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Research Article

Moving to Mars: The Feasibility and Desirability of Mars Settlements

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ABSTRACT

The on-going space settlement debate has raised questions whether it is possible to settle other planets, and if it was, is it something humans should do. The problem with this space ethical discussion is that it can easily become too vague. To avoid this problem, we suggest a framework for identifying relevant variables that affect the feasibility constraints and desirability factors of establishing space settlements. The variables we focus on include the settlement stage, scale and time frame. Based on the relevant literature, we take mission cost, survival, habitation, water, *in situ* resources for food, oxygen and fuel energy and dependence on Earth as feasibility constraints that are relevant for the framework. None of them are hard constraints, but rather soft feasibility constraints that make it difficult to establish a permanent human settlement on Mars in the near- to medium-term future. However, in the past, humanity has achieved goals that first seemed infeasible. To justify the costs and effort, the goal must be highly morally desirable. We discuss five different desirability factors that could help justify the effort but as each framework has unique feasibility constraints, not all of these factors are sufficient or necessary to justify this effort. We argue that some of the desirability factors prominent in space ethical literature are not sufficient or necessary in our framework, and thus, we conclude that the normative grounds for establishing a permanent Mars settlement in the foreseeable future are weak.

1. Introduction

If humans succeed in settling our neighbouring planet, Mars, it will be a pivotal moment in the history of our species. In the long-term, it may turn out to be as consequential as the colonisation of other continents by European societies in the past centuries. Therefore, it should not be considered only as a technical engineering challenge, but a broad societal question involving multiple ethical, political and social aspects. Thinking about the future of space settlements requires considerations of everything from *motivations to moral desirability* and from *feasibility to long-term consequences*.

The plans for establishing a permanent settlement on Mars have raised many different views and opinions. Many lay people are enthusiastic about the possibility of humans extending their territories beyond this planet; there are also views, aims and hopes of Mars becoming a new extension of our society and of economic markets. Through the established occupation, it would also provide a “safehold” for humans, in case of deteriorating conditions on the Earth. The ultimate aim would be to create a survival plan or “planet B” for humankind. Many of these views are shared by various professionals. At the same time, there are a lot of questions about their feasibility, justification and of their economical, legal and ethical aspects [e.g. Refs. [1–3]]. A further question to be considered prior to human entry to Mars is whether this environment must be protected from terrestrial contaminations, at least until it is adequately surveyed for the possible existence of a local biosphere [4–7].

Since the early crewed missions to Moon in the 1970s, human spaceflight so far has been extended only to low Earth orbit (LEO) and to the space stations (MIR and ISS) there. However, different options for mission architectures and strategies for crewed missions further out to the Moon and Mars have been intensively studied over the past three decades by NASA, as reviewed for example in the study by Rapp [8]. Implementation of the mission plans is currently being developed in the Artemis space programme (including the heavy-duty Space Launch System, SLS) jointly with its international collaborators. The first aims of the Artemis programme are to return human crews to the Lunar surface and establish a crewed station both on the Lunar orbit and on the

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surface. The same or similar technologies will be later applied to crewed missions to Mars (Artemis Plan—NASA's Lunar Exploration Program Overview, NASA 2020) [9].

Also, the private company SpaceX has published its ambitious plans to transport the first crews to Mars, still within the 2020s, and start building a permanent, self-sufficient settlement there [10–12]. It is currently building and testing heavy-duty space launch and flight technology (the reusable Starship spacecraft and the reusable Super Heavy booster rocket). Neither NASA or SpaceX has yet published their final technical plans or dates for the planned mission.

Numerous robotic missions to Mars, as well as the long-term human occupation of space stations on LEO, indicate that the space flight technology for these programmes is available—in principle (on fairly high Technology Readiness Level). However, the crewed missions to deep space targets are much more demanding than any previous missions. Specific challenges for the crewed missions to Mars are caused by the physiological and psychological dangers and stresses caused by the long-duration trip in the deep space condition, within the high cosmic and solar radiation, microgravity and the isolated and cramped living condition of the crew. Heavy-duty, tightly enclosed and pressurised habitats are needed for human survival also on the Martian surface. An additional challenge is either to transport and recycle or to produce *in situ*, all necessary life support supplies (oxygen, water, food) and fuel for the accommodation and operations on the site, and for the return trip to Earth, as reviewed in the study by Fu et al. [13], Verseux et al. [14], Linne et al. [15] and Starr [16].

To promote discussion on the ethical, political and social aspects of space settlement, we offer here groundwork for a normative analysis of the feasibility and desirability of a long-term settlement outside Earth. Further on, we address several aspects of the settlement discussion *per se*. It is important that the participants of this discussion indicate the frame of their views, in terms of the stage, scale and timing of the intended settlement. We also assess the feasibility and desirability factors of settling Mars and point out that feasibility and desirability are interlinked. By desirability factor, we refer to things that increase or decrease the moral desirability of establishing a Mars settlement. Our focus is on *moral* desirability, that is, the factors that give moral reasons for doing something. There may be also entirely frivolous reasons for going to Mars, and we wish to exclude those from our analysis. These concepts are useful tools for analysing the justifiability of different settlement scenarios, as following Robert Goodin et al. [17] according to whom “questions about what can feasibly be achieved in a certain area are just as central to normative concerns as questions about what is desirable in that area”.

A full normative analysis of such a complex and for now, hypothetical issue as settling Mars requires careful consideration of a myriad of aspects and variables. We certainly do not claim to present a comprehensive normative analysis of the topic, but rather, to highlight and discuss some of the key issues.

2. Framing the issue

We identify three variables from which a framework for space settlement discussion can be developed: the pre-settlement/in-settlement/post-settlement stages, scales of settlement varying from small outpost to permanent settlement to self-sufficient society and varying time frames from short- to medium- to long-term. Each variable has its unique set of problems and raises its own ethical questions and also harbours different feasibility constraints and desirability factors.

First, it is important to identify the relevant *stage of space settlement* in question. It may be meaningful to discuss the potential Earth—Mars political relations, as in Deudney [2], even if there were no solid plans on how to establish a Mars settlement let alone a full Martian society in the first place. In addition to the meaningfulness of the discussions, it is also crucial from a moral philosophical perspective, as different stages raise different ethical questions. Borrowing a useful distinction from the *just war tradition*, we propose that the space settlement discussion should be separated into *pre-settlement*, *in-settlement* and *post-settlement* stages. These are similar to the distinct yet interrelated (and sometimes overlapping) “stages” of *jus ad bellum*, *jus in bello* and *jus post bellum* in the just war tradition. It should be noted that this similarity is merely structural, in how different strands of discussion can be compartmentalised. We are not claiming that Mars settlement and war are analogous in other ways. Each of these stages can have different criteria for when there is a just cause for going to war, what kind of conduct is justifiable during times of war and what are the conditions of just peace [18].

