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Approaches and Basic Principles of Settlements on Celestial Bodies

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Urban development is one of the most challenging areas of our time and it only gets more difficult when this task arises on other celestial bodies. The perspective of an urbanist or urban developer must catch the big picture while taking into consideration engineering, physics, social, health, psychological and economic issues as well. We intend to give a glimpse into this mindset and perspective.

Therefore, this paper consists of two main parts.

In the first part, we highlight some important arguments and points from the literature of building new settlements on other celestial bodies. Due to the rapidly evolving nature of this field of expertise, we think a summary of relevant literature is of paramount importance so that the reader can gain considerable insight into the topic. Another reason is that we would like to give a sense of the complexity of developing and managing these settlements.

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In the second part, we identify and suggest essential principles that can be applied to any planned settlements on other celestial bodies. These principles are based on literature, human history, lessons learned from habitats in extreme environments and our own experience in the Hungarian Urban Development Association.

In this paper, we use the term "settlement" for bases, colonies, villages, towns and cities[5] on other planets and moons.

SUMMARY OF LITERATURE

If humankind manages to create permanent settlements on other planets or asteroids, it will create new scientific questions. Throughout our history, we have experiences about colonisation processes and the challenges that accompanied them (Szocik et al. 2010). It is a possibility that new social and political order will be created during those expeditions, but it is highly recommended to learn from the previous colonisations on Earth. If we study those, we can easily identify what kind of conflicts could happen on the expeditions: criminal behaviour, social deviance can occur because of the background of the participants and the psychological stress caused by the travelling, and from the different adaptations of the individuals (Szocik et al. 2010). There are a lot of factors which can create conflicts among the expedition crew. Conflicts can easily emerge from stress in a divided group, people with different social status, rivalries between the colonies, etc. The literatures all agree that to prevent social disorder in new colonies, international laws for space expeditions should be created, and later controlled by intergovernmental institutions (Szocik et al. 2010). Throughout history, colonies on Earth had a lot of different political structures: there were examples of scientist-led technocrats, military maintained dictatorships, and direct and represented democracies as well (Wójtowicz–Szocik 2021). It

[5] The distinction methods between towns and cities are different in each country. In general, cities are one of the top 10–30 most populous settlements in a country's settlement structure.

is hard to predict which one will serve society in the best way, it is also possible that a brand new political structure will be created on the other planets (Wójtowicz–Szocik 2021).

For a human, the Moon is a quite hostile environment to live in (Stenzel et al. 2018: 8), but as the attention of both private and governmental actors enables more and more research projects to be carried out to solve these problems, we get closer and closer to colonising the Moon. But first of all, what are the main challenges of establishing human settlements on the Moon, and how much do these differ from the obstacles of living on other planets, such as Mars?

First of all, one of the biggest challenges, both on the Moon and Mars is harvesting, mining or extracting water (Matt et al. 2011). Recent research has shown that there is water ice on both planets. On the Moon, it is located on the poles (Gibney 2018: 475), and while the dendritic valley networks on the surface of Mars show that once there was fluvial activity on the planet (Howard et al. 2005: 3), right now there is only frozen water available there. Locating these spots on the planets is a complex task because of the regolith layers that might be covering them. And even if we can find these spots, transforming them into liquid form is an even bigger task, because for example on the Moon, the water spots that have been found are located in permanently shaded craters as cold as −249 °C, which are the naturally coldest spots known in the Solar System. One possible way to transform water into liquid form is using giant mirrors and the power of the Sun, as it is done for example in Norway, Rjukan (Gibney 2018: 475). The only problem with beaming reflected solar energy from mirrors at mountain peaks of eternal light to solar arrays in permanently shadowed craters is that it would require a complex infrastructure, both to aim the mirrors into the right spots and then also to capture the harvested water efficiently (Ellery 2020). Another solution, which requires less infrastructure is to equip rovers with drills and wireless ovens, that can mine both regolith and the ice buried under it, and then with the use of high-power lasers they could also warm the ice to produce liquid water (Gibney 2018: 475). Finally, a possible method is to deploy a transparent tent made of 0.1 mm thick polyethylene on the ice spots to use the greenhouse effect to warm the frozen water (Arnhof 2016: 4). Another noteworthy fact is that water hydration exists on the Moon in minerals at all latitudes, but this will be more difficult to extract than from ice (Ellery 2020). Producing water is not only an important task for human consumption but by electrolysing it into its constituent parts (oxygen and hydrogen) it could also be harvested for propellant (Gibney 2018: 475).

