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Supply Chain Sustainability in Outer Space: Lessons to Be Learnt from Remote Sites on Earth

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Abstract: Space exploration, with its enormous distances and extreme environments, is a challenge to technology, human habitation, sustainability, and supply chains. On the flip-side, however, it can provide a new vantage point on how to improve human life and planetary prosperity. This objective requires the development of economic and sustainable supply chains and a governance framework to guarantee fundamental human needs and well-being under the limitations of distant and inhospitable environments. This review describes learnings for human habitation in space from remote communities on Earth that have developed and survived over generations. These include a long history of human survival strategies on Tristan da Cunha, Pitcairn Islands, Nauru, and Easter Island. Their supply chain management solutions and their problems can guide the implementation of logistics systems for the efficient use of resources in space, to satisfy vital needs of human survival but also to ensure social and governance in space, e.g., build-up of thriving communities, mobility, and industrial activities. This review demonstrates that there are significant gaps in recent space supply chain studies with respect to the space environment, social and governance. Analysis of established practices and concepts from remote regions on Earth can readily respond to these deficiencies and thus supplement space exploration. This review recommends extending the assessment of supply-chain assets from the near future to long-term strategic. This implies going far beyond current space supply chain reports to include aspects of social responsibility and governance, such as sustainable health systems, product quality management, and local decision-making.

Keywords: supply chain; space economy; ISRU; remote places; sustainability; logistics

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1. Introduction

As human activities in outer space extend their reach to the Moon and Mars, more complex and sophisticated supply chains will be required. Implementing logistical frameworks that match the environmental conditions of off-Earth environments will involve many areas of science [1] to study how natural phenomena will influence the space economy [2]. Certainly, extending the reach of business to places such as the Moon or Mars will be a new milestone in the era of the "democratization of space" [3].

Consequently, infrastructures and systems will have to be developed to coordinate the respective flows of materials, money, and information [1,4]. Measures will also have to be taken to optimize travel and reduce transportation costs [5,6]. In addition to the above, the in situ resource utilization (ISRU) approach is expected to become the main strategy for creating supply chains that are not dependent on Earth-based resources [7]. If so, unlike what has occurred on Earth throughout human history, economic activities related to settlements created outside our planet will be conceived as systems based on sustainability, understood holistically and realistically. Learning about the functioning of supply chains can be taken from historic failures in setting those up. The Vikings from today's Denmark and Norway made long-distance trips of a logistic complexity equivalent to a Moon or Mars trip today in view of the limited technological capabilities in the past. The Vikings attempted to colonize remote islands deep in the Atlantic Ocean, including Orkney, Shetland, Faroe Islands, Iceland, and Greenland. They even reached out to the eastern shores of North America. The remote site of those Viking colonies caused various logistical problems in the supply of essential goods for human habitation. The further away from their homelands they were, the more severe the problems: the Greenland colony could not be sustained in the longer term, and the Viking settlement of North America failed completely.

The logistical challenges of moving goods and supplies in hostile environments were significant for Viking forces. While they used carts and wagons for overland transport, ships provided a more efficient means of travel over longer distances. However, the vulnerability of both wagons and ships hampered supply activities during active campaigns. To address this, Vikings likely relied on periodic resupply from regional base camps and scouted suitable sites in advance for future encampments, coordinating parallel overland and overwater convoys to support each other [8]. Thus, this review addresses both the current context and some important historical background on how human groups in remote regions of the Earth have coped with the circumstances of remoteness from nodes of economic development. Whether sovereign island nations or territories belonging to larger countries, the more remote parts of the world are no longer as isolated as in the past but increasingly benefit from a small but growing supply of external goods. Also, the export of a few selected goods to world markets and an openness to tourism are enabling conditions for the receipt of direct income.

The history of humankind has been characterized by the repetition of actions or beliefs that have made societies successful, and any attempt to change these traditions can lead to violent negative responses. While a significant proportion of previous human settlement successes have been the result of repeating actions that have been tried and proven successful in the past, major transformations come with major risks. Since the human settlement of space is still an unknown topic for humanity, this perspective recommends revisiting often long-forgotten habitation concepts, even if these are flagged by historians as "failures". Learning can be

- Setting supply chains correctly with the purpose of them being neither too advanced (due to the risk of becoming too complex) nor simplistic (due to underdelivering) but "reliable" (just what is needed);
- Consider population increase and, therefore, the need for growth potential of the supply chain in question;
- Adjust life and business to supply chain, but without compromising well-being and social integrity;
- As small-community remote supply chains are intrinsically vulnerable, fast decision-making in a community manner will be useful for debottlenecking if needed (as catastrophes would impact on everyone to the same degree).

Various alternatives are currently being considered to establish the networks and nodes of economic activities, as well as the roles of the potential actors involved [9]. A clear definition of how to deal with risks and potential benefits based on coordinated efforts will allow the creation of economic frameworks that are not only adaptable and flexible but also cost-effective and based on local resources [10].

It is worth highlighting the opportunities offered by the different celestial bodies considered in this review. First, the so-called near-Earth asteroids (NEAs), given their proximity to our planet, are considered environments that would offer the opportunity to test various strategies proposed for the economic exploitation of extraterrestrial space in places such as the Moon or Mars [11–14]. Likewise, the existence of water, metals, and raw materials in the NEAs for the production of semiconductors makes their exploitation an attractive proposition and has led to the creation of companies such as planetary resources or deep space industries (DSI) [15,16].

The Moon, the natural satellite of the Earth and, in spatial terms, relatively close to our planet, also represents another invaluable source of opportunities and resources. The existence of water, regolith (unconsolidated rocky material), and diverse silicate and oxide mineral species, among others, makes it possible to project the use of these as inputs to facilitate exploration of our satellite, as well as for the development of scientific activities in the region between the Earth and the Moon, known as cislunar space [14,16]. It is also foreseen that, if the circumstances become favorable for this purpose, raw materials will be exported to Earth to serve the terrestrial economy [17].

As far as Mars is concerned, carbon dioxide is available in massive quantities in its atmosphere, which can eventually be used to produce propellants and oxygen as an input for life support systems, among other products. In addition, recent evidence indicates large areas where water is present, specifically in regolith deposits [18,19], which may imply good prospects for resource utilization.

Implementation of supply chains based on the increasing use of raw materials available on the Moon and Mars will, therefore, be an essential element for the initiation of a whole series of economic activities leading not only to the deepening of space exploration but also to the adoption of innovative ways of managing the resources available on Earth.

Recent significant advancements in space logistics and sustainability practices have been achieved by both governmental and private sector initiatives. NASA's Artemis program to return humans to the Moon and establish a sustainable presence has emphasized the development of reusable rocket technologies and in situ resource utilization [15,20]. This program is complemented by private efforts from commercial space sector companies such as SpaceX and Blue Origin. Whilst SpaceX's Starship aims to reduce the cost of space access and minimize environmental impacts through enhanced rocket recycling processes [21], Blue Origin's New Glenn rocket focuses on reusability and reducing space waste [22]. The collaboration between these programs and advancements in technologies such as orbital waste management and green propellants underscores the urgent need for sustainable practices in space logistics to support long-term space exploration and utilization [23].

It is understandable that the debate on the form or forms that such supply chains and their management should take, calls for the involvement of various disciplines and schools of thought. Hence, an overview of past and present experiences can help formulate a broader perspective on the strategies that should ultimately be prioritized when it comes to supplying various goods and services off-Earth.

In this respect, the small and isolated societies of the past, such as the Rapa Nui (Easter Island), are ideal laboratories for understanding the consequences of human-induced environmental degradation and associated crises. What can we learn from today's small and isolated societies? This question is relevant to the extent that, although economic growth is an enormous challenge due to the difficulties that remoteness implies for commercial interchange, these small island societies benefit nowadays from a limited supply of external goods and the arrival of tourists. This progressive openness is also allowing these regions to export certain goods to world markets, obtaining revenues of enormous importance to their economies.

The organization of the supply chains in Earth's remote places could be like what should be conceived for the supply of resources in future settlements on the Moon and Mars, so the objective of this review is to analyze what knowledge might be obtained. Likewise, this manuscript reviews the supply chain context of four of the most remote inhabited places on Earth (Figure 1) and predicts the future of supply chains on the Moon taking the use of elemental resources extracted from the lunar soil as a point of reference. The above is complemented not only by a look at how logistics has been part of space exploration over the last seven decades but also by the supply of resources that would be available on the Moon and Mars. Our contribution concludes with a discussion of the lessons that could be learned for the implementation of lunar supply chains from experiences in remote places on Earth. These "learnings" are summarised in the Conclusions.

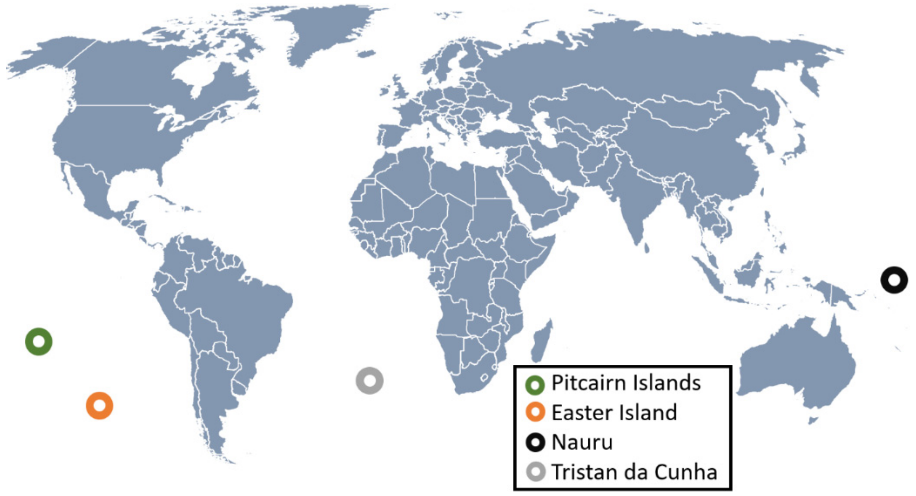


Figure 1. Some of the world's most remote places: Nauru [24], Tristan da Cunha [25], Easter Island [26], and the Pitcairn Islands [27].

Nauru is an isolated independent state in the Pacific Ocean, encompassing a land area of roughly 21 square kilometers and supporting a population of about 12,000 individuals as of 2021 [24].

Easter Island, also known as Rapa Nui, is a 164 km^2 island in the Pacific Ocean situated over 3200 km from the Chilean coast, which annexed it in 1888. For the last two centuries, Easter Island has been renowned for its significant archaeological and anthropological heritage [28]. According to the 2017 Chilean census, the island had a population of 7750. Annually, Easter Island attracts an estimated 70,000 tourists, a figure that is tenfold its resident population.

The ***Pitcairn Islands*** consist of four volcanic islands in the southern Pacific, comprising the only British Overseas Territory in the region. These islands—Pitcairn, Henderson, Ducie, and Oeno—span several hundred miles of ocean and collectively cover about 47 square kilometers [29]. The Pitcairn Islands are noted for having the smallest population among permanently inhabited islands globally, with approximately 50 residents [29,30].

Tristan da Cunha, commonly referred to as Tristan, comprises a cluster of volcanic islands in the South Atlantic Ocean, designated as a British Overseas Territory with its own constitution. This archipelago holds the distinction of being the world's most isolated permanently inhabited group of islands, situated approximately 2787 km from Cape Town, South Africa; 2437 km from St. Helena; 3949 km from Mar del Plata, Argentina; and 4002 km from the Falkland Islands. The territory encompasses the sole inhabited island, Tristan da Cunha, which spans a diameter of roughly 11 km (6.8 miles) and covers an area of 98 square kilometers (38 square miles), along with Gough Island, Inaccessible Island, and the smaller, uninhabited Nightingale Islands. As of October 2018, the population of Tristan stood at 250 residents, all of whom possess British Overseas Territories citizenship. The main island lacks an airstrip, necessitating travel to and from Tristan exclusively by boat, which entails a six-day voyage from South Africa [31].

The ***Moon:*** The Moon's relative proximity to the Earth (approximately 377,000 km), as well as the extensive amount of information regarding lunar resources gathered as a result of past exploration activities, allow us to infer there are interesting opportunities for the implementation of solid supply chains that drive the development of the economy [32]. Likewise, lunar resources, in addition to meeting the needs of the cislunar environment, are expected to complement supply chains on Earth [33]. Nevertheless, the lunar environment is harsh, and any resource exploitation endeavor will need to be resilient in the face of extreme conditions, such as the abrasiveness of the regolith and huge temperature variations, among others [34].