Similarly, each settlement stage raises its own set of questions and problems. These different stages are *distinct, and at least partially independent.* For instance, if a space settlement is established unjustly or unethically (i.e., against the principles or criteria found for the pre-settlement stage), it is still important to inquire about the principles and criteria for good and just conduct therein. There is still a duty to make the best out of a bad situation. Their distinctness does not mean that they never overlap or that there cannot be back-and-forth movement between different stages. The stages are also *interlinked*, for instance, in the sense that understanding what is best for the post-settlement stage can affect what is acceptable in the previous stages.

If humankind starts to establish a more continuous or permanent presence outside Earth, the situation will constantly shift and require re-evaluation. Thus, the plans for Mars settlement missions can never be fully set, as they are in constant fluctuation, just as any long-term endeavour that involves humans. The moral philosophical project would then involve mapping out relevant ethical questions and problems for each stage, discerning their interrelations and finding ways to tackle them. Each settlement stage is likely to raise its own inquiries in different fields, such as politics, economics, law, biology, ecology and engineering.

A second important variable for framing the space settlement debate is the *scale of settlement*. Similar to the space settlement stages, *an outpost*, *a permanent settlement* and *a self-sufficient society* outside Earth will raise different questions and problems. In terms of continuous human presence on Mars, mere scientific or economic outposts with limited and shifting populations would be more analogous to research outposts in Antarctica than, say, a settler colony. In the most extreme case, the target of discussion could be a Martian self-sufficient human society. Then, the discussion would be more analogous to independent nation-states that have seceded from their motherland. Mere outposts and full-blown societies raise very different questions, so one should be careful when discussing things under the wide umbrella of ‘space settlement’.

A third variable is the different time frames that can shift the realm of possibility and also have different ethical implications. Consider the claim that establishing a functioning settlement on Mars is impossible. The claim may be true in the near-term, but it is far from clear that the claim is valid fifty, hundred or ten thousand years later. We simply do not know how the future unfolds, although we can make educated guesses. In relation to feasibility, if one assumes that technological change continues, it is natural to think of the time frame as a representation of the level of technological capability. For example, near-term would designate current technology, medium-term future foreseeable technology and long-term future would denote more speculative future technologies.

This list of variables (see Table 1) is not exhaustive, but it includes those that we find most important for the feasibility and desirability assessments and for the more general space settlement discussion in space ethics. There are other important factors that we have omitted from our analysis, like the degree of robotization or automatization, which would certainly affect the feasibility and desirability of space settlement. Perhaps in the future, thanks to robotics, sending *people* to Mars is simply an unnecessary and completely avoidable risk. But this again depends on what we hope to gain from going to Mars. Similarly, the location of the planned settlement would affect feasibility and desirability considerations. For example, Mars, Moon and Ceres, according to Janhunen [19], would all have their own challenges and benefits. Deudney [2] presents another, perhaps more geopolitical framework for assessing the space expansionism and its feasibility claiming that the feasibility assumptions by the space expansionists are related to the desirability of their aims. For the following feasibility and desirability discussion, we want to frame the issue into the pre-settlement stage, with a permanent settlement in mind, in the near- to medium-term future.

3. Feasibility

In political philosophy, feasibility considerations are used either to rule out certain political proposals or as a tool to compare competing political proposals [20]. Thus, feasibility assessments can be made both in a *binary sense* and a *scalar sense*, where the former asks if bringing about some outcome is possible, and the latter asks how probable it is to bring about some outcome [20,21]. Feasibility assessments involve considering *hard* and *soft constraints*. Hard constraints make it impossible and thus infeasible to bring about some outcome, at least in certain circumstances, so they are more important for ruling out things in a binary sense. Soft constraints, on the other hand, affect feasibility comparatively or change the likelihood of some outcome. Thus, they assess feasibility in a scalar sense and allow the ranking of different proposals according to their feasibility. Some political proposals, for instance, can be more feasible than others for a variety of reasons like the general political atmosphere or the state of the economy [20].

Hard constraints categorically rule out certain outcomes, while soft constraints can be altered, for example, with developing technologies or societal change [20]. However, some hard constraints like the lack of some technological means can be time-sensitive [21]. In the early 19th century, it was infeasible to send people to the Moon because of the hard physical constraint of a great distance, Earth's gravity and harsh conditions in space (only to mention a few), but as technology developed, it suddenly became feasible in the 1960s. Soft constraints, such as limited funds or political will, can also be highly limiting, making the probability of some outcome very low. However, the border between hard and soft constraints is constantly shifting as new technological capabilities are developed.

According to Gilabert and Lawford-Smith [20], feasibility claims include the following components:

“It is feasible for X to φ to bring about O in Z”

Table 1
Variables in the space settlement debate (our chosen framework in italics).

Settlement stage	Scale of settlement	Time frame
Pre-settlement	Small outpost	*Near-term future*
In-settlement	*Permanent settlement*	*Medium-term future*
Post-settlement	Self-sufficient society	Long-term future

Here X refers to the agent, φ refers to a set of actions, O refers to the outcomes and Z in the conditions in which an agent may perform those actions to bring about certain outcomes [21]. In relation to the space settlements, the equation variables can indicate multiple different values. The X can present any public or private stakeholders or their collaborative combinations, φ can present any developmental processes, O can present the whole mission or any separate part of it and Z can be defined as any given time span, or a given political or funding frame. Thus, the theoretical variables are vast.

The framework discussed in the previous section is important for the feasibility assessment. For instance, if the time frame is set to the long-term future, one could treat almost any constraint as eventually surmountable. This may have unwanted implications, such as leaving too wide an array of outcomes possible. However, our focus is on current plans and current or foreseeable technological capabilities up to the medium-term future. Also, the scale of settlement is important. Small-scale outposts, for instance, do not face similar feasibility constraints as larger settlements or full-blown self-sufficient societies. Finally, the stage of settlement is also important. The pre-settlement stage of a Mars settlement has a set of feasibility constraints that involves the conditions of both Earth and Mars and must also consider the economic, social, ecological and cultural conditions of planet Earth.

3.1. *Feasibility constraints for Mars settlements*

At the present time, the principal technologies for crewed missions to the Martian surface either exist or are under development, but multiple challenges and feasibility constraints are to be faced before humans can safely enter and spend time on the Martian surface. It is possible that most, if not all of them may be overcome by technical means, and the technologies would be further developed via the experience gained *on site*. Still, the very strict circumstances may limit the achievable outcome of the missions. The most obvious obstacles for the crewed flights, and moreover, to the more permanent settlements, are the following.