Secondly, a unique challenge of extraterrestrial planets is their soil, called regolith. By far the most well-known of them is the Moon, the main components of which are oxygen and silicon *(Figure 1).* However, oxygen is chemically bound in different metal oxides, so even if its extraction via electrolysis would give the highest yield, it would require temperatures above 2,100 °C. Other extraction methods would require some additives, such as hydrogen or carbon, which could only be brought from Earth initially (Stenzel et al. 2018: 11). While the composition of the regolith is similar to the basalt found on Earth, its physical attributes are very much different. Without a properly defending atmosphere, the continuous pummelling and tilling action of small meteorites, referred to as 'gardening', along with severe temperature fluctuations, have created a fine, dust like fabric with a mean particle size of 40–130 μm (Ellery 2020). On the Moon's surface, it can be several centimetres deep. It is also noteworthy, that regolith is electro-statically charged through interaction with the solar wind, and as a result of this, it is very abrasive and clingy, fouling up vehicles and spacesuits very quickly (Thangavelu 2014: 23). Moreover, the landing of a spaceship on the surface of the Moon can cause severe dust storms, which is a crucial factor to account for when planning the layout of a lunar habitat. While right now we only have a small amount of information about the regolith on Mars, it is certain that one of its components is perchlorate, which has toxic effects (Oze et al. 2021).

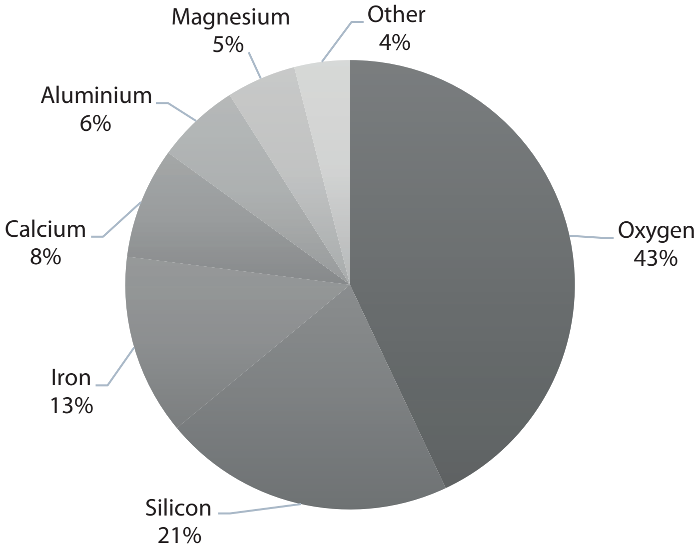

Figure 1
The composition of regolith on the Moon (varies by location)
Source: Compiled by the authors based on GIBNEY 2018: 477.