Mars: While the Earth is 147 million km from the Sun, Mars is 228 million km [35], with a variable distance concerning planetary orbits [36,37], and has two moons (Phobos and Deimos) [35]. It has also been established that the so-called "Red Planet" is rich in regolith, water, and carbon dioxide [38] and that it can probably harbor life and/or that life has existed in the past [39]. The U.S. National Aeronautics and Space Administration (NASA) has prioritized Mars within its space exploration activities [40].

Previous studies have often addressed supply chain assets for human space exploration from the viewpoint of solving only individual technical problems, such as water splitting into hydrogen and oxygen. Even when a suite of technical problems has been considered, the scope has been limited to the supply of basic needs for human survival. Thus, these space studies have not been conducted under a comprehensive assessment umbrella that addresses "human capital" and "human well-being" as parts of a new "space life" concept that allows the current "space survival" paradigm to be overcome based on a constant fight against extreme threats. Our study aims to fill that gap by amending and embedding literature reports on past single achievements with a contextualization from the establishment of remote Earth supply chains. Our Perspective takes the viewpoint that these experiences, from past and present, provide learnings that go well beyond technical issues since they also embrace the social, governance, and even cultural dimensions of space habitation.

2. Methodology

This study employs a comparative analysis, which is a research methodology common in social sciences for cross-cultural studies [41]. This methodology is translated in this approach as a systematic side-by-side comparison of single supply-chain challenges and achievements learned from remote cultures on Earth in the pursuit of pinpointing how off-Earth human settlements might thrive according not only to space environment conditions but to required technological innovation. This analysis is carried out conceptually, starting from an idea and viewpoint and aiming to translate all those single viewpoints into a comprehensive "perspective". This side-by-side approach allows us to "unify" the assessment of strengths and weaknesses in the translation of remote Earth supply chain concepts for use in space. This aim for methodological consistency embraces very divergent aspects of human supply chains, including technologies, food, economy (brands), health, environmental (self-sufficiency), and governance (decision-making) [42].

This study is not a technical paper, and as a perspective, it is based on surveys and published data. The islands/communities were chosen according to listings of the "most remote inhabited places on Earth". About 10–15 remote sites are consistently listed in the web. We excluded remote locations that have a continental connection in favor of remote islands, assuming that the land-based supply chain is, from a transport point of view, different from "empty space" transport. This left about eight islands. To narrow it down to the four sites considered, the first preference would have been to select sites with extensive scientific documentation going back several centuries. However, this is only the case for Easter Island. Thus, the key criterion was the availability of extensive and authoritative documentation on the web, and that led to the chosen islands.

Our study follows a methodology that was introduced in social and business literature. "Comparative analysis" is known for complex matters (as our study), to provide meaningful conclusions rather than giving a multitude of hypothetical scenarios [43]. By means of comparative analysis, a pattern assessment for trend recurrences of present and future supply chains on Earth and in space is performed. This way, we can decipher which of the (vast) web information is worthy of consideration. True comparative analysis uses data filtering and decision-tree analysis, as published in technical papers. However, the qualitative (perspective) nature of our study does not allow for an approach that supports the gathering of quantitative data.

3. Space Supply Chains—State of the Art

The European project Eden is purposed to design and test bio-regenerative life support to explore permanent space habitation. Central to that objective is the development of edible food supply chains and closed-loop systems for resource regeneration [44]. The SpaceNet supply chain study proposes interplanetary supply chain management and logistics architectures based on intermediate nodes as a planning tool for space logistics [45]. The supply chain design is based on SpaceNet simulations and modeling for space exploration logistics within the "MIT Space Logistics Project" [46]. The SMORS supply chain study designed a mathematical programming conceptual model to organize and optimize supply chain efficiency based on the AMPL programming language [47]. This approach was developed on the backdrop of real space missions, such as the VERITAS and Venus (NASA) explorations [48]. The MSP supply chain study introduced principles and methodologies for supply chain logistics using a multistage linear programming (MSP) model, which optimized material flows, propellant production, and in-space infrastructure allocations [49]. The results highlighted the interdependencies in space logistics, asking for frequent interactions among spacecraft and the establishment of complex propellant supply networks. The SpaceX supply chain study describes in detail the scenario of a human mission to Mars on such a company spacecraft [21]. Details are comprehensively discussed and modeled, as far as space travel itself is concerned, down to the use of spacesuits by the astronauts.

Table 1 summarizes the scope of these different approaches in encompassing major human supply needs and their various assets, as compared with the supply chain insights in this review taken from remote places on Earth.

Table 1. Supply chain methodologies proposed in recent literature were analyzed for their breadth in encompassing major human supply needs (upper case) and their various assets (lower case) and compared with the scope covered in this review. The main off-Earth site as a node for the supply chain asset is listed to the right.

Supply Needs and Assets	Eden	SpaceNet	SMORS	MSP	SpaceX	Our Work	Main Off-Earth Site
NEAR-FUTURE STRATEGIC							
NUTRITION							
Food-payload	X	X	X	X	X		Space
Food-grown	X					X	Moon/Mars
Animals						X	Space
Fertilizers	X					X	Moon/Mars
MATERIALS							
Minerals			X			X	Moon
Metals		X					Asteroids
Construction materials	X	X	X			X	Moon
Clothes (astronaut suits)					X		Space
Oxygen		X			X		Moon/Mars
Water	X	X	X	X	X	X	Moon/Mars
TRANSPORT							
Hydrogen-fuel		X	X	X		X	Moon
Methane/propellant		X			X	X	Moon/Mars
Power/batteries						X	Space
Transport paths			X	X		X	Moon
Vehicles		X	X			X	Moon
Logistic nodes				X	X	X	Space/Moon
COMMUNICATION							
Communication flow		X			X	X	Space
Network and cybersecurity		X				X	Space
HEALTH		X				X	Moon/Mars

Table 1. *Cont.*

Supply Needs and Assets	Eden	SpaceNet	SMORS	MSP	SpaceX	Our Work	Main Off-Earth Site
LONG-TERM STRATEGIC							
ECONOMICS							
Budgetary and schedule risk		X					Space
Trade			X			X	Moon/Asteroids
High-quality products						X	Moon
Brands/Monopoly						X	Moon
Tariff/currency						X	Moon
SOCIAL							
Jobs/labor						X	Space/Moon
Education		X				X	Moon
GOVERNANCE							
Common-pool resources and kin-related group governance			X				
Investor rights and business						X	Moon/Mars
No-take zones						X	Moon/Mars
SELF-SUFFICIENCY							
Avoid feast and famine cycle						X	Moon/Mars
Fund for self-sufficiency						X	Moon/Mars
PRODUCT QUALITY							
Safety-quality assurance						X	Moon/Mars
Good manufacturing practice						X	Moon/Mars
Product safety						X	Moon/Mars
ENVIRONMENTAL NODES							
Climate change, deforestation, and soil erosion		X					Moon/Mars
Water supply, sanitation, solid waste management			X				Space/Moon
Environmental monitoring	X			X		X	Moon/Mars
PRODUCTS							
In situ manufacturing						X	Space/Moon
SPACE LAW							
International and political risks		X					Moon/Mars

The perspectives for supply chain assets, given in Table 1, were selected with the ambition of a holistic approach, meaning to consider all supply chain issues faced by remote islands. Some evidently have a space counterpart, such as the supply of food and critical metals, as well as transportation. Other recent studies also focus on the well-being of potential space settlements. This includes the operation of space-based 3D printing manufacturing platforms [50], the formulation of space meals to meet the nutritional requirements of astronauts or space inhabitants [51], and the development of horticultural systems for sustainable space environments [52]. Additionally, studies explore the potential production of goods as business opportunities for the space economy. Examples include in-space manufacturing of nanomaterials for therapeutic delivery and tissue regeneration [53], and the in-space manufacturing of satellite structures aimed at enhancing accuracy and resilience in the manufacturing process [54].

Some Earth supply chain issues might not seem of foremost importance for future supply chains in space—and some may not even be relevant. Nonetheless, for consistency, and to retain the comprehensive ambition of this review, we include the latter perspectives next to those considered imperative for space supply chains. One example of an imperative space perspective is how to organize a currency. Currency determines macroeconomics on Earth and will inevitably at some point in the future, also do so in space. A national or supranational reserve bank, for example, could moderate the growth of the money supply to control inflation and adjust import/export factors. In the mid-to-far future, a "space bank" could similarly support goods produced in-space over substitutive goods from Earth or other supply nodes.

4. Learning from Remote Earth Sites for Space

4.1. Economics

The economics of remote sites on Earth have dynamics behind world economics [55]. Among the reasons for this are supply chain limitations and scale of trade.

4.1.1. Wealth of Economics

The *Pitcairn Islands* conducts trade mainly with the United Kingdom (UK). The corresponding trade in goods and services (exports plus imports) was less than GBP 1 million in 2022 [56] (Figure 2), positioning this territory as the UK's 228th trading partner in 2022. Nauru, for its part, reported economic growth of around 0.7% in 2020 and 1.5% in 2021 [57], as well as a GDP per capita in 2023 of USD 11,228; however, the dependence on external sources for non-tax revenues makes its revenue base as a nation narrow and volatile [57]. As far as Easter Island is concerned, it had been a relatively prosperous entity a few hundred years before the first European discovery in 1722 [58], demonstrating that wealth growth is possible in remote locations.

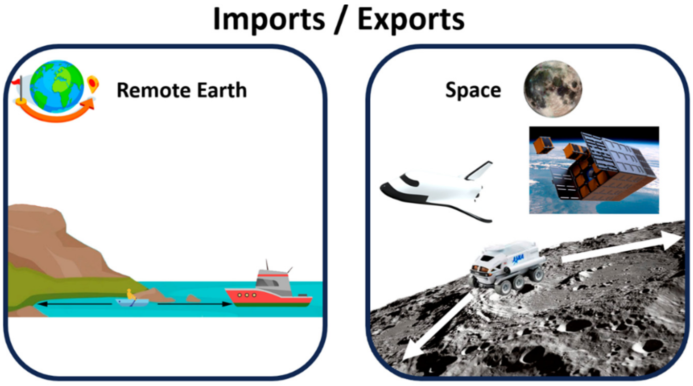


Figure 2. Import/export options in remote Earth and in space missions.

Space: Multiple space economic forecasts and outlooks have been published [59–62] even though no space economy has yet been established [63].

4.1.2. Abundant Available (Primary) Goods

Nutrients

Nitrogen (N), phosphorus (P), and potassium (K) are called macronutrients for crop growth since they are the most required by plants for their optimal development. Other elements, such as iron (Fe), copper (Cu), and manganese (Mn), are micronutrients, since, although crops also need them, the quantities in which they are required are lower. Likewise, other chemical elements, such as carbon (C), are beneficial for plant nutrition.

Remote islands report little or nothing about the economic use or availability of nutrients in their territories. It should be noted, however, that Nauru had a vibrant phosphate mining industry in the past. Reserves are almost completely exhausted at present.

The *Moon* contains essential elements for the existence of organic compounds, such as carbon and nitrogen, in lunar minerals, although in very low concentrations [37]. In this sense, carbon ions are present in concentrations between 10 and 280 µg/g of regolith [64,65], while nitrogen can be present in igneous rocks and regolith, although with a variable isotopic composition [66,67].

Metals

As noted, phosphate mining had been a main activity of *Nauru's* economy in recent decades. The *Pitcairn Islands* could potentially generate income from rich resources on the seafloor, including manganese, iron, copper, gold, silver, and zinc, within an exclusive economic zone that extends 370 km (230 mi) offshore and comprises an area of 880,000 km^2.

The *Moon's* mare regolith is especially rich in iron oxides, which are considered to be more advantageous for water production than silicates [68]. In addition, lunar highland plagioclase feldspar contains aluminum, usable for the construction of light structures and the production of reflective or coating materials (Figure 3) [33]. Baasch et al. [69] have demonstrated it is possible to cast aluminum parts using lunar regolith simulant. Likewise, lunar regolith contains metals, including calcium and aluminum (Highlands), or iron and titanium (Maria), which can be found within minerals also containing oxygen and/or silicon (Table 2) [70,71]. Elements such as potassium, phosphorus, and rare earths are found in lesser yet still relevant quantities [72], especially in mare regolith. Mars: The distribution of Martian elements, mainly given as their oxides, is shown in Table 3.