3.1.1. *Cost of the missions*

The total expenses of crewed Mars missions are difficult to estimate, but some references can be found for their separate parts. Considering the whole programme's costs, a comparison can be made to the report from NASA stating that the Artemis programme will cost a total of € 93 billion between 2012 and 2025 (NASA Report No. IG-22-003) and completion of that programme to include a 500-day Mars mission in the 2030s would cost about an additional 30 billion dollars [22]. In 2017, Utrilla and Welch published theoretical calculation [23] on the most economical total cost, putatively achievable to a private enterprise and based on modified Mars Direct architecture, to carry out a crewed mission to Mars (including two preparatory flights) to be in the range of 30 billion US dollars. Such high costs may be justified for a short-term highly desirable scientific mission, the implementation of which would nevertheless require strong political and budgetary commitment decades before the launch [1,8]. Such missions are now strongly advocated and are included in the (collaborative) plans of NASA and the private enterprise SpaceX. However, extending these missions to establish a permanent settlement on Mars would commit the responsible agencies to continue the flight programmes, with multiple additional flights in every suitable launch window and with the costs soaring with the size of the settlement(s).

The main parts of the initial programme costs come from the design of the mission architecture and the development, building and testing of the vehicles and other technologies needed *en route* and on-site. The first components of the technology, that is the heavy-duty launch systems, are currently being established, but for the large part of the missions, for example for the descent to Mars, the ascent from Mars, or survival on the surface, the technologies have not been fully designed or developed yet [8].

The final cost of each mission will depend on the specific rocket technology, crew and cargo size, and on the overall design and architecture of the mission [8,11]. A large part of the costs of the travel *per se* is consumed for the launch. For instance, in the past, the launch costs of different space rockets to LEO have varied between $ 5000 and $ 50 000/kg cargo. In the future, this cost may be reduced to about $ 2000/kg by the reusable Falcon rockets [23].

Also, the fuel and technical cost of landing on the Martian surface, and launching again from there for the return trip, depends on the mission architecture, and the size of the crew and cargo—and, of course, of the development and building of the respective vehicles, as reviewed in the study by Rapp [8].

The long travelling time to Mars (about 8 months each way, using LOX-methane propulsion) adds a significant amount of costs and challenges to the missions to Mars, not in fuel, but in the amount of life support supplies and other needs of the crews during the travel, back and forth. Most of the water and oxygen can be recycled in the ship by the renewal technologies that are currently used on the ISS. As a routine, >90% of water is recycled [8,12,24]. Meanwhile, all food for the travel, and also for the stay has to be transported as cargo, as food cannot be produced *en route* due to the lack of space in the ship, neither are the production facilities initially available on the surface. Some of the resources are lost as non-recyclable wastes. In case fuel production is not available on the Martian surface as yet, the cargo must also include the fuel for the launch from Mars, and the return trip to Earth. In addition, a large portion of cargo must be allocated for the life support and mission equipment that are needed on the target site.

To make all this transport feasible in the first place, large parts of the necessary supplies, equipment and infrastructure should be transported to the site by separate cargo flights before the arrival of the crew, to improve the safety and functionality of the crewed missions [11,12]. Thus, the mission requires not only one but a fleet of flights.

The long distance means that emergency help or evacuation in case of emergency is impossible or at least very slow to arrive. Consultation to the home base and expert advice from Earth happens only via a radio connection, and with a delay of 5–20 min [25].

3.1.2. Survival on Mars

Images of the Martian surface portray the landscape as somewhat familiar: It is similar to rocky, mountainous, sedimented and eroded terrains on Earth [26]. Beyond these similarities, the Martian environment is totally different, inhospitable and detrimental to terrestrial life.

On the surface, the low air pressure of the Martian atmosphere and its very low oxygen content (0.13% [14]) mean that unprotected humans would suffocate there fast by hypoxia. The low air pressure would also cause immediate degassing of the blood in their lung vesicles, a condition similar to a strong divers' disease. Hard UV radiation blasts the surface unhindered, and the level of biologically effective radiation is more than 1000 times higher than it is on the Earth's surface. This is detrimental to any exposed bio-organisms, as shown even for the very durable spores of microbes such as *Bacillus subtilis* [27].

The hard particle radiation (composed of the Galactic cosmic radiation, solar particle radiation and occasional solar particle events) is also intense, and its damaging effect is increased by the flux of energetic secondary particles born in the shielding materials. Still, radiation is attenuated to about half of what it is in Martian orbit due to the shielding by the planet; levels may also vary between different locations (e.g., levels are lower in some parts of the bottom of Valles Marineris [28]) and need to be monitored *on site* [29]. In any case, radiation shielding is mandatory.

In addition to the radiation and air pressure, the temperature conditions are also detrimental to warm-blooded or freeze-sensitive terrestrial organisms, like animals and plants. As on Earth, the temperature on Mars varies around the planet, depending on the latitude and the time of the year and the day, so that the diurnal variation in the equatorial region can be even about 100 °C (daytime highs around 20 °C, and night time lows around −120 °C), the average global temperature is −60 °C [14]. Another hazardous factor both for human physiology and for any functional machines and technology on the Martian surface is the thinly grained and sharp dust that often blows around in heavy and long-lasting dust storms.

To survive in this environment, any living organisms must be continuously heavily protected either by space suits (short-term protection) or fully protected housing. The low gravity which is a third of terrestrial gravity causes severe strain on human physiology and this, together with the high psychological stress, may severely impair the well-being of the travellers [28]. Jointly, these stress factors may jeopardise the endurance and survival of the crews, and thus, the feasibility of a successful mission.

3.1.3. Habitats

The initial habitats for crews are postulated to be small transportable containers (modules, barracks, spaceships or landing modules) that would provide adequate shelter, radiation shielding and protection for their survival [12,28]. Living in such tight quarters is likely to cause significant psychological stress [30]. In order to thrive for a longer term on a foreign planet, people must be housed in a liveable and comfortable habitat.

Local resources (regolith, water ice) should be used for a large part of the construction materials. About two metres of regolith would reduce the radiation to levels acceptable by the ESA safety standards (0.5 Sv/y for blood-forming organs, 3 SV/y for skin), while a depth of about 90 cm may be adequate shielding for short-term protection [31]. Architectural design can be used to provide visual and comforting ques (e.g., use natural light, colours, green plants, redundant safety features, telecommunication screens, easy access to surfaces), to support societal well-being and to reduce anxiety, claustrophobia and mental stress [28,30]. Habitat building and maintenance will be one major expense of the settlement.

