaties are declining, the sustainable management of space increasingly relies on the actors' ability to coordinate themselves using flexible rules, shared norms and adaptable diplomatic practices. Hence, the objective of the next chapter is to examine the space governance as a multilevel political process, in which diplomacy, environmental regulation and security cannot be separated. It is crucial to understand how the different components interact, so as to evaluate the potential stability of the space system and to take into account the long-term ethical and political implications: who determines how space is utilized? Who bears the environmental costs of exploration? What mechanisms exist to ensure that space remains available, safe and sustainable for future generations? Ultimately, the perspective of multi-planetary ethics broadens the scope of analysis, by relating space governance not only to geopolitical stability and/or environmental sustainability, but also to the long-term survival of the human species and the responsibility towards future generations[95]. In this framework, outer space represents a new normative and ethical frontier, in which the apparently technical choices concerning orbits, resources and infrastructure acquire profound political, ecological and moral significance.

As developed in this thesis, we can locate the governance of outer space within a larger transformation of the global political order. The multilevel governance approach, applied to the spatial system, has shown how authority is no longer confined to a single sovereign center, but rather distributed across a multitude of levels and actors that interact in a non-hierarchical way, resulting in a polycentric and inherently unstable decision-making system (Del Canto Viterale, 2024). Therefore, space cannot be analyzed as an extraordinary domain or technologically independent of the international system, but as a subsystem that reproduces and amplifies the contradictions between sovereignty, the market, security and the commons. The lack of a central authority, the fragmentation of regulations and the dual-use nature of space technologies make the governance of space a matter of systemic coordination rather than formal regulation, where the norms are generated by practices, standards, flexible agreements and forms of soft power rather than through direct legal imposition.

It is within this framework that a structural limit of governance theories emerges, as they continue to be anchored to an exclusively technical-instrumental rationality. As highlighted by the humanistic reflection on space exploration, the implicit assumption that the choices regarding the spatial environment can be optimized only in relation to efficiency, safety and scientific progress obscures the normative dimension that is present in all of these choices (Klinger, 2019). At this point, the humanities come in as an ethical element necessary to make visible the value premises that inform the choices: who determines what risks are acceptable, which lives are at risk, which temporal horizons are privileged, and which are excluded. They do not come in as external knowledge or as a posteriori moral correction. The absence of this normative reflexivity creates a lack of legitimacy that cannot be addressed by purely institutional means in a multilevel spatial system with a lack of consolidated democratic mechanisms and significant asymmetry in terms of technological and informational power. Therefore, from a theoretical point of view, the combination of multilevel governance and a

[95] Szocik, K., & Reiss, M. J. (2023). Why space exploitation may provide sustainable development: Climate ethics and the human future as a multi-planetary species. *Futures*, *147*, 103110.

humanistic approach allows to reframe the space governance as a problem of distributed responsibility rather than of territorial sovereignty. If the space system is organized according to interdependent levels without a single command center (Del Canto Viterale, 2024), then the responsibility for decisions cannot be assigned to a single actor, but is derived from the interactions between States, firms, scientific communities, and informal regulatory frameworks. It is precisely in this space of distributed responsibility that the contribution of the humanities becomes structural: they permit us to inquire into the ethical and social implications of decisions that cause irreversible impacts on timescales that exceed the traditional political horizon, as in the case of the colonization of planets, environmental degradation, or the militarization of orbits. Finally, the governance of outer space cannot be conceived or constructed as a simple extension of the existing international law, nor as a problem of institutional design. On the contrary, the governance of space represents a theoretical testbed for the social and political sciences, in which the models of polycentric governance and the reflections of the humanities converge to question the very foundations of the global order. Thus, space appears as a theoretical frontier, before being a technological one: a scenario in which the ways in which humanity manages irreversibility, uncertainty and inter-generational responsibility will determine not only the future of space exploration, but the very forms of coexistence of humans beyond the Earth.