Table 2. Chemical composition of lunar regolith [72–74].

Element	Low-Ti Mare Soils (%)	High-Ti Mare Soils (%)	Highland Soils (%)	KREEP Soils (%) [a]
O	60.26	60.30	60.82	60.47
Si	17.30	15.86	16.31	17.35
Al	5.56	5.70	10.66	6.48
Mg	5.53	5.70	3.84	5.39
Ca	4.44	4.60	5.92	4.43
Fe	5.85	5.29	1.90	4.47
Ti	0.66	2.01	0.17	0.62
Na	0.26	0.231	0.29	0.44
K	0.06	0.05	0.05	0.19
Mn	0.08	0.07	0.03	0.06

[a] KREEP refers to a certain type of lunar basalts that contains K (potassium) + rare-Earth element + P (phosphorus).

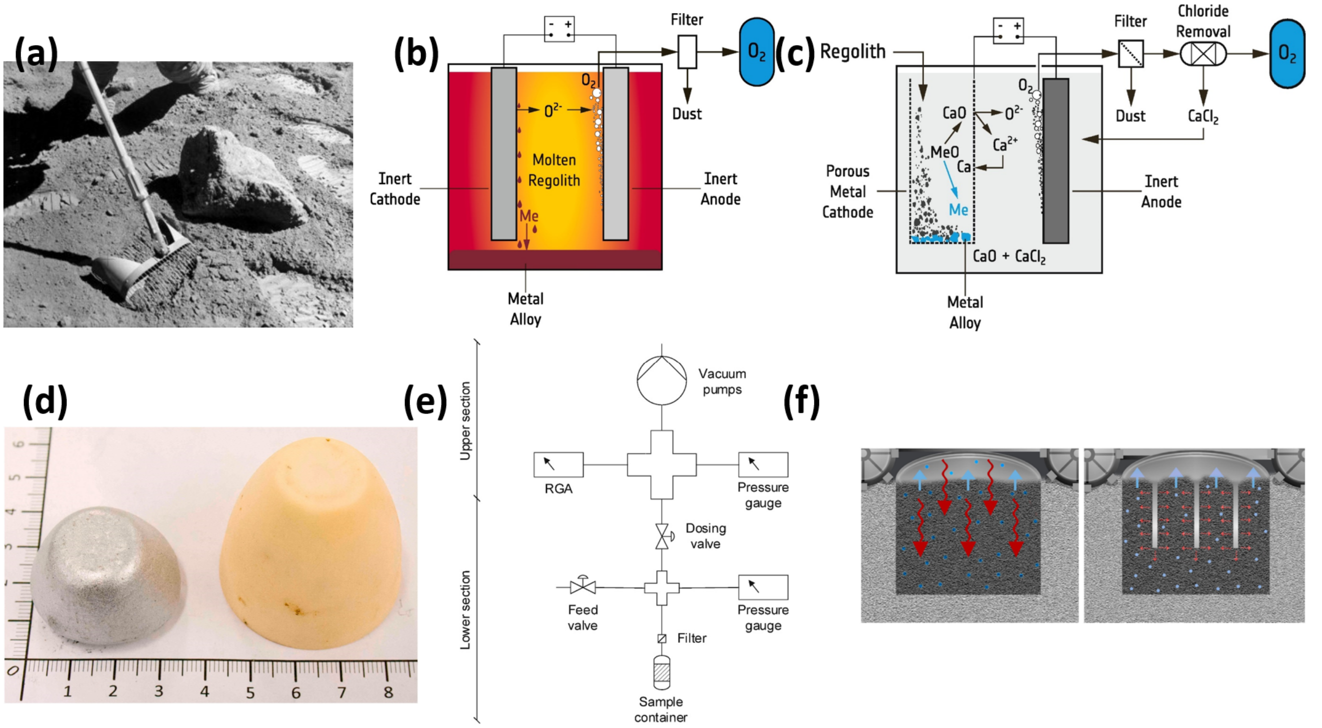


Figure 3. Possibilities of exploitation of the lunar regolith. (**a**) Lunar regolith [75] (reproduced with permission from McFadden et al., *Encyclopedia of the Solar System*, published by Elsevier, 2006). (**b**) Molten regolith electrolysis (MRE) and (**c**) molten salt electrolysis (MSE) as techniques for extracting water [76] (reproduced with permission from Schlüter et al., *Planetary and Space Science*, published by Elsevier, 2020). (**d**) Final aluminum casting using regolith as a mold material [70]. (**e**) Volatile extraction system [77] (reproduced with permission from Reiss et al., *Planetary and Space Science*, published by Elsevier, 2019). (**f**) Heating configuration in a water extraction model [78] (reproduced with permission from Brisset et al., *Planetary and Space Science*, published by Elsevier, 2020).

Table 3. Chemical compositions of different Martian regolith samples from different missions, including Viking Lander 1 (VL-1), Viking Lander 2 (VL-2), and Pathfinder [79] (reproduced with permission from Barkó et al., *Lubricants*, published by MDPI, 2023).

Oxide		VL-1 (wt %)	VL-2 (wt %)	Pathfinder (wt %)
Alkaline	K_2O	<0.15	<0.15	0.3
	Na_2O	n.a.	n.a.	2.1
	Cl	0.7	0.5	0.5
Alkaline Earth	CaO	5.9	5.7	5.6
	MgO	6	6	7
Metal	Fe_2O_3	18.5	17.8	16.5
	TiO_2	0.66	0.56	1.1
	MnO	n.a.	n.a.	n.a.
Non-metal	SiO_2	43	43	44
	Al_2O_3	7.3	7	7.5
	P_2O_5	n.a.	n.a.	n.a.
	SO_3	6.6	8.1	4.9
	Total	89	89	89.5

Animals

Nauru exemplifies the relevance of abundant available animal resources for the economy of remote sites on Earth [80]. As the islands considered in this review are located within large oceans, the fisheries sector is a major source of revenue.

The *Pitcairn Islands* are also rich in animal marine products, including spiny lobster and a large variety of fish such as nanwee, white fish, moi, snapper, big eye, cod, yellow tail, and wahoo, all of which are caught in deep water [81]. Tristan da Cunha reported that fishing is the mainstay of the island's economy, and the main product is the Tristan rock lobster (Jasus) fishery [82].

Space: We do not have any current evidence of life on the Moon, Mars, or beyond; nonetheless, the search for lifeforms continues. Given the absence of known plants or animals on the Moon and Mars, the development of in situ food production technologies is necessary to sustain human presence in the long term.

4.1.3. New Sources of Growth and Broadening the Revenue Base

Nauru's aim to broaden its economic base and secure new growth avenues requires the implementation of supportive policies to boost investments in human capital and infrastructure. Additionally, efforts to enhance the business environment will be essential [83].

Easter Island and its history provide learning about investment in resource growth, which has been mathematically modeled by defining an intrinsic growth (or regeneration) rate [59]. In addition to the above, Easter Island is considered to have failed to establish a Ricardian production structure that produces goods competitively using constant return-to-scale technologies [84].

Space offers abundant resources, mainly in the form of regolith and minerals, which are expected to be a key factor for the implementation of the required supply chains. The construction of economic and housing infrastructures [85] and the production of metals, propellants, and nuclear energy, could be the first activities to take place based on the exploitation of promising space resources.

The *Moon*'s surface is covered with regolith, which, in turn, consists of a layer of unconsolidated material in the form of fine grains [65,86] glass, breccia, agglutinate, crystalline rock fragments, and mineral fragments [87]. In the lunar mare, the regolith layer can be between 4 and 5 m thick, while in the highlands it can be between 10 and 15 m thick [71,87,88], depending on the underlying geology [89], as well as on external factors, such as volcanic eruptions, impacts, cosmic radiation or solar wind [33]. Highland regolith contains minerals such as plagioclase, pyroxene, and olivine, common in anorthosite rocks.

Maria regolith contains plagioclase, olivine, pyroxene, and ilmenite, common in basaltic lava flows [71]. Silicates are the most abundant minerals on the Moon, with more than 70 vol% of regolith [9,90,91]. Lunar silicates are sources of both oxygen and water [92].

Mars: A layer of unconsolidated, basaltic material, mainly volcanic, covers the Martian surface, and the current discussion focuses on the distribution of elements and the apparent absence of organic carbon (Figure 4, top) [93]. Unlike the lunar regolith, the Martian one interacts with the atmosphere, including wind [94,95], and one example of this is water transforming into ice [95]. The Martian regolith offers an opportunity to recover water and minerals for various uses and construction materials [95]. However, the use of this material should be carried out with caution, considering the presence of perchlorate (ClO_4^-), a harmful and toxic compound (Figure 4, middle) [96].

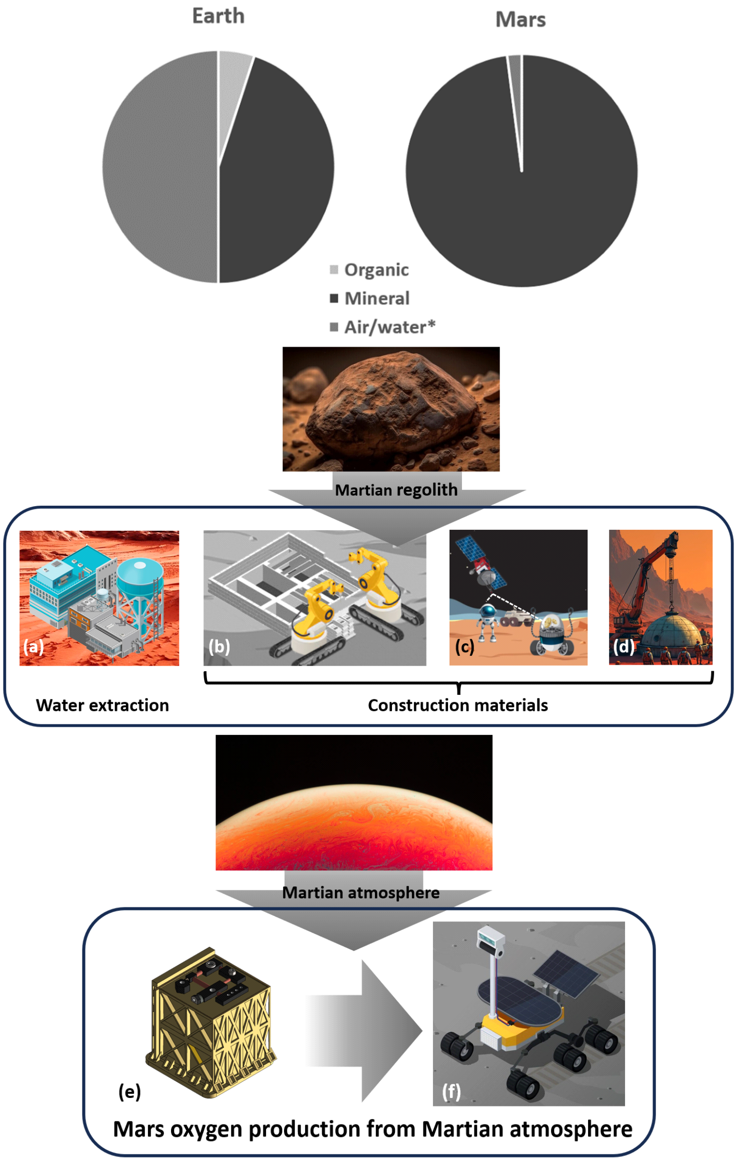


Figure 4. (**Top**) Comparative average soil compositions on Earth and Mars. (*) Air not contained in Mars soil. (**Middle**) Martian regolith can serve as a base material for water production and infrastructure construction materials. At present, methods for the extraction of water are being tested, such as the capture of molecules after heating the regolith (**a**). Methods such as 3D printing (**b**), remote control of robots (**c**), and intelligent construction (**d**) can make a decisive contribution to the development of infrastructure together with materials obtained from regolith. (**Bottom**) Since 2021, a machine has produced oxygen on Mars. (**e**). The Perseverance rover (**f**).

At least four groups of minerals exist on the Martian surface, such as silicates, sulfides, sulfates, and oxides [97]. Silicates include olivine, pyroxenes (ortho- and clinopyroxene), and feldspars (plagioclase and alkali). Deposits of sulfides (pyrrhotite and pyrite), sulfates (calcium, iron, and magnesium), and oxides (magnetite and ilmenite) are identified [7,98]. Zinc and copper are also present. This opens opportunities for activities, such as the construction of structures via 3D printing (Figure 4, middle) [99,100].