The habitats must provide continuous access to the essential life support supplies like breathable pressurised and clean air with suitable gas composition, potable water and water for hygienic needs. These volatiles can be mostly provided via physical and chemical processes to circulate and rejuvenate them [16]. These mechanisms must be provided on the highest possible safety level, considered as a fail-safe system by using multiple (three-fold) redundancies of each system or technology [28]. Monitoring of the human habitat conditions must be continuously followed by automatic, fail-safe and artificial intelligence-controlled monitoring systems [28]. Even with the most secure construction, the function of the life-supporting infrastructure may be jeopardised for example by acts of sabotage, or by unexpected hazards, such as strong sandstorms or solar particle events.

3.1.4. Water

Due to the low air pressure and the very low average temperature, water does not exist on the surface in liquid form. It either evaporates or freezes immediately, and ices exposed to the atmosphere sublimate fast. However, small ice deposits can be detected even quite close to the surface [32], and large reservoirs of water ice [33–36] and even liquid aquifers [37] have been detected in the deep subsurface by remote mapping from the orbit. For more accurate prospecting, the characterization of local water sources is the first step of preparation for a putative base camp, and even more so, for a permanent settlement. Water excavations or mining, storage and transport [38] need their own infrastructure and design. As a precaution for the supply, some water needs to be transported also from the Earth for the safety of the crews [12].

The early guidelines for space missions allowed only a minimal amount, or 1.8 kg of water/day for human consumption [39], but a more normal lifestyle, allowing also for washing (one shower/day) would require the use of 14 kg water/day/person or more [12]. In addition to human needs, water is excessively valuable for multiple activities, for instance as a source of fuel. Production of the fuel components (oxygen and methane) for the return trip of the SpaceX vehicle requires 600 tons of water, corresponding to an ice volume of about 730 m^3 of ice (a cube of about 9 m at each side) [12]. In addition, water is needed for multiple other purposes like plant growth, habitat maintenance, laundry, binding of dust and for processing of the Martian regolith into a cement-like substrate for producing construction material [12,16,28].

One problem in the utilisation of the local water sources is that the quality of the subsurface water, or their possible high content of perchlorates and other toxic salts are not known [40,41]. The subsurface may also contain various harmful organics, and putatively, even extinct, or still viable life forms. To make water suitable for human consumption it needs to be purified and monitored for its quality, as reviewed in Heldmann et al. [12], Starr [16] and Amini et al. [28].

3.1.5. In situ resources for food, oxygen and fuel

The total amount of life support supplies needed for any size of a crew, for any duration of a mission, can be calculated based on the amount of supplies needed per person per day. For instance, the total need of food has been calculated for a crew of six for a hypothetical mission of a total of 525-day visit on Mars (calculated mission scenario), about 15 000 kg [39,42]. Also, an adequate amount of water and oxygen must be transported, but their amount is not dependent on the duration of the trip as these volatiles can be mechanically circulated throughout the trip. It may also be feasible to produce food and oxygen on the Martian surface from the local resources, and also via recycling all the wastes, biomaterials and CO_2. The food production would happen by various photosynthetic organisms such as plants, algae and cyanobacteria, and further on, via processing by various cell cultures and small animals such as insects, fish or crustacean [14,42–45]. Through past decades, methods have been developed in many laboratories to design closed loop *in situ* production systems, by circulating the wastes back to the resource pool via various bio-regenerative methods or pyrolysis, as described in the reviews by Janhunen [19], Horneck et al. [39] and Clauwaert et al. [46]. However, functional closed-loop food production systems have not been established yet, as reviewed in the study by Rapp [8].

Setting up photosynthetic food production would also have its own intrinsic cost: these production organisms must be maintained within certain species-specific air pressure, temperature and radiation-shielded conditions, as reviewed in the study by Verseux et al. [14], Horneck et al. [39] and Perchonok and Cooper [42].

Plants typically do not tolerate CO_2 concentrations above 400 mbar or freezing temperatures. They also do not tolerate high levels of mineral salts, reactive oxygen species (perchlorates) or nitrous oxide in the growth substrate. Thus, the Martian regolith is not directly suitable as a growth substrate for plants [42,43], but it must be processed for this purpose either by desalting, and/or via production and addition of suitable biomaterials (algae, plant materials, wastes, cyanobacteria) [14,45].

Additional problems in the utilisation of traditional crop plants are their long growth periods (typically, a few months from seeding to harvest) and the high portions of the unusable parts in the total crop. Further problems are the possible insecurity of the successful crop, the specific growth conditions, infrastructure and equipment and the high amount of work and skills needed in different steps of production [42]. These delay the set-up and possibilities for a self-sufficient community. Wheeler [43] predicts that the on-site production would start on a small scale, producing initially only a minor supplement to the food.

In the plans for a settlement on Mars, it has been proposed that the minimal human energy need would be 2000 kcal/day, which is a rather low-level provision compared to the average diet in western countries, of nearly 3500 kcal, or in the whole world, of 2800 kcal [47]. It has been also estimated that this amount of food stock could be produced in an area of 50 m^2/person [44]. This assumption would require that the crops would produce ultimately high yields, i.e. more than the typical maximal yields of the field crops in terrestrial conditions (e.g., in the range of 0.8 kg/m^2 for small grains, 5 kg/m^2 for potatoes, and 10 kg/m^2 for tomatoes/season [48]). Even with that estimated (minimal) cropping area, the food production for a population of 1000 persons would need an area of five hectares. Construction of this size of plant growth space in the protected, shielded and temperature-regulated conditions, with suitable infrastructure, will take considerable time and investment.

3.1.6. Energy

The settlement plans described above are based on an assumption that an adequate/non-limiting energy supply is available on the Martian surface. The plans assume that this energy is available, in part, from local resources, such as solar and wind energy on the planetary surface, and water to produce hydrogen and methane [12,16,28]. Indeed, these energy forms are available, in variable amounts depending on the location, and the time of the day and the year. Their harvest and conversion to usable form require suitable machinery like windmills and photovoltaic panels, to be transported from Earth. However, both production methods are vulnerable to local sandstorms: the very thin sand particles carried by the frequent winds easily cover the solar panels and may also easily jam the rotating bearings of the windmills.

To provide a heavy-duty backup for the local energy sources, the current mission plans are relying on the use of multiple 160 kW nuclear fission reactors (NASA design reference missions), as reviewed by Rapp [8]. The design for the extendable crew habitat initially planned to house up to nine persons is planned to be powered by multiple smaller (10 kW) nuclear reactors [28].