BIBLIOGRAPHY

- Abood, S. (2019). Martian environmental psychology: The choice architecture of a Mars mission and colony. In The human factor in a mission to Mars: An interdisciplinary approach (pp. 3–34). Cham: Springer International Publishing.
- Anderson, G. (2019). The politics of settling space. Futures, 110, 64-66.
- Andrade, S. S. (2025). Spatial Suitability Analysis of Mars for Robotic Colonization and Future Human Settlement (Master's thesis, Universidade NOVA de Lisboa (Portugal)).
- Antarctic and Southern Ocean Coalition. (n.d.). Who governs Antarctica? Understanding the unique governance of the continent.
- Antonsen EL, Myers JG, Boley L, Arellano J, Kerstman E, Kadwa B, Buckland DM, Van Baalen M. (2022) Estimating medical risk in human spaceflight. NPJ Microgravity.
- Arney, D. C., Jones, C. A., Klovstad, J., Komar, D. R., Earle, K., Moses, R., ... & Shyface, H. (2015). Sustaining human presence on mars using ISRU and a reusable lander. In AIAA Space 2015 Conference and Exposition (p. 4479).
- Arnhof, M. (2016). Design of a human settlement on Mars using in-situ resources. 46th International Conference on Environmental Systems (ICES-2016-151)
- Baghchehsara, A., Pate, S., Schlegelmilch, B., Rana, Z., Cinelli, I., Inamdar, K., & Ernst, F. Autonomous Operations for Spaceflight Mission Control: Challenges and Benefits.
- Balistreri, M., & Umbrello, S. (2022). Should the colonisation of space be based on reproduction? Critical considerations on the choice of having a child in space. Journal of Responsible Technology, 11, 100040.
- Blair, J. A. (2011). Private spaceflight, public interest: Regulating commercial space tourism through a new application of the public function test. Georgia Law Review, 45(2), 585–623.
- Bell, A. V. (2023). Selection and adaptation in human migration. Evolutionary Anthropology: Issues, News, and Reviews, 32(6), 308-324.
- Berkman, P. A., Lang, M. A., Walton, D. W. H., & Young, O. R. (Eds.). (2011). Science diplomacy: Antarctica, science, and the governance of international spaces. Smithsonian Institution Scholarly Press.

- Brown, O. (2008). Migration and climate change. International Organization for Migration. Pdf.
- Campa, R., Szocik, K., Braddock, M. (2019). Why Space Colonization Will Be Fully Automated. Technological Forecasting and Social Change, 143, 162–171.
- Carto, S. L., Weaver, A. J., Hetherington, R., Lam, Y., & Wiebe, E. C. (2009). Out of Africa and into an ice age: on the role of global climate change in the late Pleistocene migration of early modern humans out of Africa. Journal of Human Evolution, 56(2), 139-151.
- Casagrande, G. (2025), "Looking out of the cradle. Possible geographical perspectives on the beginning of human expansion in outer space", in Casagrande, G., D'Ascenzo, A. (a cura), *Oltre la Terra verso l'Esogeografia*, Società Geografica Italiana, Roma, 71-93
- Chang, Y. W. (2015). The first decade of commercial space tourism. Acta Astronautica, 108, 79-91.
- Chatzitheodoridis, E., Clerc, P., Kereszturi, A., Mason, N., Persson, E., Possnig, C., ... & Tracht, K. (2025). Towards Permanent Settlements on Mars (from 1000 to 100,000 People). In Mars and the Earthlings: A Realistic View on Mars Exploration and Settlement (pp. 253-339). Cham: Springer Nature Switzerland.
- Cinelli I. and Brown L., "Innovation in Medical Technology Driven by Advances in Aerospace," 2018 40th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), Honolulu, HI, USA, 2018, pp. 941-944, doi: 10.1109/EMBC.2018.8512444
- Cinelli I., "Introduction to the Special Section on Healthcare for Space, Space for Healthcare," in IEEE Open Journal of Engineering in Medicine and Biology, vol. 4, pp. 156-157, 2023, doi: 10.1109/OJEMB.2023.3309591.
- Cinelli I., "How Space Operations Drive Innovation In Human Healthcare," in IEEE Open Journal of Engineering in Medicine and Biology, vol. 4, pp. 158-161, 2023, doi: 10.1109/OJEMB.2023.3244042.
- Cinelli I., "Space Medicine Requirements open to Innovation in Biomedical Engineering," 2018 40th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), Honolulu, HI, USA, 2018, pp. 973-976, doi: 10.1109/EMBC.2018.8512326.