For its part, the atmosphere of Mars contains large amounts of carbon dioxide (CO_2) from which oxygen can be obtained (Figure 4, bottom) [101,102]. Since 2021, a machine the size of a toaster has produced oxygen on Mars. This device is in the Perseverance rover and is part of the Mars Oxygen In situ Resource Utilization Experiment Project (MOXIE) [103]. Technologies to release lunar oxygen include Molten MRE, MSE, and the reduction of ilmenite by hydrogen [104]. Martian Helium-3 (^{3}He) could be used for nuclear fusion [105,106].

4.1.4. Manufacture Exceptionally High-Quality Products

The *Pitcairn Islands* host one of the world's healthiest bee populations. The bees in Pitcairn are notably docile, allowing beekeepers to handle them with minimal protective gear [29]. The honey they produce is of exceptionally high quality and is exported to countries such as New Zealand and the United Kingdom (Figure 5) [29]. In London, Fortnum & Mason sells this honey, which is reputedly favored by King Charles III and was previously a favorite of Queen Elizabeth II.

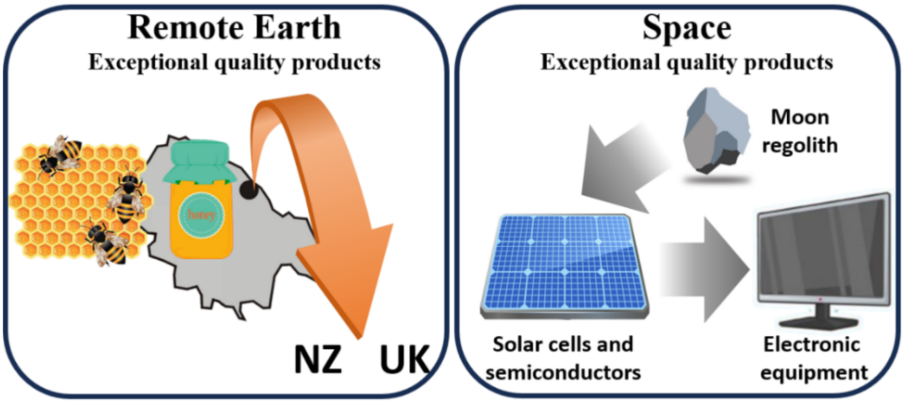


Figure 5. Exceptional high-quality products from remote Earth and space.

The *Moon* comprises resources, silicates, and minerals (for example, platinum) that may be useful for the manufacture of thin film materials, used in turn for the production of semiconductors for solar cells and various electronic equipment, including computers (Figure 5) [37,107]. Other products, such as construction materials, machine parts, and other artifacts, could be manufactured from the aluminum and titanium present in the regolith using additive manufacturing techniques [108,109].

4.1.5. Create Brands and Protected Monopoly

The *Pitcairn Islands* have established export brands such as "bounty products" and "delectable bounty," which feature dried fruits, including bananas, papayas, pineapples, and mangoes. Honey production and its related products are maintained as a protected monopoly [29]. Additionally, the local authorities have developed coin marks and postage stamps aimed at collectors, alongside .pn domain names and various handicrafts for passing ships, particularly those traveling from the United Kingdom to New Zealand via the Panama Canal [29]. The first postage stamp issued by the Pitcairn Islands was in 1940, and these stamps quickly became popular among collectors, making their sale the primary source of income for the community.

Tristan da Cunha established a high-quality fishery committed to sustainable seafood management practices, which is reflected in the achievement of the Marine Stewardship Council (MSC) blue ecolabel. This has made it possible for Tristan's fishery to meet European requirements for food safety conditions, which, in turn, has enabled exports to the European Union [110]. Tristan also has small-scale tourism [111].

Nauru has managed the Australian Regional Processing Center (RPC) for asylum seekers at various times (2001–2008, 2012–2019, and again from September 2021) [112].

The *Moon* will have to consolidate brands to position its products and services in the market based on regulatory and stability criteria for each type of economic sector [113,114]. The joint work of private companies and space agencies will be necessary to provide regulatory stability and establish clear guidelines on property rights [115].

4.1.6. From Reliance (Imports) to Resilience: Food and Fuel

Nauru: Its size and remoteness limit potential growth and increase its dependence on food and fuel imports. The development of the fisheries sector, through activities such as fish processing, offers great prospects and can help drive further economic growth.

The *Moon* has water present as ice at the poles [116] and in the regolith of lunar rocks [70]. Oxygen can be released either from lunar regolith, including silicates or oxides (about 40% of the regolith is oxygen) [117] or from ice in the lunar poles [33,118]. *Helium 3* (^{3}He), an isotope of helium, is considered a potential fuel for nuclear fusion reactors, enabling a breakthrough in space power generation. This ion is believed to be available in greater quantities on the Moon than on Earth [119]. Additionally, some "volatiles" (such as hydrogen, oxygen, carbon dioxide, or methane) could be used for life support and propellant production, among other purposes [120,121].

Mars has an atmosphere rich in carbon dioxide (CO_2), which constitutes 96% of the total [122–124]. The MOXIE project, whose development is based on operating a small device incorporated into the Perseverance rover, is the first demonstration of how CO_2 could be converted into oxygen [125–127]. For its part, water on Mars is found in loose granular soils, in hydrated minerals, and, above all, in solid form in glaciers [128–130]. However, water extraction would face challenges related to the excavation, drilling, and processing of the extracted materials [131]. *Space:* The thermal mining process could be used to produce water based on the thermal extraction and condensation of water vapor. Hydrogen and oxygen would be separated by electrolysis to produce liquid fuels [131–133].

4.1.7. Tariff and Currency

Easter Island belongs territorially to Chile, and the official currency is the Chilean peso (CLP). However, given the increase in tourism in recent decades, it is also possible to make transactions in other currencies, such as the U.S. dollar (USD) or the Euro (EUR) [134].

Nauru uses the Australian dollar (AUD) as the official currency.

Pitcairn Islands has the New Zealand dollar (NZD).

Tristan da Cunha does not have its own currency and the British pound sterling (GBP) is the one used nowadays. The parent island of Saint Helena, 2430 km to the north, uses its own currency, the Saint Helena pound (SHP), although this is tied to sterling [135]. Although the Bank of Saint Helena does not maintain a physical branch in Tristan da Cunha, inhabitants of the latter can use its services [58].

4.2. Social and Governance

4.2.1. Jobs and Labor

Nauru promotes regional labor mobility schemes by dismantling its RPC to create labor offshoring [58]. *Easter Island* data on historical asset and population growth and decline were used to estimate an optimal proportion of the labor force going to resource exploitation and manufacturing and service activities [136]. Consistent with the above, it is considered that the resource sector should absorb slightly less than half of the available labor supply, e.g., a proportion of about 40%.

4.2.2. Education

Nauru: Education is offered at no cost for children of school age. However, significant obstacles remain in enhancing school attendance, literacy levels, and graduation rates (Figure 6a) [137].

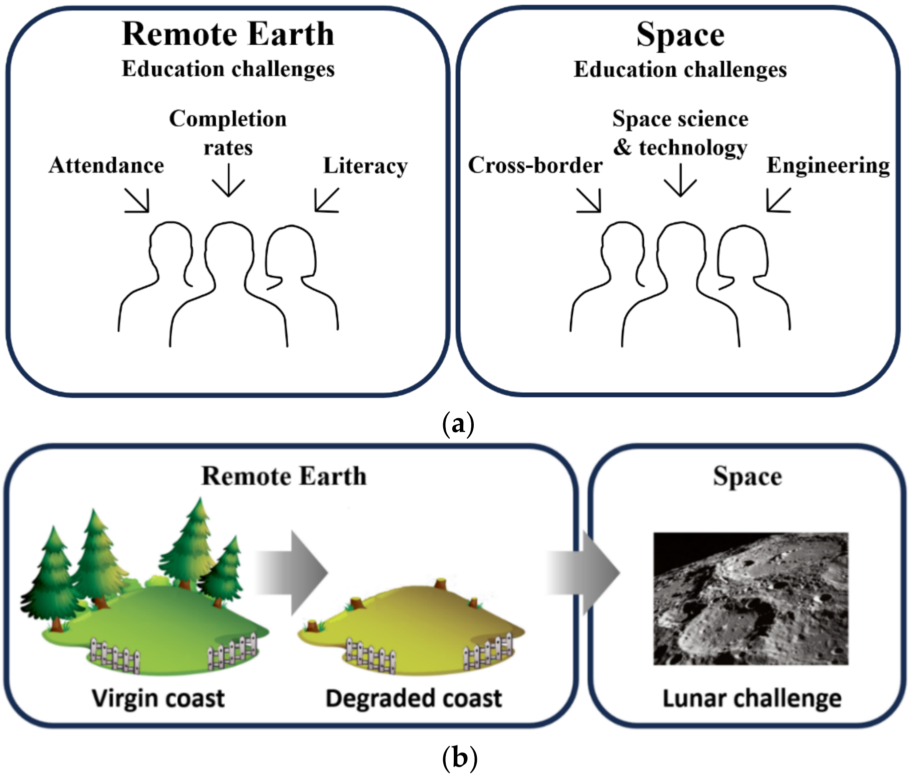


Figure 6. (**a**) Orientation of education challenge: Differences between remote Earth and space settlements. (**b**) Resources degradation by human overshooting from remote Earth and lessons to be learned in future lunar settlements.

Space: Education capacity development must be grounded on high-level knowledge and expertise in space science and technology. A long-term, in-depth program and vision likely need to be developed, e.g., to provide opportunities in developing countries, which some reports believe to be the major next-generation adaptors [138]. Space education must cross borders, both nation-wise and discipline-wise, as practiced in the United Nations (UN)-affiliated Regional Centers for Space Science and Technology Education. This may facilitate the adoption of engineering into space science [139].

4.2.3. Avoiding Feast and Famine Cycles and Supply Chain Disruptions

Remote locations can experience threat and collapse when relying on a slow-growing resource base while experiencing non-sustainable population growth.

Nauru has experienced delays in construction projects due to supply chain disruptions [137].

Easter Island has been commonly used as a reference for modeling population overshoot and endogenous resource degradation (Figure 6b) [140]. There are two views on what is known as the "Rise and Fall" of Easter Island [141]. The first is based on the interaction between population growth and excessive use of resources as the main cause of the collapse based on the application of concepts from the Malthusian model of population growth and the predator–prey model of Lotka-Volterra [59,142–148]. The second strand is based on the theory of conflict between different social groups on the island, reflected in the adoption of strategies such as non-cooperative negotiation concerning land use and population growth.

In addition to Easter Island, it is also considered that, in the ancient Mesopotamian states, there were historical processes of decline of the prevailing way of life at the time and that, among the triggering factors of these crises, was the reduction of the availability of resources for the population. The extinction of the Akkadian empire (2350–2150 BC) is one of the most emblematic examples of the latter, as soil degradation and the intensive use of agricultural land led to a decline in food production [149]. This, coupled with a steadily increasing population, contributed to civic collapse and the breakdown of governance [150]. Extensive irrigation made it possible to cope with the situation for a while [151]; however, the increase of salinity in the soils caused the yield of agricultural production to decrease again, leading to a 50% lower yield per hectare by 2000 B.C. than 300 years earlier [152].

Consequently, the settlement of human beings on celestial bodies other than Earth should be undertaken in such a way that, as far as possible, the emergence of phenomena such as accelerated population growth or a decrease in the supply of resources necessary for life support is avoided. One of the main challenges in this regard would be to achieve self-sufficiency, at least partially, to depend less on Earth supplies, which would necessitate the adoption of more rigorous sustainability criteria. Assuming, then, that this scenario becomes the one that takes place, planning and regulation of the development of settlements based on the determination of the potentialities and limitations of the physical environments would acquire full meaning [153].

4.2.4. Communal Ownership, Common-Pool Resources, and Kin-Related Group Governance

Remote islands: A community approach favors consensus-based decision-making by prioritizing collective needs [154]. In his Nobel Prize-winning economics research, Ostrom advocated group-level cooperation on common pool resources [155] so that tendencies that may lead to a tragedy of the commons are avoided by imposing top-down regulatory structures or privatizing resources [156]. Wilson has proposed design principles, such as group identity and shared resources, decisions made by consensus, collective choice agreements, monitoring by group members, and agreed-upon mechanisms for conflict resolution (Figure 7) [157]. The application of the aforementioned principles can facilitate relatively autonomous groups conducting their affairs and interacting on a larger scale through adequate coordination between subgroups.