3.1.7. Support flights from the Earth

Considering the primary needs of the infrastructure (water harvesting, housing, power systems, communication capabilities, human health, and safety), it appears that self-sustaining food production could be established only later, after the building of high-quality human habitats [12,28]. Thus, during the early establishment of the habitats, food supplies should be transported from the Earth.

The total need for food and other unique items, for each person per day on the Martian surface, is about 2 kg/day. Thus, over the 26-month period (i.e., duration between the optimal launch window for supply flights) each person would consume about 1560 kg of these supplies. A crew of ten persons staying on the Mars base would need about 16 000 kg of food supplements and other personal needs. Scaling up the number of inhabitants directly indicates the amount of cargo that is needed for the supplements, for example 1 600 000 kg is needed for a 1000-person community. This indicates that 16 cargo ships with a hundred-ton cargo capacity [44] would be needed every other year just to haul food for the community. This amount is to be added to the number of travelling passengers, and all the technical supplies needed for building up the habitats and the settlement. The high number of space flights bears not only the direct cost of the flights, but also the hidden cost of a significant increase in greenhouse gases in the Earth's atmosphere, caused by the launch exhaust gases.

Cargo that is needed for building all the functional infrastructure (the habitats, growth rooms), the energy production (windmills, solar panels, nuclear reactors, nuclear fuel and liquid fuels including water, hydrogen, oxygen and methane), storage and handling, electric networks, computer servers and data networks, heavy-duty machinery, high-pressure fuel production, handling and storage facilities, pre-prepared landing pads, radiation shields, exterior shelters, dust-control equipment, and so on [12], mounts up to considerable weights. This need continues on some level through the existence of the settlement.

3.2. Overview of the infrastructure

The presented overview of the feasibility constraints is only a strongly simplified description of the total requirements of settlement enterprises. It brings up the point that the very basic resources for human existence (planetary surface, water, carbon source, minerals, sunlight) do exist on the Martian surface, and that it may be feasible to utilise them *as in situ resources* for human survival. It also points out that these resources are scarce and difficult and expensive to exploit. The destination is so remote and located in such a dangerous deep space environment that human missions, let alone the long-term settlement there will be very costly.

4. Moral desirability

For an object of evaluation to be morally desirable, there must be moral reasons for wanting it. For instance, the object is somehow morally valuable or is necessary for pursuing some other morally valuable goal. It should be noted that moral desirability is a theoretical normative concept, and not, for example, an approximation or generalisation of what people in fact seem to desire. For example, becoming a dictator could be highly desirable for some people. However, there are a number of reasons why, in reality, a dictatorship would be *morally* undesirable. Similarly, the majority of people could find a Mars settlement (or the idea of it) highly desirable (as an object of their subjective desires), while further moral philosophical inquiry could show that such ideas are indeed morally undesirable. Interestingly, if a Mars settlement would be generally perceived as desirable in the non-normative sense (that people want it for whatever reasons), this would increase the political feasibility of such plans. However, not everything that could be done ought to be done, and therein lies the function of moral desirability assessments: they give guidance on whether some possible things are worth pursuing. This means that for an all-inclusive normative analysis, both the feasibility and the desirability of the object of evaluation need to be considered in an appropriate amalgam [49].

4.1. What makes Mars settlements desirable?

In this section, we discuss five reasons for going to Mars: science, long-term survival of humanity, economic opportunities and resources, inspiration and adventure. In narrowing down and identifying the factors or rationales in favour of Mars colonies, we have followed previous literature including [3,8,50–52].

4.1.1. Science

Since the beginning of the space-faring era in the 1960s, Mars has been a highly interesting target for exploration. The current atmosphere is so thin that water cannot exist there in liquid form, but with an adequate greenhouse atmosphere, it could harbour liquid water on its surface. In the distant past a thicker atmosphere has allowed the existence of large amounts of water on the surface [53,54]. During this time the conditions have been potentially habitable, and it is possible that the planet has hosted some kind of simple life. It is even conceivable that some of the putative early life forms would have adapted and found refuge in some subsurface locations and could still exist in such locations on the planet [53,54]. The possibility of either extinct or extant life on Mars is one of the most compelling questions to be solved in the search for extraterrestrial life, as reviewed by Rapp [8] and Cockell [53]. In addition, research of the whole Martian environment, terrain, geology, history and resources are of high interest both for science and for human exploitation and settlement [8].

Therefore, the first crewed mission to Mars will likely be scientific in nature. Indeed, many argue that the pursuit of scientific knowledge provides the strongest reason to go to Mars [8,50–52]. Arguably scientific knowledge and understanding are valuable in themselves. Moreover, scientific innovations and findings can vastly improve human society and many of us are simply interested in finding answers to life's ‘big questions’, such as are we alone in the galaxy and what is the origin of terrestrial life? Going to Mars can help us answer these questions. Hence, one valuable thing we may gain by establishing a permanent human presence on Mars is increasing scientific knowledge [3,51,52,55].

There are good reasons to include humans in the scientific exploration of Mars for at least as long as robotics and artificial intelligence remain not advanced enough [56,57], but these benefits can probably be acquired by small scientific outposts. However, any human activity on Mars, meaning even small outposts, can jeopardise science goals due to the contamination risk that humans bring with them; humans cannot be sterilised from microbial populations to the extent that robots and spacecraft can. Indeed, several researchers have warned against contaminating Mars before the question of existing life is properly solved [e.g. 5,6,58]. Planetary protection policies have been developed to avoid harmful forward and back contamination (NASA interim directive 2020) [59]. Careful planning and effective implementation of planetary protection requirements is vital for mission success [60]. Of course, large-scale settlements and more invasive human activity on Mars would be even in a greater conflict with scientific goals. As Schwartz [50] notes, any perturbations in the Martian subsurface due to, for example, habitation or excavation would likely contaminate materials that could potentially contain biosignatures of past life on Mars. The basic problem with the conflict between science goals and Mars settlements, according to Schwartz [50], is that settlement activities “will produce equivocal observations that impair researchers' abilities to constrain and understand the various atmospheric, climatological, hydrological, and geological processes at play on Mars.”

This suggests rather strongly that the order of precedence of different Mars missions should be *science first* since other preceding activities can deprive us of marvellous scientific findings [50,51]. Thus, for the time being, human impact on the Martian environment should be kept minimal, in order not to jeopardise valuable investigations. This of course does not mean that when enough time has passed and Mars has been rigorously studied in its pristine condition, that other activities on Mars could not take place. Yet, it can be challenging to draw this line; what does it mean for Mars to be sufficiently scientifically explored?