- Cockell, C. S. (2008). An essay on extraterrestrial liberty. Journal of the British Interplanetary Society, 61, 255–275.
- Cohen, M. M. (2015). First Mars habitat architecture. AIAA SPACE Conference and Exposition (AIAA 2015-4517).
- Clément, G., & Bukley, A. P. (2014). Human space exploration–From surviving to performing. Acta Astronautica, 100, 101-106.
- Climate Refugees. (2023). Forced to Move: A Climate Story. Climate Refugees.
- Criswell, D. R. (1981). Human roles in future space operations. Acta Astronautica, 8(9-10), 1161-1171.
- Cross, M. K. D., Pekkanen, S. M. (2023). Space Diplomacy: The Final Frontier of Theory and Practice. The Hague Journal of Diplomacy, 18(2), 193-217
- Crucian, B. E., Choukèr, A., Simpson, R. J., Mehta, S., Marshall, G., Smith, S. M., ... & Sams, C. (2018). Immune system dysregulation during spaceflight: potential countermeasures for deep space exploration missions. Frontiers in immunology, 9, 1437.
- Cuberos, E. G. R. (2020). Terra forming of social systems and human behavior: a new era for AI, human-robotic interactions (HRI), and multidisciplinary social science. Int Rob Auto J, 6(4), 165-169.
- DeBenedectis, E. A., Kite, E. S., Kerber, L., Wordsworth, R., Lanza, N. L., Cockell, C. S., ... & McKay, C. P. (2024). Can We Green Mars In 100 Years?. LPI Contributions, 3007, 3229.
- Del Canto Viterale, F. (2023). Transitioning to a new space age in the 21st century: A systemic-level approach. Systems, 11(5), 232.
- Del Canto Viterale, F. (2024). Global governance of the space system: A multilevel governance analysis. Systems, 12(9), 318.
- Duda, K. R., Newman, D. J., Zhang, J., Meirhaeghe, N., Zhou, H. L. (2021). Human Side of Space Exploration and Habitation. In G. Salvendy & W. Karwowski (Eds.), Handbook of Human Factors and Ergonomics (5th ed., pp. 1480-1502). John Wiley & Sons.
- European Space Agency. (2018). Comparing the atmospheres of Mars and Earth [Image]. ESA.
- European Space Agency. (2025). Medical research.