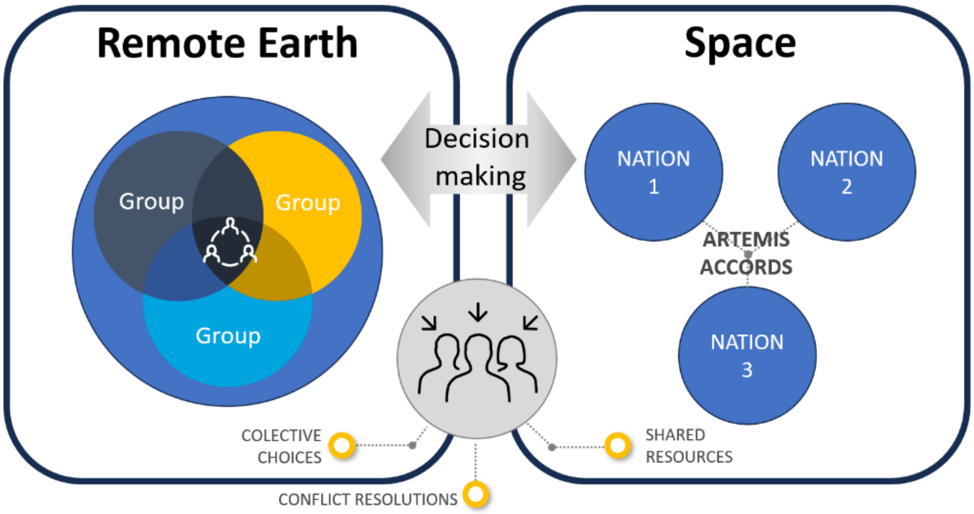


Figure 7. Social structure on remote Earth and space for decision-making.

Easter Island: A study has concluded that working cooperatively in small groups related to relatives would provide benefits associated with cooperation, exchange, and conflict avoidance [158].

A relevant part of decision-making is procurement and ownership, as follows.

The *Pitcairn Islands* have established a procurement policy for the purchase of goods and services [29], including (i) value for money. (ii) purchase by competition, (iii) improved quality of suppliers, (iv) compliance with legal and international obligations, and (v) sustainable production. Authorized officers are asked to consider (i) priority of goods, (ii) end use of goods, (iii) whole life costs and quality, and (iv) sustainability, among other aspects. Rules have been defined for managing the supplier relationship, asking for proactive public relations with key suppliers.

Tristan da Cunha possesses a distinctive social and economic framework where every resident family engages in farming, and the land is collectively owned. Individuals from outside the community are forbidden to purchase land or establish residence on Tristan [58].

Easter Island manages access to common-pool resources at a local level, such as drinking water, agricultural land, and marine foraging locations [158]. Small, relatively autonomous groups with governance structures make decisions that are comparable to Ostrom's design principles.

Space can adapt the ownership models mentioned above to avoid past catastrophic failures ("Tragedy of the commons") in remote places on Earth. In this regard, The Outer Space Treaty states that space, including the Moon and other celestial bodies, "is not subject to national appropriation by claim of sovereignty, by use or occupation, or by any other means" [159]. Accordingly no state can claim ownership of any part of the Moon, unlike traditional state sovereignty on Earth. However, many states have interpreted this as allowing the extraction of resources for in situ use and, potentially, export, and have enacted national laws authorizing ownership of space resources. Hence, how the non-appropriation principle can be applied to multiple and competitive uses of the Moon remains an unresolved and controversial question.

At the lunar South Pole, for example, in the Shackleton and Shoemaker craters, among others, communities could focus on the economic exploitation of sectors belonging to such places, alternating this activity with others such as food production, energy generation, and management housing. To avoid potential conflict situations at the geopolitical level, the Artemis Accords propose several mechanisms to facilitate international cooperation and risk mitigation, such as the development of interoperable facilities and the designation of safety zones [160]. While the Artemis Accords are not binding on countries not participating in the space program of the same name, they provide a set of principles that could be reflected in rules of conduct on the Moon. Therefore, in the absence of cooperation, it may be necessary to impose various forms of governance according to emerging needs [161].

Although the lack of a current global consensus on the development of space activities could be interpreted as a potential source of conflict in the future, the history of space exploration records numerous successful initiatives characterized by strong coordination and cooperation of all parts. Therefore, the delineation of research paths will be key to guaranteeing not only the emergence of a solid scientific team for long-term space exploration but also the implementation of an action plan for the respective effectiveness of the research of the equipment. In addition to conceptualizing and measuring team cohesion and its technical roles, it would be necessary to clarify the "social roles" that crew members must fulfill [162].

Likewise, local involvement and solutions by the crews in the supply chain decision-making process will help reduce the risks for them and the missions [163]. The design of supply chains and infrastructure shall go hand in hand with the production of various ISRU-based goods [164].

4.2.5. General Fund for Self-Sufficiency

The *Pitcairn Islands* have transferred some profits to a general fund which contributes significantly to self-sufficiency. This fund covers regular community needs (e.g., construction of schools) and payment of salaries [165]. In *Tristan da Cunha*, subsistence agriculture coexists with conventional business initiatives [58], such as that of the Ovenstones fishing company, which operates a factory and manages a fishing concession, pays royalties, and employs islanders [162]. *Nauru* established economic support to stimulate transport to ensure reliable freight service [113].

The *Moon*: Assuming that the lunar settlements have become self-sufficient in terms of their basic needs, networks of cooperation could be formed between them, which may be based on a system of commercial monetary exchange or bartering of goods depending on circumstances and needs. As an example, the proximity of the habitats located around the Lunar South Pole would facilitate mutual visits, which would make light rovers a useful means of transportation.

4.2.6. Investor Rights, Access to Land, and Business Registration

Easter Island has provided global learning to minimize the risk of occurrence of situations of environmental and social collapse as happened on this island in the past. It would be advisable, according to some authors (i.e., Malthus), to reach a consensus concerning both the renewable resources that could be freely accessed and the established property rights [166].

The *Moon*: The use of lunar resources should be based on the implementation of highly efficient production systems and the consolidation of responsible consumption habits. An example of this would be off-Earth food production, which, for efficient use of water and nutrients, would have to be developed through closed cycles [164]. On Earth, environmental, social, and governance (ESG) orientation is increasingly taken into account when it comes to defining the availability of resources and the conditions under which they are exploited and/or processed. The application of the ESG approach could even influence the definition of the final market price of both inputs and finished products, both on Earth and in space.

4.2.7. No-Take Zones to Protect Vulnerable Ecosystems

The *Pitcairn Islands* are situated within an expansive Marine Protected Area (MPA), spanning 841,910 square kilometers, aimed at preserving the marine ecosystem. This initiative protects untouched coral atoll reefs and endangered species [165]. Activities considered harmful, such as fishing, mining, and waste disposal, are prohibited in 99.5% of the MPA. This conservation effort operates under the auspices of the Blue Belt Programme, an initiative of the UK Government aimed at bolstering marine protection across more than 4 million square kilometers of marine environment surrounding UK Overseas Territories. In contrast, *Tristan da Cunha* is encompassed by the largest no-take zone in the Atlantic and the fourth largest globally, spanning 687,247 square kilometers [167]. The Tristan Marine Protected Area prohibits mining and fishing activities (with the exception of local lobster fisheries). The Royal Society for the Protection of Birds (RSPB) has identified Tristan and its adjacent ocean as one of the most pristine ecosystems on Earth [168].

4.3. Safety, Quality Assurance & Health

4.3.1. Diseases

The *Pitcairn Islands* show the economic potential of a disease-free ecosystem. Their disease-free bee populations produce exceptionally high-quality honey [169].

Nauru's population has a high incidence of non-communicable diseases, which is partly due to the scarcity of medical facilities and the high incidence of risk factors [84].

The *Moon's* Lunar settlements will require high-quality health services because of the enormous distance from Earth and the challenges of living in an environment characterized by phenomena such as partial gravity, radiation, and extreme temperature fluctuations, among others [170]. While the World Health Organization (WHO) recommends that there should be 2.5 medical professionals (doctors, nurses, and midwives) per 1000 inhabitants on Earth, this figure is likely to be much higher on the Moon, given the circumstances and risks [171]. Hence, the design of the mobility infrastructure to connect the various human settlement sites at the South Pole will also need to consider health eventualities and emergencies, including infections, psychological disorders, and accidental and natural death.

Space, for its part, offers a pollution-free environment, so manufacturing high-quality products with a minimum amount of contaminants or impurities would be highly feasible. Therefore, producing goods such as optical fibers and metal alloys, among others, would find space as an ideal environment [172].

4.3.2. Good Manufacturing Practices

Tristan da Cunha established food-safety system functions and good manufacturing practices (GMPs) for sustainable fishing and seafood traceability [83]. Credible certification and ecolabelling programs have enabled Tristan Lobster to bear the blue MSC eco-label. Five Tristan Fishery Inspectors underwent a training course by Swift Micro Laboratories, a South African company [83], which included microbiological product testing, quality-management systems, and on-site technical consultancy service. Practical application was demonstrated at the factory level.

The *Moon*: The economic activities on the Moon, such as mining, may take place framed by principles that guide the practice and methods of prospecting, metallurgy, engineering, processing, environmental management, and stakeholder relations (Figure 8) [173]. Learning is to progress with high-quality products whose value and importance will not be solely economic.

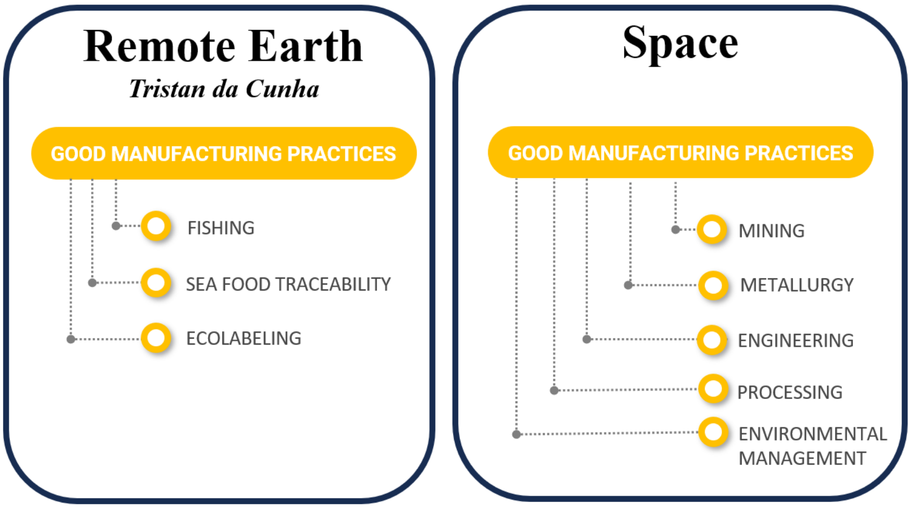


Figure 8. Promotion initiatives of good manufacturing practices in remote Earth and space.

Quality assurance of products and materials produced on the Moon will inevitably be a permanent task. As one of the most important economic activities in the future, mining will have to establish parameters based on the highest standards [174]. Setting the same or better quality standards as for production on Earth, with GMP's as a prime example, will create the conditions for highly automated processes. This will require extensive communication and interaction between the various economic sectors. The first space settlements will be responsible for constructing and commissioning the necessary equipment and networks [161]. Subsequently, coexistence between humans and machines will take place as the latter becomes an integral part of the labor team [161].

4.3.3. Product Safety and Audits

The *Pitcairn Islands have* developed safety standards according to international trade, with staff training and on-site technical consultancy [175].

Space: Several review articles have analyzed space safety risks, primarily from a human perspective; that is, the risks of space travel to the health of spacecraft members on their way to other celestial bodies. The International Space Station has become a valuable source of information about the mitigation of risks and investigation of how space affects human health [176]. In this regard, one of the main threats is exposure to cosmic rays, which is why shielding measures are one of the main safety management approaches [177].