4.1.2. Long-term survival

Humanity faces many risks that could wipe humans out of existence, such as pandemics, nuclear apocalypse, extreme climate change, ecological collapse, rogue artificial superintelligence, supervolcanic eruption, asteroid or comet impact and other risks that have not been foreseen yet [61–63]. Thus, a common rationale for settling Mars is that a settlement in space reduces the risk of human extinction [63–67]. The idea rests on a simple statistical fact: it is less likely that an existential catastrophe occurs simultaneously on two planets rather than it happening in a single location at a time.

Protecting humanity is indeed a noble cause and avoiding premature annihilation is largely considered extremely desirable. Therefore, if settling Mars helps us to safeguard humanity, it vastly increases its moral desirability. However, there is much to be said about this idea and generally, one has to be careful in situations where an object of evaluation seems to be almost infinitely desirable because one can easily be charmed by such arguments. Careful consideration may show that these hopes are either not realistic or that there are severe limitations to what can be justified in the name of such goals.

First, for a Mars settlement to properly work as a hedge against human extinction, it needs to be sufficiently self-sustaining and sustainable. Thus, this rationale does not increase the desirability of settlements that are highly dependent on Earth for their survival, as are the settlements that are feasible in the foreseeable future (see Section 3). Albeit it is good to recognise that outposts and medium-scale settlements are likely necessary steps to one day achieving a more self-sufficient society on Mars.

Second, some extinction risks can be to some extent correlated between Earth and Mars. For example, a pandemic, war or misaligned artificial intelligence might affect both [62]. This means that a Mars settlement does not lower the total risk of human extinction as much as one might first assume.

Third, building a settlement on Mars is a much more expensive way to mitigate extinction risks than are some low-hanging fruits on Earth. These more cost-effective ways could include things like investment in global catastrophic risk research, efforts to increase global food security, enhancement of pandemic readiness and development of asteroid and comet deflect capabilities [62,64]. Also, even after settling space, Earth will quite certainly continue to be the home for the vast majority of people. Thus, we have good reasons to avoid catastrophes on Earth in spite of the worries for humankind's long-term survival. This highlights the crucial point that settling space should not distract us from efforts to mitigate global catastrophes on Earth [3].

These three points illustrate the limitations of the long-term survival argument and consequentially the moral desirability it can provide for Mars settlement enterprises. Everything said above does not undermine the case that in the long run space settlements are probably a good way to safeguard humanity, and thus we eventually may have a moral obligation to extend human life to outer space.[1] However, what it does question is the urgency to settle Mars. In general, the considered time frames have interesting implications for desirability since short-term costs can yield great long-term benefits. On the other hand, spanning the timeframe too far and wide can obscure some important elements of short-term considerations like, in our case, the well-being of the first space settlement inhabitants.

4.1.3. Economic opportunities and resources

Another argument in favour of settling Mars is that a settlement on Mars provides new economic opportunities, in other words, it accelerates economic growth (for arguments along these lines, [67,68]). This idea is sometimes coupled with the hope that we can mitigate our negative environmental impact on Earth by using resources from space and perhaps even move polluting industries there [69,70]. Economic opportunities on Mars could include things like the exploitation of Martian resources, mining of the Main Belt asteroids and tourism. The basic sentiment is that space is full of riches that could benefit humankind, and a human presence on Mars helps us to tap into these goods.

Other things being equal, increasing the well-being of humans (or any other sentient beings for that matter) is quite obviously morally desirable. The same applies to limiting the deleterious effects that humans have on the terrestrial environment. Nonetheless, before adding these factors to the moral calculus in favour of Mars settlements, one has to question if the conquest of Mars can really provide these benefits. And if it can do so—at what price would they come?

First, as discussed in Section 4.1.1., the economic exploitation of Mars can conflict with scientific goals. Furthermore, it is in no way guaranteed that the economic prospects on Mars will widely benefit the well-being of humankind as a whole. Instead, it seems more likely that the benefits are mainly reaped by a relatively small group of already well-off people—at least as long as we lack proper distributive legislative frameworks. This setting seems unfair since the costs of lost scientific opportunities would be bared by all. Hence, forbearance is called for [50,51]. Also, Persson [71] has raised a worry that if a settlement is governed by profit-seeking companies, the civil liberties of the individuals on Mars, such as freedom to move or assembly, might not be much cared for. Such concerns decrease the desirability of certain kinds of settlements for obvious reasons.

Second, Stoner [52] has noted that it will be significantly more cost-effective to mine the Moon or near-Earth asteroids than Mars. Thus, the mineral wealth of Mars will not provide an urgent reason to go there. Moreover, consider the feasibility constraints for Mars settlements as discussed in Section 3. It seems that economically viable space settlements that in theory could provide ease to our environmental predicament, lie many decades if not centuries into the future. This is evidently too late to provide any help to our current ecological crisis.

For now, Mars is simply too far away and has too deep of a gravity well to provide sufficient return for investment when it comes to space resources. As Cockell [72] notes "[s]pace does not offer a panacea." For the moment, we have to learn to live more sustainably on Earth. This again does not mean that in the *long-term*, the economic opportunities on Mars could not provide a good reason to go there.

4.1.4. Inspiration

It has been argued that space settlements provide opportunities to experiment with alternative forms of social order and political systems [71,73]. Settling Mars has also been advocated on the grounds that by doing so we avoid societal stagnation. The idea behind this is that space and more precisely Mars provides a new frontier, the conquest of which promotes cultural diversity, technology, and innovation [74]. Even the opportunity for humans to seek new spiritual insights has been offered as a rationale for space

[1] Perhaps, we also have a duty to expand *life in general* to space in face of uncertainty about the existence of extraterrestrial life. Mars could be one step in this process. Though, if we want to maximise the longevity of life originating from Earth then ideal targets would be habitable exoplanets orbiting young stars with long lifespans [96].

settlements [3]. Furthermore, according to Schwartz [51] "[a] common theme of space advocacy [...] is that spaceflight ought to be given increased support because it is uniquely educationally inspiring." Similar arguments could apply specifically to Mars missions and the eventual settling of the planet. Thus, it seems that Mars is a canvas to which we project our dreams and hopes [75].[2]

Undoubtedly, if Mars settlements provide a rich and strong source of inspiration that helps us achieve various societal goods, this increases its desirability. Nevertheless, we have to be cautious of putting too much weight on these arguments because they may be ill-founded. For example, Schwartz [76] has criticised the narrative of avoiding social stagnation through settling the space frontier. In another paper, they undermine the claim that spaceflight is somehow especially educationally inspiring by showing that there is no clear evidence that spaceflight spending has a positive impact on the increased scientific literacy of the public, or the number of STEM students [77].