- Evans, J. M., Knapp, C. F., & Goswami, N. (2018). Artificial gravity as a countermeasure to the cardiovascular deconditioning of spaceflight: gender perspectives. Frontiers in physiology, 9, 716.
- Ferreira-Snyman, A. (2021). Challenges to the prohibition on sovereignty in outer space-A new frontier for space governance. Potchefstroom Electronic Law Journal/Potchefstroomse Elektroniese Regsblad, 24(1).
- Frandsen, H. O. (2022). Looking for the rules-of-the-road of outer space: A search for basic traffic rules in treaties, guidelines and standards. Journal of Space Safety Engineering, 9(2), 231-238.
- Gallagher, N. (2010). Space governance and international cooperation. Astropolitics, 8(2-3), 256-279.
- Gardiner Natasha Blaize, Gilbert Neil, Liggett Daniela, Bode Michael (2024), Measuring the performance of Antarctic Treaty decision-making
- Gatti, M., Palumbo, R., Di Domenico, A., & Mammarella, N. (2022). Affective health and countermeasures in long-duration space exploration. Heliyon, 8(5).
- Giachino, C., Pucciarelli, F., Bollani, L., & Bonadonna, A. (2023). Is generation Z ready to fly into the space? The future of tourism is coming. Futures, 145, 103064.
- Gilbert, A. Q. (2023). Implementing safety zones for lunar activities under the Artemis Accords. Journal of Space Safety Engineering, 10(1), 103–111.
- Giordano A., (2025) "Human Migration, Settlements and Life in Outer Space: Some Initial Reflections on an Imagined Population Exogeography", in Casagrande G., D'Ascenzo A. (a cura), *Oltre la Terra, Verso l'Esogeografia*, Memorie della Società Geografica Italiana, Rome: Società Geografica Italiana.
- Giordano A., (2025) "Orbital Thresholds: Exogeography and the Evolving Geopolitics of the High Boundary", *Geopolitica. Journal of Geopolitics and Related Matters*, vol XIV, n. 1, pp. 119-142.
- Goldberg, Z. J. (2021). Ethical responsibility in space exploration. In Moving technology ethics at the forefront of society, organisations and governments (pp. 157-168). Universidad de La Rioja. Pdf
- Grimm D, Grosse J, Wehland M, Mann V, Reseland JE, Sundaresan A, Corydon TJ. The impact of microgravity on bone in humans. Bone. 2016 Jun;87:44-56. doi: 10.1016/j.bone.2015.12.057. Epub 2016 Mar 24. PMID: 27032715.
- Groeneveld, E. (2017, May 15). Early human migration. World History Encyclopedia.

- Gustafson, R. J., Rice, E. E., Gramer, D. J., & White, B. C. (2003, January). A view of future human colonies on mars. In AIP Conference Proceedings (Vol. 654, No. 1, pp. 1250-1257). American Institute of Physics.
- Haqq-Misra, J. (2025). A model for economic freedom on Mars. Space Policy, 71, 101652.
- Hassler, D. M., Zeitlin, C., et al. (2014). Mars' surface radiation environment measured with the Mars Science Laboratory's Curiosity rover. Science, 343(6169), 1244797.
- Havercroft, J., & Duvall, R. (2009). Critical astropolitics: The geopolitics of space control and the transformation of state sovereignty. In Securing outer space (pp. 50-66). Routledge.
- Heldmann, J. L., Marinova, M. M., Lim, D. S., Wilson, D., Carrato, P., Kennedy, K., ... & Coyan, J. (2022). Mission architecture using the SpaceX Starship vehicle to enable a sustained human presence on Mars. New Space, 10(3), 259–273.
- Iliopoulos, N., & Esteban, M. (2020). Sustainable space exploration and its relevance to the privatization of space ventures. Acta Astronautica, 167, 85-92.
- Internal Displacement Monitoring Centre. (2024). Internal displacement in 2024: Monitoring the crisis, measuring progress.
- International Space University. (2009). ACCESS Mars: Assessing cave capabilities and establishing specific solutions. SSP 2009 Team Project Report.
- Jayakumar, D., Pachiyappan, J. K., Roychowdhury, P., Kuppusamy, G., MR, J., Karri, V. V. S. R., ... & Khan, F. S. (2024). The impact of cardiovascular deconditioning in space: A review. Acta Astronautica.
- Jones, H. W. (2014). Life support for deep space and Mars. 44th International Conference on Environmental Systems.
- Klinger, J. M. (2021). Environmental geopolitics and outer space. Geopolitics, 26(3), 666–703.
- Lane, H. W., Smith, S. M., Rice, B. L., & Bourland, C. T. (1994). Nutrition in space: lessons from the past applied to the future. The American Journal of Clinical Nutrition, 60(5), 801S-805S.
- Leon, G. R., Atlis, M. M., Ones, D. S., & Magor, G. (2002). A 1-year, three-couple expedition as a crew analog for a Mars mission. *Environment and Behavior, 34*(4), 672–700.