Thirdly, both Mars and the Moon have significantly different atmospheres than the Earth. The red planet's surface pressure at mean radius ranges from 4 mbar up to 9 mbar which is much smaller than the Earth's 1,013 mbar, and it is because the atmosphere of Mars is roughly 100–250 times thinner (SUCHANTKE et al. 2020: 440). Moreover, the red planet, just like the Moon has no magnetic field (GIBNEY 2018: 477; EHLMANN et al. 2016: 1932). The latter has also no protective atmosphere (GIBNEY 2018: 477), and while Mars has bigger temperature swings than the Earth, the Moon can have the biggest out of the tree, with 123 °C (253 °F) noon and even –233 °C (–387 °F) predawn temperature on its equator. The Moon also does not have any seasons and only has one sixth the gravity of Earth (THANGAVELU 2014: 23), while Mars has one-third of our mother planet's gravity (SUCHANTKE et al. 2020: 440). These attributes combined, especially the lack of a significantly protective atmosphere can have serious implications, such as meteorite showers, solar particle storms (Thangavelu 2014: 23), or in the case of Mars, the Galactic Cosmic Radiation can be up to 77 cSv, while the allowed annual dose for a NASA astronaut is 50 cSv (Arnhof 2016: 5). To survive under these conditions, humans will need protecting shelters, which can be achieved by going into under surface caves or by constructing bases with the method of in-situ resource utilisation (ISRU). Not only ISRU is much more cost-effective than transporting everything from Earth, but it also has a wide range of techniques. From the simpler methods, like using inflatable components, or reinforcing the shelter with bags of regolith (Arnhof 2016: 5), to the more complex ones, like reusing the leftover parts of previous landing structures, or 3D printing with locally available resources. The recycling of abandoned structures is also a promising concept from a sustainability viewpoint. According to a recent analysis, there are already 20 tons of aluminium and 7 tons of carbon fibre-reinforced plastic on the Moon, which could be reused with additive manufacturing techniques (Stenzel et al. 2018: 9). There is also a growing interest in regolith-based 3D printing methods, which could even be used to produce bricks (Arnhof 2016: 5; Stenzel et al. 2018: 10; Gibney 2018: 476).

Possible locations for permanent settlements on other planets are the lava tubes, which represent volcanic activity from the past (Hörz 1985: 407). Those kinds of geological phenomena occur on the surfaces of both Mars and the Moon (Haruyama et al. 2012; Léveillé–Datta 2010), on the Earth, it would be unusual to consider it to settle such environments. Places which are suitable for establishing settlements are graben with pits, volcanic vents and craters created by exogen phenomena such as meteor impacts (Blamont 2014: 2140).

The following areas are more suitable for settlement on Mars (Blamont 2014: 2142):

- Radiation is much higher than in the case of our planet, the atmosphere is not as protective as here, according to previous calculations, the difference between surface and cave 'habitants' absorption of radioactive rays was three scales better for the second option (Harris 2003: 7).

- Externalities in temperature are mitigated by the cave's pits.
- Dust on Mars contains harmful composites, but deep areas are protected.
- Meteor impacts are more likely on the surface of Mars, but caves are more protected if such an event happens.
- Cave settlements help to create in-situ resource utilisation, where new resources and materials can be studied outside the settlement area.

There are also some hazards which can come up during cave habitations: We do not have any data about the geological stability–instability of those areas, this information is crucial in the case of lava tubes (Blamont 2014: 2143). If we think about transportation, elevators and ropes would play a significant role in entering the settlements, rovers will be used mostly for surface mobility (Blamont 2014: 2144). Firstly, the first space colonies should be created on the Moon, and then the experiences gained there can be adopted in later processes. Inflatable structures are the best solutions for cave dwelling; at the beginning, it is recommended to start with 10 to 20 meters deep tubes, then extend them up to 100 meters (Blamont 2014: 2143). Blamont also suggests how the settlements should be made: there would be two different tunnels at the bottom of the deep spaces, two tunnels in opposite directions, the first one for social, private and housing functions, the second one would be the place for industrial activities, recycling processes and commercial functions. The cave entrances could be used as a place for photovoltaic panels, land zones for spaceships, depos of rovers for surface mobility and communications systems to the Earth (Blamont 2014: 2144). He gives a detailed description of the colonisation process; robots and automatic systems will play an important role in his vision of discovering and creating new colonies. The energy needs of the settlements should be managed with nuclear power, which needs fewer materials but can produce enough energy (Blamont 2014: 2143).

Another challenge related to these techniques is energy production, which is likely to be covered mostly by solar power, but for backup, nuclear power, for example a Liquid Fluoride Thorium Reactor is a wise choice according to recent research (Thangavelu 2014: 22; Arnhof 2016: 3). And even with these available technologies, it is likely that the colonisation of a planet will be divided into three major phases: in the first phase, robots are going to prepare the surface for the first human habitats; in the second phase, the first bases and the basic infrastructure are going to be set up; and in the third phase, the large scale colonisation and the development of cities and societies will take place (Arnhof 2016: 7). These three steps can be observed both in the NASA's Lunar Exploration Program, called Artemis Plan (NASA's Lunar Exploration Program Overview 2020), and in the plans of the International Lunar Research Station, which is set to be built in partnership led by China and Russia (International Lunar Research Station 2021).