However, sometimes even impossible and infeasible proposals inspire action [78]. Yet, when it comes to social and political inspiration, Stoner [52] has pointed out that there are many isolated places on Earth that could provide similar inspiration and fresh opportunities for experiments in living. Any hostile and remote corner of Earth is still much friendlier to humans than the surface of Mars. So, if we want to reinvent our way of living, why not start by settling isolated places on Earth?

4.1.5. Adventure

Settling Mars will undoubtedly be an extraordinary adventure. The promise of adventure and new frontiers may serve as a strong motivation for some settlers [3].

Laing and Frost [79] have examined the motivations of space tourists. Their findings suggest that adventure-seeking and hedonic thrills are indeed major motivations for people who want to travel to space. From the key motivations that they found in their data, many relate to the idea of adventure one way or another, including *thrill-seeking, excitement, risk, freedom/escapism, novelty, curiosity and challenging oneself.* These same motivations would probably also apply to future Mars settlers. Robert Zubrin [80] seems to echo such motivations by claiming that "[t]he question of taking on Mars as an interplanetary goal is not simply one of aerospace accomplishment, but one of reaffirming the pioneering character of our society."

Arguably, adventure-seeking is not a sufficient reason to go to Mars since such desires should not be satisfied with grandiose enterprises, whose economic and moral costs and risks are significant. Nonetheless, the possible hedonic experiences associated with adventure, novelty and being part of a pivotal moment in human history count in favour of the desirability of Mars settlements. That said, the desirability or justification of Mars settlements will likely not form from a single consideration but from a bundle of reasons. Indeed, if many simply want to go to Mars (or many want that *humanity* goes to Mars) because it brings them things such as meaning, joy and excitement, that may be a part of the bundle of considerations that make the case for the desirability of settling the Red Planet.

4.2. Other factors to consider

In addition to the envisioned benefits of Mars settlements, there are factors that diminish the desirability of settling Mars that we have not considered yet. Establishing a permanent human presence on Mars involves many serious risks of great harm. For example, in the literature on the ethics of space settlements, there is a prominent worry about extraterrestrial liberty. Cockell [81,82] argues that societies in space run the risk of tyranny and totalitarian regimes. This is because the harsh environment in outer space, as discussed in Section 3, makes settlers extremely dependent on technologies for their survival. This in turn creates opportunities for centralised control, exploitation, tyrannical oversight and authoritarian governance. This risk must be taken into account in the planning of deep space missions and the design of settlements. Cockell [83] has contributed to this effort by suggesting ways how we could minimise the risk of tyranny in space through what they call "freedom engineering", including ideas such as decentralisation of vital technologies and mitigation of coercive surveillance. So, the risk of totalitarianism is not necessarily devastating. However, if the risk cannot be adequately minimised, it decreases the moral desirability of societies of the world.[3]

The fact that space settlers have to survive in such extreme conditions also makes it quite likely that the inhabitants in early settlements will have somewhat limited rights and increased duties, in general. For example, reproductive rights may have to be restricted if means and resources to foster offspring are scarce. Hence, space settlements also raise bioethical issues (on space missions and bioethics, see e.g. the study by Szocik [84], Szocik and Reiss [85] and Huttunen and Sivula [86]). Interestingly, reproduction on Mars also raises intergenerational issues which are another set of worries related to space settlements. For example, what if the chances for a good life are not great for new-born Martians? Or what if future generations on Mars cannot migrate to Earth because their bodies have adapted to the lower gravity of the Red Planet and there are no technical means to overcome this? Would it still be morally justified to reproduce on Mars (on the ethics of reproduction in space, see e.g. the study by Balistreri and Umbrello [87])?

An additional bundle of concerns is related to environmental issues. If local microorganisms live on Mars, human explorers could impose a contamination risk on them as discussed in Section 4.1.1. This is a problem if one assigns moral status to extraterrestrial microbes or wants to protect them for some other reason [88–91]. Even if Mars is lifeless, some argue that we should protect the Martian environment in its pristine state (at least to some extent). The motivation for this may be varied ranging from ideas that Mars as a planet has moral standing, to the claim that Martian wilderness is valuable to the extent it should be protected, or that Mars or some sites there have formed integrity and beauty that should be respected (for an overview see the study by Persson [92]). As a solution to this, as a sort of compromise, some [68,93] have suggested leaving certain parts of Mars in their pristine condition while settling others. Finally, related to environmental concerns, there is a worry that if space traffic becomes large in volume it could have detrimental effects on Earth's environment. Frequent space launches could affect especially ozone depletion, climate change and ecosystem toxicity negatively [94].

Also, some of the feasibility constraints discussed above make it less likely that a permanent settlement could guarantee life-support for all of its denizens. Schwartz [95] has argued that we should not establish space settlements that cannot guarantee such basic rights as water or breathable air, and that political philosophical considerations about space settlements should be more demanding rather than lenient because of them being burdened by demanding environments. This demandingness can decrease the desirability of permanent settlements.

[2] Arguably, we also project our fears to the Red Planet.

[3] Unfortunately, it may increase the *subjective* desirability for some actors.

All of these worries, considered in this section, if not accounted for to an adequate extent, decrease the moral desirability of establishing a permanent human presence on Mars.

5. Discussion

None of the feasibility constraints discussed in Section 3 seems to be hard constraints. In other words, it seems possible to establish a settlement of some sort on Mars in the medium-term future. However, even if something is possible (in theory) it does not mean that it will likely be achieved or that it could be achieved without massive costs. Therefore, identifying that Mars settlement is possible in the binary sense is not very interesting.[4] Instead, it is more relevant to discuss the feasibility of Mars settlements in a scalar sense in relation to soft constraints. As we have discussed, there are some extreme difficulties involved. They may be overcome but likely it would be costly (at least in the near future). As for immense costs, they need to be justified. Such justification can be searched for from the moral desirability of Mars settlements.

If the desirability of establishing a Mars settlement is particularly high, there may be reasons to find ways for trying to make it more feasible. For instance, the extremely high desirability of lowering the risk of human extinction can give action-guiding reasons for seeking out ways to overcome even hard constraints, not to mention the more easily malleable soft constraints. On the other hand, if establishing a Mars settlement is highly infeasible, it can also lower its overall desirability. There may be costs people are not willing to pay or risks that make such plans unpalatable. In this way, feasibility considerations can be factored into the overall desirability of some outcome. Thus, feasibility and desirability can affect each other.