- Léveillé Richard, (2010) A half-century of terrestrial analog studies: From craters on the Moon to searching for life on Mars, Planetary and Space Science.
- Lima, J. (2020). Charting a Human Rights Framework for Outer Space Settlements. Proceedings of the 71st International Astronautical Congress (IAC) – The CyberSpace Edition, 12-14 October 2020. International Astronautical Federation.
- Loggins, A. (2024). Voyagers of Mars: The first CHAPEA crew's yearlong journey. National Aeronautics and Space Administration.
- Lordos, A., & Lordos, G. (2020). Preparing for the socio-behavioural challenges of a populous, semi-independent settlement on Mars through a new generation of multi-team, empowerment-oriented Mars analogue missions. In International Astronautical Congress – The CyberSpace Edition.
- Mai'a, K., & Pekkanen, S. M. (2023). Introduction. Space Diplomacy: the final frontier of theory and practice. The Hague Journal of Diplomacy, 18(2–3), 193–217.
- Makanadar, A. (2024). Urban futurism: Exploring the viability of self-sustaining Mars colonies as a solution to climate change & overpopulation. Futures, 155, 103293.
- Man, J., Graham, T., Squires-Donelly, G., & Laslett, A. L. (2022). The effects of microgravity on bone structure and function. npj Microgravity, 8(1), 9.
- McElroy, M. W., Jr. (2023). The Space Industry of the Future: Capitalism and Sustainability in Outer Space. Taylor & Francis.
- McKeown, B., Dempster, A. G., Saydam, S., & Coulton, J. (2025). The space resources fund: A solution to the space resources benefit sharing dilemma?. Space Policy, 71, 101663.
- Metzger, P. T. (2015). The cost and risk of space settlement. New Space, 3(3), 145–155.
- Michel, N., Suedfeld, P., Weiss, K., & Gaudino, M. (2015). Affective, social and cognitive outcomes during a one year wintering in Concordia. Environment and Behavior, 48(7), 1073–1091.
- Mindell, D. A., Uebelhart, S. A., Siddiqi, A. A., & Gerovitch, S. (2009). The Future of Human Spaceflight: Objectives and Policy Implications in a Global Context. American Academy of Arts and Sciences.
- Musk, E. (2018). Making life multi-planetary. New Space, 6(1), 2-11.

- Nagaraja, M. P., & Risin, D. (2013). The current state of bone loss research: data from spaceflight and microgravity simulators. Journal of cellular biochemistry, 114(5), 1001-1008.
- NASA. (2024). The Artemis Accords: Principles for a safe, peaceful, and prosperous future. National Aeronautics and Space Administration.
- NASA Astrobiology. (2023). Life at low pressure: Planetary protection and the habitability of Mars. NASA Astrobiology Institute.
- NASA. (n.d) Humans to Mars: Preparing for the Journey. NASA.
- Neef, R. (2021). *Artemis accords: A new path forward for space lawmaking?* Adelaide Law Review, 42, 569.
- Neukart, F. (2024). Towards sustainable horizons: A comprehensive blueprint for Mars colonization. Heliyon, 10(4).
- Oltrogge, D. L., & Christensen, I. A. (2020). Space governance in the new space era. Journal of Space Safety Engineering, 7(3), 432-438.
- Orosei, R., Ding, C., Fa, W., Giannopoulos, A., Hérique, A., Kofman, W., ... & Xu, Y. (2020). The global search for liquid water on Mars from orbit: Current and future perspectives. Life, 10(8), 120.
- Pagnini F., Thoolen S., Smith N., Van Ombergen A., Grosso F., Langer E., Phillips D. (2024) Mindfulness disposition as a protective factor against stress in Antarctica: A potential countermeasure for long-duration spaceflight?,Journal of Environmental Psychology.
- Pass, J. (2017). Astrosociology education and the future of space exploration, exploitation, and settlement. In AIAA SPACE and Astronautics Forum and Exposition (p. 5160).
- Pekkanen, S. M. (2019). Governing the new space race. American Journal of International Law.
- Petrescu, R. V., Aversa, R., Apicella, A., Kozaitis, S., Abu-Lebdeh, T., & Petrescu, F. I. (2018). There is life on mars?. American Journal of Engineering and Applied Sciences, 11(1), 78-91.)
- Pyne, S. J. (2016). Space: A third great age of discovery. Space Policy, 37, 113–119.
- Qaisar, R., Karim, A., & Elmoselhi, A. B. (2020). Muscle unloading: A comparison between spaceflight and ground-based models. Acta Physiologica, 228(3), e13431.