4.4. Environmental

4.4.1. Climate Change, Deforestation, and Soil Erosion

Nauru experiences deep adversity due to climate change, characterized by droughts and limited freshwater resources, coastal degradation, storm surges, inundation, and oceanic acidification [84], so adaptation through the construction of appropriate infrastructure works is necessary. In this sense, initiatives such as the Sustainable Urban Development Project aim to improve water supply, sanitation, and solid waste management, and contribute to a better urban planning capacity in the country. Likewise, a USD 22 million Solar Energy Development Project finances a solar power plant and battery storage system and strengthens the Nauru Utility Corporation [177].

The *Moon*: The area east of the Amundsen Crater, at the lunar South Pole, may be a good location for the construction of power generation infrastructure that takes advantage of both the solar radiation during the lunar day and the low nighttime temperatures. In addition, it will be important that the system is purposed to have energy storage capability by, for example, developing infrastructure combining the use of lunar regolith as a storage medium (thermal conductor) and thermoelectric conversion [178]. This would allow it to operate continuously regardless of immediate demand [179].

4.4.2. Water Supply, Sanitation, Solid Waste Management, and Land and Environmental Degradation

The *Pitcairn Islands* lack a continual water supply; nonetheless, the solitary inhabited island features three intermittently sustained seasonal springs [29]. Nauru has suffered for many years from soil degradation due to phosphate mining in its central region. In addition, the population resides mainly in the narrow coastal lands, which increases its vulnerability to climate change [83].

Easter Island has experienced extensive deforestation and soil erosion [136].

The *Moon*: In the absence of plate tectonic activity, the Moon's surface would not regenerate and heal like the Earth's, so our satellite's vulnerability to mining risks would be greater [180]. This is of paramount importance, given that future missions will be longer, with a greater demand for storage of supplies and protection against environmental hazards [181]. Also, more advanced infrastructures will be needed, such as propellant depots, refueling stations, vehicle parking ports, logistics centers, or ISRU plants [6,45,182,183]. Consequently, missions will also need access to services such as spacecraft and production equipment maintenance, cargo management optimization, and space debris management [176].

4.4.3. Steady-State Adjustment of Population and Resource Stocks

The *Pitcairn Islands* derive regular income from more than half of the active fishermen, who account for approximately 80% of the catch [175]. Ensuring the future conservation of fishing waters and, thus, fishing revenues make informed management decisions essential. A monitoring system, the Baited Remote Underwater Video Systems (BRUVS), has been installed to ensure that a sustainable fishing industry on Pitcairn remains on track.

The *Moon*: Economic and social development and environmental conservation in human settlements on our satellite will require preventive and/or corrective actions related to applying two approaches. The first of these has to do with the proper management of information on the state of resources and how they are used. This means that environmental indicators such as material footprint, resource productivity, or consumption footprint, among others, will be essential for sound decision-making [181]. The second approach is based on the application of circular economy strategies (such as recycling and recovery, among others) through which materials and energy consumption will be optimized [184].

4.4.4. Environmental Monitoring

Tristan da Cunha has reinforced environmental surveillance following the sinking of the MS Oliva Shipwreck, which had a significant negative effect on local fauna [167]. Satellite monitoring facilitated by the UK government ensures that, especially in the Marine Protected Areas, no contaminated population enters the local supply chain. Likewise, the control exerted ensures that the closed area is adequately established so as not to interrupt commercial fishing. The absence of environmental monitoring can lead to significant risks, as demonstrated by the example of the stranding of the semi-submersible oil platform PXXI in 2006 [168]. The legs of the platform were largely covered with non-native species, including dead corals, barnacles, oyster shells, hard corals, large mussels, and large dark red anemones. Furthermore, the existence of said structure implied the appearance of the Brazilian snapper in the waters near Tristan. The *Pitcairn Islands* monitor the fish ecosystem using the aforementioned BRUVS system, based on regional and global data [185].

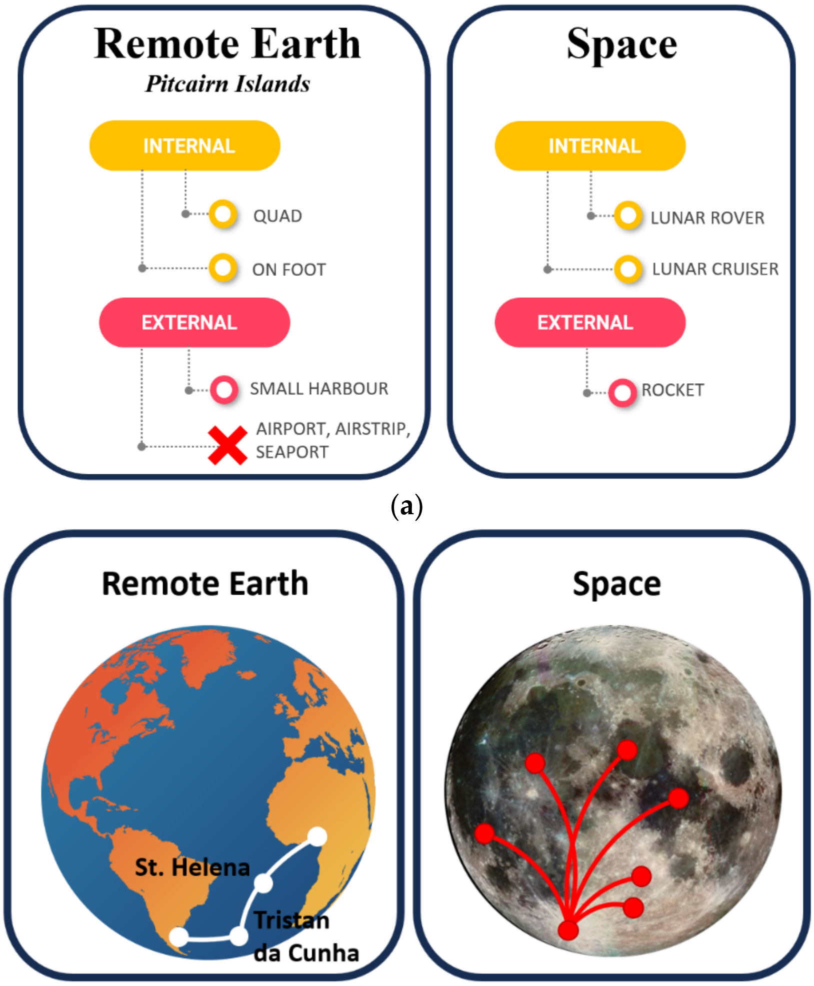
4.5. Transport/Supply Chain

4.5.1. Infrastructure Gaps and Local Transport

Experiences from the most remote places on Earth can help us understand how to design supply chains that can be adapted to highly challenging conditions in terms of distance, travel times, and infrastructure. The above makes sense to the extent that the eventual availability of materials resulting from the development of space supply chains could contribute to the reduction of the environmental, economic, social, and geopolitical risks of life on Earth [186].

The *Pitcairn Islands* exemplify the current reality of mobility in the remote places addressed in this review. The islands are accessible to settlers only by ship or boat and not to routine travelers because jagged rocks restrict access to the shoreline. Although the islanders depend on boats to transport people and goods [187], there is currently no adequate seaport. The one currently operating is shallow and has a launch ramp that can only be accessed by small boats (Figure 9a) [29]. A dedicated passenger and cargo supply vessel, the MV Claymore II, was the main transport from Mangareva in the Gambier Islands of French Polynesia until 2018, when it was replaced in 2019 by the MV Silver Supporter [29]. Within the territory of Pitcairn, the only inhabited island, a 6.4-km paved road connects Bounty Bay to Adamstown. *Tristan da Cunha*, like the Pitcairn Islands, does not have an airfield, although Saint Helena, which is relatively nearby, does have a landing strip [31]. As far as shipping is concerned, South African fishing boats visit the islands eight or nine times a year, while three other boats regularly serve Tristan da Cunha, with less than a dozen visits a year. Finally, until 2018, a mail ship, the RMS Saint Helena, was used to connect Tristan with Saint Helena and South Africa, albeit irregularly [58]. *Nauru* is transforming the largely inoperable Aiwo ship port into a climate-resilient international port through the so-called Climate Resilient and Sustainable Connectivity Project [84].

Space: Supply chain networks may not follow the local approach taken by Earth's remote islands but rather develop sophisticated logistics with nodes, archetypal of supply chains, after European explorers discovered the American continent. Compared to the space missions carried out today, the logistical approach has not changed much since the first missions following the 1957 launch of the Sputnik satellite by the then-Soviet Union. In general terms, this approach is framed in a simple "transportation" method by which the goods and services required by crews and equipment are supplied [188–190]. "Carry-along" logistics was the predominant paradigm in the six missions of the Apollo program between 1969 and 1972 and the subsequent space shuttle program (U.S. Space Transportation System (STS), 1981–2011). Each mission was independent, meaning that supplies and astronauts were transported at the same time and on the same ship, eliminating any need for a logistical support network [190]. The details of the logistics, quantities, and types of supplies were decided by the respective scientific teams involved [189].



(**a**)

(**b**)

Figure 9. (**a**) Comparison between internal/external means of transportation on remote Earth and space. (**b**) Remote Earth and Moon logistics with nodes and connections.

Since the “transportation logistics” period, the “age of competition” has catalyzed partnerships among space agencies [1,189]. At the beginning of space exploration, few countries were active; however, today, around sixty nations participate in various missions, evidencing the beginning of a new era called “New Space” [1,190]. This has led to the need to develop more complex supply chains, such as “ground replenishment logistics”, which have made it possible to supply goods and maintenance to the Skylab space station (launched by the United States), the Salyut and Mir stations (launched by the Soviet Union), and currently, to the International Space Station (ISS) through various types of vehicles from different points on Earth [189]. This logistical approach fits well with the need to maintain short non-resupply periods (three months on average on the ISS) compared to the longer duration of a space mission [190].

Although space logistics have worked well until now in terms of maintaining a basic level of operations, it has sometimes been characterized by insufficient deliveries, which has been reflected in inadequate maintenance and poor asset management [191]. Associated with this is the complexity of the procedures due to problems related to the existence of different standards for stowage, inventory, operation, and maintenance of equipment, causing delays in the tasks to be performed by the crews (Figure 9b). Due to the aforementioned drawbacks, failures and logistical difficulties have been reported in planning the return of equipment to Earth [181,190].

The infrequent launch windows and the long journeys that will be made between different locations are aspects to be considered when designing the logistical systems required for the expansion of human activities in space [191]. The above will imply that the implementation of the transportation network will require the establishment of "outposts" (nodes). To this end, attention is currently focused on the study of places such as the Earth–Moon Lagrange points, some NEAs, the Moons of Mars (Phobos and Deimos) and their orbits, the low orbit of Mars and regions of the latter planet, such as the craters Eberwalde and Gale and Mawth Vallis. For their part, low Earth orbit and geostationary Earth orbit (LEO and GEO, respectively) and launch bases on Earth are nodes that could complement the capabilities of the lunar, Martian, and cislunar nodes (Figure 10) [6,179,191–195].

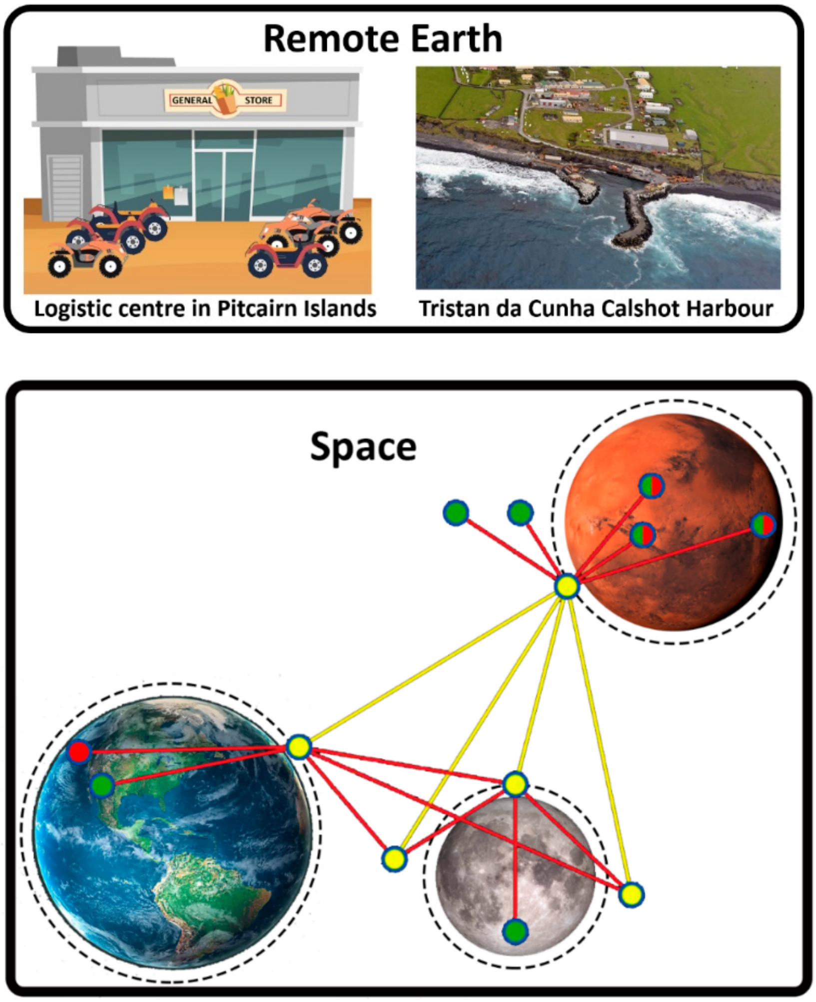


Figure 10. Inter-planetary logistic connections in remote Earth and space (green: origin nodes, red: destination nodes, yellow: transit nodes) [191].