Feasibility constraints are always assessed in a context. As Lawford-Smith [21] notes, they are time-sensitive and agent-relative. To determine the relevant context for evaluating a Mars settlement, we have suggested a framework with three variables: settlement stage, scale of settlement, and time frame. The framework we chose for discussion is a pre-settlement stage for a settlement in the near to medium-term future. The feasibility constraints we have discussed pertain primarily to this chosen framework, although similar constraints can be relevant for others. In Section 4, we discussed the moral desirability of Mars settlements by examining reasons to settle Mars. These reasons must also be given in a context and thus match the chosen combination of the framework variables.

Some desirability factors can be achieved in *various* frameworks. For example, science can be conducted on all settlement scales. Thus, an outpost, a larger settlement and a self-sufficient society can all enjoy the moral desirability from science. Yet, if a smaller-scale settlement is *sufficient* for achieving scientific goals, it may be an *overreach* to use the desirability of science to justify anything larger than an outpost. A larger-scale settlement would then require additional justification. Hence, the desirability from science does not automatically translate to all scales.

The list of framework variables discussed in this paper is not exhaustive. For instance, the level of automatisation or robotisation could add an interesting layer of considerations; if the economic or scientific desirability factor could be achieved with robots and could be entirely automated, there would not be a need to send humans into space. Thus, robots could be sufficient for achieving these benefits, and thus taking on the feasibility constraints of sending out humans could not be justified. Although, changing the framework by adding extensive robotisation would again change the feasibility constraints.

Furthermore, some desirability factors are *only* achievable in certain frameworks. For instance, the desirability from humanity's long-term survival is arguably only achievable in an adequately self-sufficient society, since outposts or settlements that are highly dependent on Earth for their survival would not significantly lower the risk of human extinction. So, achieving this settlement scale is *necessary* for realising the desirability from long-term survival. In this case, the burden of overcoming the soft feasibility constraints of a settlement cannot be justified on the desirability of survival alone, as it remains underwhelming towards achieving that goal.

However, one can argue that the settlement is a necessary step for achieving the next settlement scale. Thus, the desirability of survival can indirectly, or by extension, justify the settlement *if* the ultimate goal is a self-sufficient society. However, this argumentative move comes with the cost of changing frameworks, which means that the survival desirability factor must be balanced out with the new set of feasibility constraints involved in the society scale. Also, if the goal is to establish only a small settlement and not anything of a larger scale, survival cannot be used to justify its costs.

Note that this same dynamic applies to time frames. For example, if one argues that we should settle Mars and utilise space resources in order to alleviate our current ecological crisis, it is necessary to stay in the time scale of near or medium term. Such a desirability factor cannot be cashed out if space activities that take pressure from Earth's environment are only feasible in the very long term.

So, not all desirability factors are applicable to all cases. One must be careful to acknowledge the sufficiency and necessity of certain framework variables for different desirability factors. Otherwise, one risks overreaching or underwhelming the desirability factors. This demonstrates the importance of identifying the relevant framework for discussion. Feasibility and desirability assessments always occur in *some* framework, and not being clear on the framework can lead to conflation, confusion, and in the worst case hasty decision-making. When performed correctly, feasibility and desirability assessment is an important analysis and policy tool. Merely claiming that something is possible does not mean that it is feasible, at least not in the scalar sense. On the other hand, identifying the relevant desirability factors is equally crucial, as human history knows many cases where seemingly infeasible outcomes were pursued and achieved because of their extremely high desirability. Thus, the technological question about settling Mars should be accompanied by normative considerations: why should we ever do it?

Interestingly, the extreme difficulty of setting up a sustainable settlement on Mars portrays to us the value of the unique "planetary services" that are available to us on planet Earth. These include gravity, tectonic activity and volcanism which serve to move the volatiles between the atmosphere and the deep mantle, the magnetosphere that blocks heavy ionic radiation, and the atmosphere that blocks hard UV-radiation from the sun and attenuates the harsh temperature variations. All of this allows the Earth to maintain liquid water on the surface and has made possible the development of complex ecosystems.

Our efforts to set up habitable conditions on Mars also provide us valuable insight into our dependence and adaptation to our familiar terrestrial conditions, for instance to the gravity and atmosphere of this planet. We are also dependent on the complex ecosystems that provide various "ecosystem services" such as food chains, carbon cycles, degradation of organics and pollinators that facilitate our food production and livelihood. The natural terrestrial

[4] Lawford-Smith [21] points out that "We can admit that an action is really hard for an agent but still insist (a) that it is feasible for him, in the binary sense that it is one of his options, and (b) that what is interesting for scalar feasibility is only the extent to which that action is likely to produce the outcome."

resources (in their part) facilitate the industrial lifestyle, and the wide and varied societies facilitate the cultures, education, exchange economy, and social care of its members. These rich ecological, social, cultural and economic networks are arguably preconditions for good life and thus it is important to ask can they ever be extended to Mars?

6. Concluding remarks

This paper had two aims. The first was to provide a framework for future discussion on space settlement that ensures that the discussants are engaging in the same discussion. The second was to show how feasibility and desirability assessments of space settlement are interlinked and can provide useful tools for analysing the justifiability of different space settlement scenarios. The guiding question was how to discuss in a meaningful and constructive way whether we should establish space settlements. We suggest that the ‘should’ is comprised of two components: feasibility (‘could we?’) and moral desirability (‘is it morally desirable?’).

First, we suggested a framework for the space settlement discussion. It ultimately has two functions. The first is practical, as the framework ensures everyone is participating in the same discussion. This seems simple, but the risk of conflating different framework variables like space settlement stages, scales, and time frames is evident. The second function is more theoretical. Each framework contains a unique set of feasibility constraints, and not all framework variables are necessary or sufficient for all desirability factors. Without identifying the relevant framework one can underwhelm or overreach desirability factors when trying to justify the costs of overcoming some of the feasibility constraints.

Then we examined the concept of feasibility and identified some of the key feasibility constraints for a Mars settlement in our chosen framework, that is, a pre-settlement stage plan for a Mars settlement in the near- to medium-term future. We concluded that none of the identified feasibility constraints count as hard constraints, that is, none of them make Mars settlement plans impossible, but there are serious soft constraints that make Mars settlement plans extremely costly and difficult to achieve.

Finally, we discussed five different rationales for settling Mars. All of them—except the moral desirability from science—face at least some severe limitations. Because of these limitations, the moral desirability of settling Mars is more questionable than what is often assumed. When this insight is coupled with the feasibility-related challenges, the justification of a permanent settlement on Mars in the coming decades becomes unconvincing.

Author contributions

Mikko M. Puumala: conceptualization; investigation; writing; editing. Oskari Sivula: conceptualization; investigation; writing; editing. Kirsi Lehto: conceptualization; investigation; writing; editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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