- Reschke, M. F., Bloomberg, J. J., Harm, D. L., & Paloski, W. H. (1994). Space flight and neurovestibular adaptation. The Journal of Clinical Pharmacology, 34(6), 609-617.
- Rivera, M. V., Vargas, M., Cornejo, J., Plascencia, P. V., Guillen, K., Maquera, E., ... & Cinelli, I. (2024). Space Nursing for the future management of astronaut health in other planets: A literature review. The Open Nursing Journal, 18(1).
- Roser, M., & Ritchie, H. (2023, June 1). How has world population growth changed over time? Our World in Data.
- Rovetto, R. J. (2013). The essential role of human spaceflight. Space Policy, 29(4), 225-228.
- Salazar, J. F. (2017). Antarctica and Outer Space: relational trajectories. The Polar Journal, 7(2), 259–269.
- Salotti, J. M., Da Fonseca, T., Lainé, A., & Moisset, C. (2011, October). Impact of human factors on the growing rate of a martian population. In Impact of Human Factors on the Growing Rate of a Martian Population (pp. 1-5).
- Salotti, J.M., Labache, L., Pellet, E., Riffaud, P., Chator O. (2015). Human Factors Issues for a Sustainable Settlement of Mars. 9th IAA Symposium on the Future of Space Exploration, Turin.
- Salotti, J.-M. (2020). Minimum number of settlers for survival on another planet: The case of Mars. Scientific Reports, 10, 11780
- Sandal GM, van deVijver FJR, Smith N. Psychological Hibernation in Antarctica. Front Psychol. 2018 Nov
- Sanders, G. B., & Larson, W. E. (2011). Progress made in lunar in situ resource utilization (ISRU). AIAA SPACE 2011 Conference & Exposition.
- Santos M. A. d., Herbert J., Cinelli I., Burmann J. A. L., Soares V. V. and Russomano T., "Development of a Digital Platform: A Perspective to Advance Space Telepharmacy," in IEEE Open Journal of Engineering in Medicine and Biology, vol. 4, pp. 168-172, 2023, doi: 10.1109/OJEMB.2023.3237988.
- Schmidt, N. (Ed.). (2022). Governance of emerging space challenges: The benefits of a responsible cosmopolitan state policy. Springer. https://doi.org/10.1007/978-3-030-86555-9
- Seibert, G., Fitton, B., & Battrick, B. (Eds.). (2001). A world without gravity: Research in space for health and industrial processes (ESA SP-1251). European Space Agency.