While Figure 11 shows only the main input and output nodes of the supply chain, the actual structure would certainly be more complex. The primary nodes in Figure 11 could be supported by additional intermediate nodes, as shown in the example of services on Pitcairn Island. These complementary nodes could be called "asteroid nodes", as these celestial bodies would make transporting goods easier compared to planets or large moons. The main advantage of asteroids is that their gravity is weaker than that of the Moon or Earth, which would reduce fuel needs, and, consequently, transportation costs (Figure 11) [115].

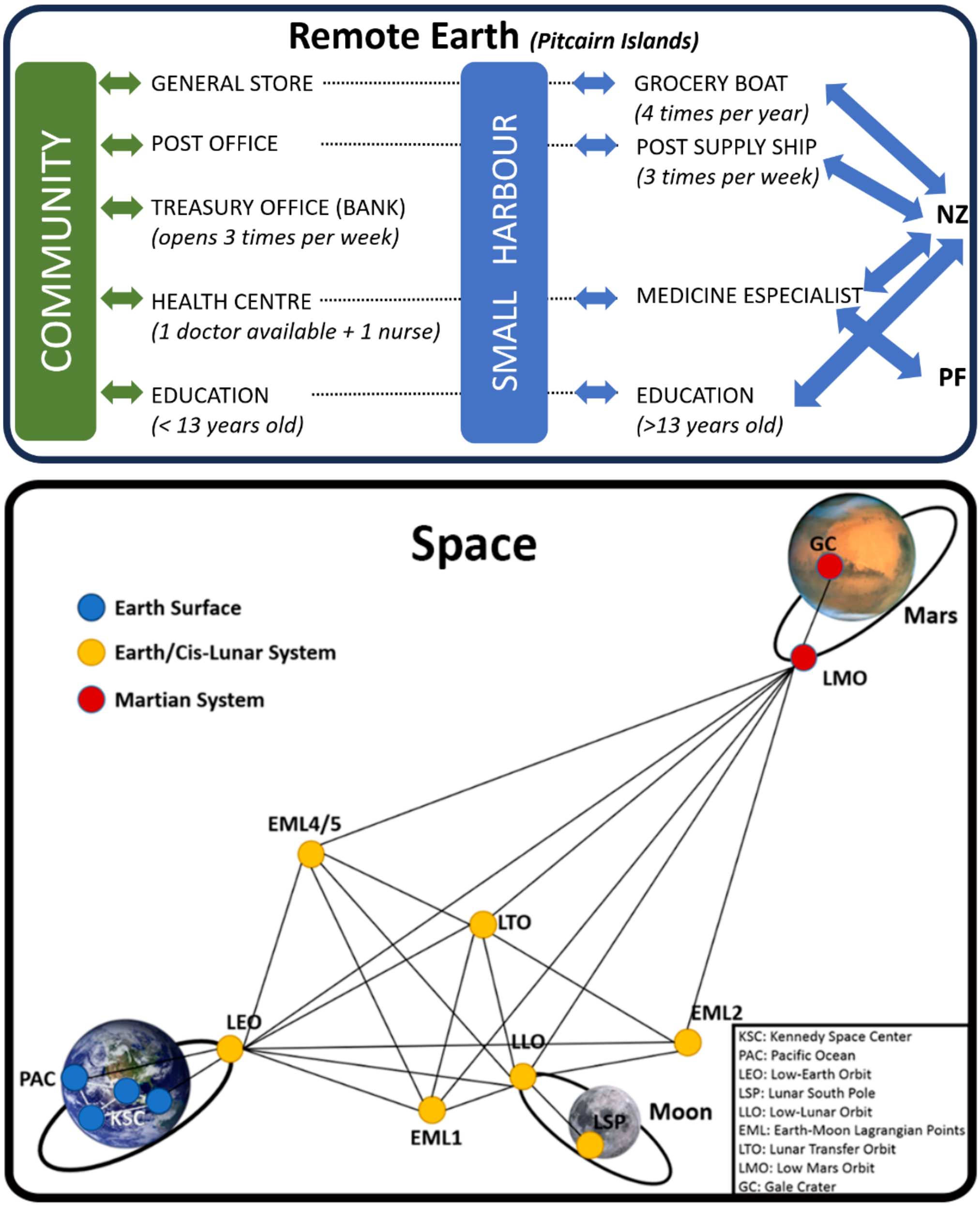


Figure 11. Remote Earth and inter-planetary logistic nodes, including asteroids [190].

4.5.2. In Situ Manufacturing

Remote islands do not practice in situ manufacturing.

The *Moon:* The transformation of space raw materials should consider not only the issue of initial space settlement [196,197] but also the production of more complex goods (in situ manufacturing) for human well-being [33,197]. As time passes, more goods are expected to be produced off-Earth, leading to a progressive reduction in the supply of payload goods [198]. Achieving complete ISRU autonomy of supply chains would also reduce the need for information flow, eventually making remote control of production from Earth obsolete [199].

Space supply chains will need to use space raw materials [200] for ISRU-relevant goods [200–203]. Likewise, the ISRU is anticipated to facilitate additive manufacturing and 3D printing to, among other purposes, reduce the weight of spacecraft and reduce costs [7,204]. Reducing ship launch costs will be a critical aspect of the development of supply chains since, currently, the mass of fuel used in transportation is very large; on average, more than 90% of the total weight of vehicles [205].

Once the initial transportation and service infrastructure required for both the Cislunar station and the lunar South Pole is operational, new settlements should begin to be established. At the South Pole, the Haworth, Faustini, Sverdrup, and Slater craters could be the first options to host habitats along with mining and industrial facilities complementary to those of the Shackleton or Shoemaker craters. Likewise, in areas located between the South Pole and the Equator, such as Mare Nubium or Mare Imbrium, industrial infrastructure could be established to take advantage of the potential availability of regolith minerals and elements (i.e., KREEP). The increase in the number of settlements at various points on the Moon would eventually imply the implementation of transportation systems that can cover long distances.

4.5.3. Supply Chain Inventory

Information on supply chain inventories is scarce for *remote islands*.

Space: Given the particular conditions of environments outside the Earth, the construction of radiation shelters, roads, housing, and facilities for the take-off and descent of vehicles will be required [197,206], as well as facilities related to autonomous operation systems [33,197]. In a complementary manner, the development of the ISRU will initially entail the creation of local supply chains [1,207,208]. Other important aspects to consider for the implementation of off-Earth supply chains will be the different processes and performance measurement systems. In addition to these, flows (information, objects, and materials), interdependencies in terms of information and processes, information systems, interactions between the various actors involved, and good practices shall be included in management frameworks (Table 4) [209].

Table 4. Components of the supply chain. This analysis is based on NASA's ISRU compilation [209].

Supply Chain Parts	Definition	Components of Each Part
Processes	Description of activities that take place in the supply chain.	Planning, execution, and enabling processes.
Performance measures	Tools for measuring and assessment of supply chain performance.	Key performance indicators and metrics.
Material flow	Movement of materials from upstream to downstream of the supply chain	All the materials, the transitions, and the flows involved.
Information and information flow	Definition of the aspects required for planning, executing, and enabling the supply chain.	Information is necessary for the performance and the different flows.
Information and process interdependencies	Relations between different processes and supply chain actors.	Interdependencies regarding information and processes.
Objects flow	Explanation about objects and their interactions.	Objects, their transitions, flows, and relations across the supply chain.
Information resources and application systems	Determination of all the information sources and enterprise application systems throughout the supply chain.	Information, data structure, and information resources interactions.
Decisions	Planning, execution, and management aspects of the supply chain.	Decisions, information required for decisions, and decision-making processes.
Complex interactions	Description of relations taking place at all levels of the supply chain.	Interactions between partners, processes, material, information, decisions, etc.
Best practices	Identification and definition of activities, interdependences, and prerequisites of practices.	Best techniques, operational procedures, business models, or technology.

4.5.4. Supply Chain Infrastructure

Information regarding supply chain infrastructure is scarce for remote islands.

Space: Supply chain components and processes should be organized at the systems level based on engineering principles or requirements to meet the demand for products and services. Likewise, supply chain risk management will be an essential element in that it will help to avoid delays and shortfalls [86].

In addition, the respective ISRU systems will contribute to streamlining logistics systems from the supply of goods needed for life support, energy and propellant production, and mobility (Figure 12) [210]. The first stage of implementation of ISRU systems will be prospecting, which will be aided by mapping and positioning tools and estimation of resource supply [33,196,211]. This will be followed by excavation, drilling, resource acquisition, and post-processing [33,196].

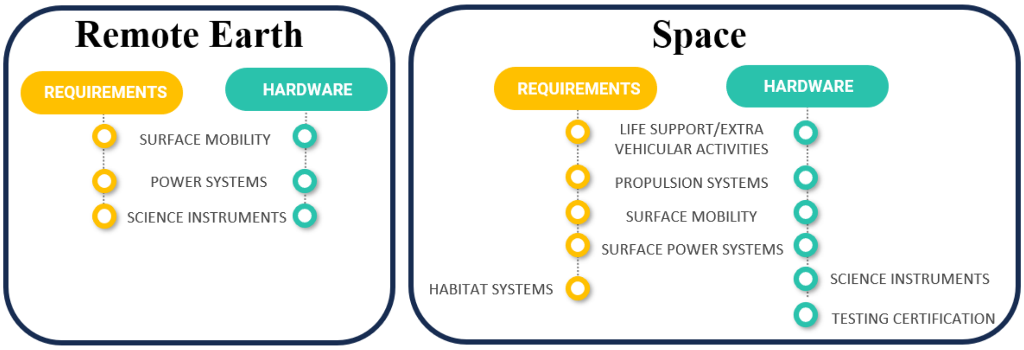


Figure 12. Interconnectivity between life support infrastructures and systems to be implemented in remote Earth and space [211].

4.5.5. Transport: Vehicles and Services

<u>The *Pitcairn Islands*:</u> The main mode of transport is four-wheel drive quad bikes (Figure 13a). When quad bikes are not needed, it is common for people to walk short distances [29].