- Shaw, R., Soma, T. (2022). To the Farm, Mars, and Beyond: Technologies for Growing Food in Space, the Future of Long-duration Space Missions, and Earth Implications in English News Media Coverage. Frontiers in Communication, 7, 1007567.
- She, X., Wang, J., Xu, W., & Xiao, L. (2025). Research on the impact of extraterrestrial lava tube environments on human survival and countermeasures. Space Habitation, 1(1), 100002.
- Siamwala JH, Rajendran S, Chatterjee S. Strategies of Manipulating BMP Signaling in Microgravity to Prevent Bone Loss. Vitam Horm. 2015;99:249-72. doi: 10.1016/bs.vh.2015.05.004. Epub 2015 Jun 25. PMID: 26279379.
- Smith, D. S., & Scalo, J. (2007). Risks due to solar X-ray flares during astronaut extravehicular activity. Space Weather, 5, S06004.
- Smith, T. L. (2025). Martian diversity: A government for pluralistic communities on Mars. Space Policy, 72, 101687.
- Soroko, S.I., Aldasheva, A.A. Individual strategies of human adaptation under extreme conditions. Hum Physiol 38, 626–633 (2012).
- Sparrow, R. (1999). The ethics of terraforming. Environmental Ethics, 21, 227-246.
- Spector, S., & Higham, J. E. (2019). Space tourism in the Anthropocene. Annals of Tourism Research, 79, 102772.
- Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O., & Ludwig, C. (2015). The trajectory of the Anthropocene: the great acceleration. The anthropocene review, 2(1), 81-98.
- Stuster, J. (2010). *Bold Endeavors: Lessons from Polar and Space Exploration.* Naval Institute Press.
- Su, J., & Li, J. (2025). Toward an international legal framework for the protection of outer (McKeown, B., Dempster, A.G., Saydam, S., & Coulton, J., 2025)space heritage. Space Policy, 71, 101625.
- Szocik, K., Norman, Z., & Reiss, M. J. (2020). Ethical challenges in human space missions: A space refuge, scientific value, and human gene editing for space. Science and Engineering Ethics, 26(3), 1209–1227.
- Szocik, K., & Reiss, M. J. (2023). Why space exploitation may provide sustainable development: Climate ethics and the human future as a multi-planetary species. Futures, 147, 103110.

- Szocik, K., Shelhamer, M., Braddock, M., Cucinotta, F. A., Impey, C., Worden, P., ... & Munévar, G. (2021). Future space missions and human enhancement: Medical and ethical challenges. Futures, 133, 102819.
- Szocik, K., Wójtowicz, T., Braddock, M. (2020). The Martian: Possible Scenarios for a Future Human Society on Mars. Space Policy, 54, 101388.
- Tafforin, C., & Abati, A. (2024). Interaction and Communication Abilities at Mars Desert Research Station.
- Tavassoli, M. (1986). Medical problems of space flight. The American journal of medicine, 81(5), 850-854.
- Tomlinson, P. (2023). *Space colonies: A realistic plan*. Troubador Publishing Ltd.
- Tosini, G., & Aguzzi, J. (2005). Effect of space flight on circadian rhythms. Advances in Space Biology and Medicine, 10, 165-174.
- Trappe, S., Costill, D., Gallagher, P., Creer, A., Peters, J. R., Evans, H., ... & Fitts, R. H. (2009). Exercise in space: human skeletal muscle after 6 months aboard the International Space Station. Journal of applied physiology, 106(4), 1159-1168.
- Tronchetti, F. (2013). The political and legal challenges of a Mars settlement. Astropolitics, 11(1–2), 63–74.
- United Nations Office for Outer Space Affairs. (n.d.). The Moon Agreement. United Nations.
- United Nations High Commissioner for Refugees. (n.d.). Climate change and displacement, UNHCR.
- United Nations Network on Migration. (2024, June 4). CLIMB database.
- Vico, L., & Hargens, A. (2018). Skeletal changes during and after spaceflight. Nature Reviews Rheumatology, 14(4), 229-245.
- Williamson, M. (2003). Space ethics and protection of the space environment. Space Policy, 19(1), 47-52.
- Wójtowicz, T., & Szocik, K. (2021). Democracy or what? Political system on the planet Mars after its colonization. Technological Forecasting and Social Change, 166, 120619.
- Young, D., & Docherty, N. (2025). An anticipatory regime of multiplanetary life: on SpaceX, Martian colonisation and terrestrial ruin. Science as Culture, 34(2), 168–193.
- Zheng, N., Ding, C., Su, Y., & Orosei, R. (2024). Water Ice Resources on the Shallow Subsurface of Mars: Indications to Rover-Mounted Radar Observation. Remote Sensing, 16(5), 824.

- Zhu, R. R., & Haqq-Misra, J. (2025). Can a referendum solve problems of shared sovereignty on Mars?. Space Policy, 101701.
- Zubrin, R. (1995). The economic viability of Mars colonization. Journal of the British Interplanetary Society, 48(10), 407-414.