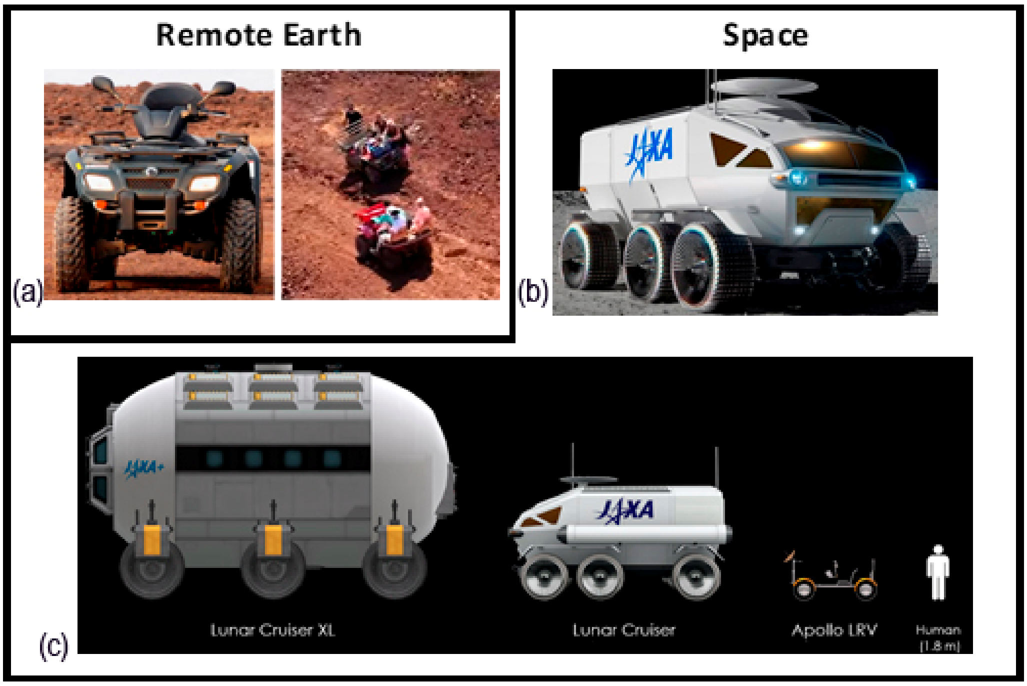


Figure 13. Transport vehicles for (**a**) remote Earth, (**b**) lunar cruiser prototype (JAXA project—Japan Aerospace Exploration Agency), and (**c**) prototypes and facilities for lunar exploration (JAXA).

<u>The *Moon*:</u> In addition to the implementation of commercial activities [192], such as mining, tourism, and waste management [193], the implementation of reliable and efficient transport systems will be paramount to boost the spatial economy [212]. Therefore, it will be necessary to adapt transportation to the sophistication of supply chains [180]. This should be reflected not only in the design, construction, and operation of vehicles with reliable and accurate propulsion systems but also in the optimization of communications between vehicles, nodes, and control centers [97,181].

Vehicle design deserves special consideration due to its importance for the proper functioning of supply chains (Figure 13b). Like on Earth, in space, there must be means of transportation designed to meet different requirements in terms of time, distance, and individual movement [192]. Consequently, it is envisaged that, for example, tugs would be in charge of moving loads within orbits and removing space debris, while service vehicles could be designed to operate between the different centers or nodes. Other types of vehicles would provide complementary services [181]. In regard to mobility over short distances on the surface of large celestial bodies (for example, between points of different lunar craters), the operation of rovers with traction adapted to the irregular topography could be pertinent (Figure 13c). These vehicles would be used to move small groups and/or smaller loads. For long-distance travel between industrial facilities, human settlements, and rocket launch sites, it would be desirable to use magnetically levitated train systems along viaducts properly protected against radiation and regolith, which would use energy more efficiently.

It is pertinent to point out that reducing the negative impact of regolith on transportation on the Moon will be pivotal when designing procedures, systems, and vehicles, as this material is particularly fine and abrasive, and, therefore, represents an enormous danger to the function and durability of engines and equipment (Figure 13c). Consequently, and if attention is also paid to the testimonies of astronauts who have been in contact with the regolith, it could be inferred that the exploration of the Moon would be an activity comparable, in certain risks, to the extraction of carbon on Earth [213].

More specifically, assuming that the Moon would be the ideal environment for the development of the first infrastructures and processes related to the space economy, the operation of rovers and vehicles with similar characteristics could occur between the craters Shoemaker, Shackleton, Faustini, Slater, Sverdrup and Haworth (South Pole) to connect nearby settlements and industrial facilities. Likewise, trains based on magnetic levitation could operate between the South Pole and areas such as Mare Nubium (located in the Southern Hemisphere, hundreds of kilometers from the Pole). The Mare Nubium region could represent an important source of minerals and valuable elements given the volcanic nature of the regolith found there, therefore, the exploitation of the resources of the said region could benefit the inhabitants of the South Pole. In this order of ideas, similarly to Earth, transportation methods such as the train could facilitate the expansion of economic activities to other areas of the Moon [214].

Space: In terms of mobility between celestial bodies and/or space transfer stations, the use of rocket-powered passenger and cargo tugs, either powered by fuels produced by ISRU or with electric propulsion, would make it feasible to cover the enormous distances in space.

Along with the infrastructure necessary for mobility, highly accurate and reliable navigation and communication systems would need to be established to allow operations to be carried out safely and ensure the operability of supply chains.

In the near future, covering enormous distances would initially be required to supply goods to the lunar settlements from Earth, since the ISRU systems would not yet be sufficiently developed. Therefore, if the high economic cost of such transportation is added to the challenge of transporting goods over hundreds of thousands of kilometers, it is evident that the difficulties inherent to supply chains will be even greater for life on the Moon than those experienced historically in remote places on Earth.

4.6. Supplementing Current Space Supply Chain Concepts with In-Practice Sustainability Principles from Remote Islands on Earth

This Perspective intended to supplement potential space supply chain concepts by drawing on in-practice sustainability principles from remote islands on Earth. Figure 14 summarizes this and compares the comprehensiveness of the supply chain approaches, detailing which specific supply chain goods are addressed in each strategy, as assessed in this review.

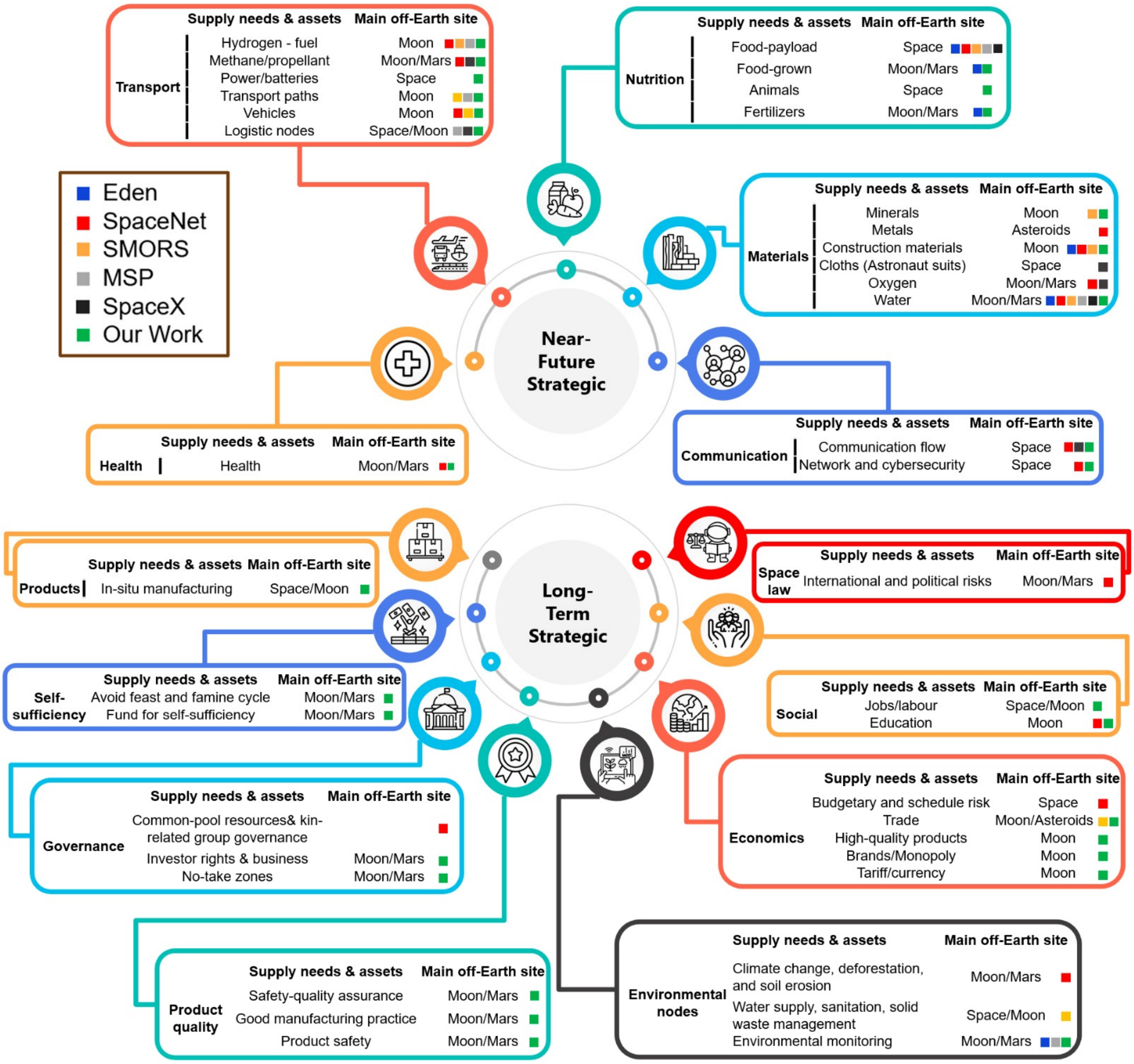


Figure 14. Summary of all supply chain approaches described and compared in this work, indicating which specific supply chain goods are addressed by each supply chain strategy.

5. Conclusions

The long history of human survival and resilience under harsh conditions present on remote sites of the Earth provides an invaluable basis for human space exploration on the Moon and Mars. These insights cover a broad spectrum, including but not restricted to economics, environment, labor, products, and the governance required for decision-making. Beyond repeating those here, several general conclusions can be drawn.

Remote sites on Earth face special economic constraints and are environmentally vulnerable. They are in a sort of "transitional" state at present, and largely, though not completely, decoupled from the rest of the world. Consequently, they provide learning for the future development of settlements and supply chains necessary for the space economy, both in terms of potential problems and solutions. Likewise, remote places are examples of what a community can and cannot achieve with the means currently available on Earth. These learnings cannot be transferred one by one. Space is full of resources, but humanity is unfamiliar with how they could be exploited. Remote places on Earth lack resources, and often, their exploitation has to do particularly with fishing activities since remote places are usually islands in the ocean.

In addition to the responsible exploitation of natural resources, the governance of remote places on Earth represents a crucial topic in terms of the lessons that should be kept in mind for the management of life in space. Such governance has been reflected in decision-making in remote places on Earth for hundreds of years. When facing harsh conditions, the "islanders" managed to develop their own ways of dealing with the imposed limitations and learned to make their lives livable due, among other factors, to the construction of solid communities.

The learnings from remote Earth-to-Space, taking into account what has been addressed in this perspective, are:

- to improve inward/outward materials flow to foster economics (Figure 2);
- to develop technologies for the provision of indispensable products from abundant raw materials (Figure 3);
- to survive in environments with low contents of organic material (carbon) but rich in minerals (Moon/Mars) or rich in air/water (remote Earth sites) (Figure 4);
- to understand the local resources and circularly extract these (Figure 4);
- to produce high-quality products (Figure 5);
- to identify shortcomings of learning in small, isolated societies and to provide countermeasures to finally achieve good learning (Figure 6a);
- to use resources circularly and to adjust demand (population growth) to production and resupply (of goods) (Figure 6b);
- to facilitate effective decision-making in a small and hostile environment (Figure 7);
- to provide elemental manufacturing according to local resource opportunities and to adjust human life to it (Figure 8);
- to design local transportation based on local infrastructure needs and concepts (Figure 9a);
- to structure a supply chain with adequate frequencies from multiple nodes. Supply chains with one or a few nodes operating sporadically carry the risk of interruptions (Figure 9b);
- that better logistics will promote node and supply chain connection (Figure 10);
- to develop a holistic logistics concept based on nodes (Figure 11);
- to develop advanced life support systems (Figure 12);
- that human and goods mobility by transport is essential for the supply chain; while limited on islands in vast oceans, space settlements have better opportunities (Figure 13).

Finally, the initial question can be inverted at this point and, thus, ask what might terrestrial communities learn from future space communities? Although nothing can be definitely said since the latter does not yet exist, the potential of communities in space is clearly defined and is rapidly gaining attention. In order not to limit the analysis to the formulation of a few concrete recommendations, this review has also addressed aspects that could be most influential for the development of human settlements in space, therefore providing some foundations and guidance for future research.

This study was intended to provide thought-provoking impulses from supply-chain learning from remote islands to space. It points at issues of human well-being, communal living, and sharing of resources that are under-represented in current space resource utilization models. With both present and historic learnings, this study shows the criticality of these issues and hints at problems and their solutions. This study cannot, however, provide a comprehensive translation to space settlement—this must and will undoubtedly be undertaken in future technical papers dedicated to a quantitative assessment of the hypotheses drawn from this Perspective.

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