Feeding the first settlers, and later entire colonies is another significant challenge, especially if we not only think about the Moon but Mars too. The latter one is not only further away, but its perchlorate containing regolith is also much worse for plant growth than Earth's soil (Oze et al. 2021). However, experiments have already been constructed both on Earth (for example in China) and on the International Space Station. The results have shown that the plant with the best features is kale, which could be grown in space or on different planets with simply water and red and white LED lights (Gibney 2018: 478). Feeding people is the most important question for the colonies, to maintain a long-term settlement it is crucial to start to grow food locally, this way minimising dependence on Earth (Cannon–Britt 2019). Cannon and Britt investigated a model to show how can the population of a Mars colony reach one million people. The three main key factors are planet-based food, insect farming and cellular agriculture.

In his work, Haym Benaroya attempts to give a general summary of the scientific discussion and debates on the Moon's exploration. In the first two chapters of the book, Benaroya overviews the history of the research and scientific expeditions related to our only natural satellite. He reflects on the main challenges of the tremendous enterprise, the Moon's colonisation, such as economic, ethical and environmental questions. In the fifth chapter, among others, we can read about the urbanistic, psychological and sustainability-related questions of the lunar settlements.

While the colonisation of a new planet holds enormous opportunities, that humanity has never had before, it also comes with a huge responsibility. This includes the amount of money and time spent on preparing the missions to a new planet, which could have been spent on saving people's lives on Earth or even the ecosystem of our mother planet. Moreover, it also includes the question of how humanity tries to tackle the wide range of challenges presented by the extraterrestrial environment: do we try to modify the genetics of chosen people in a way that they will be more resilient to the possible difficulties (human [bio]enhancement) or do we try to modify the extraterrestrial environment to the point where it becomes habitable (geoengineering) (Balistreri–Umbrello 2023). As technologies related to both solutions are getting more advanced, we have to address the ethical, legal and moral questions of both methods. Scientists who support geoengineering state that any genetic reprogramming project of human beings would represent an unacceptable violation of the principles the liberal-democratic societies are based upon (Habermas 2003: 66). They also assume that the more we modify people, the more they lose their human nature and become less connected to human societies (Sandel 2007: 86). Moreover, if genetically modified people would colonise another planet, there is a chance that over time they would become so much different than the humans on Earth that we would lose the coherence of our species (Fukuyama 2002: 101). On the other hand, many scientists disagree with these opinions and support human (bio)enhancement. They state that the economic costs of modifying the genetics of astronauts are much lower than modifying the environment of an extraterrestrial planet. Moreover, just like each human, each planet is unique and special in its attributes or in the way it was formed, and by modifying or destroying any parts of it, we could delete a valuable piece of our universe. Even if at the moment a material or an object seems worthless, we cannot predict how much we will need it in the long term. All in all, it is undeniable that whichever of the two we choose, we will have to take into account the possibility of serious downsides, and as a result of this, the best method is probably to evaluate case-by-case which solution is better (Balistreri–Umbrello 2023). Nevertheless, despite Fukuyama's opinion, it is likely from a biological point of view that natural evolution will change the physical and mental attributes of the colonies' inhabitants in small steps from generation to generation. The time will come when these cumulated changes after generations of reproductive isolation are so significant that these humans can be considered members of a new species ("Homo Extraterrestrialis") (Smith–Davies 2012: 28).

Moon is closer to our planet, it is much easier and cheaper to settle there than on Mars, and it can also serve as an experimental area for later missions to other planets (Szocik et al. Wójtowicz–Braddock 2020: 7). The former leader of the European Space Agency (ESA), Johann-Dietrich Wörner came up with the 'Moon Village' concept. Briefly, he imagined that in the near future, there would be a Moon Village, which would serve as a place for experiments, and replace the role of the current International Space Station (ISS) (Köpping Athanasopoulos 2019). He avoided using the word base or colony, because he can hardly believe that there would be any intentions to settle on other planets permanently. In his opinion, the 'village' word does not represent a project, but something which is maintained by the common interest of actors, in this case by the governments, private companies, etc. International cooperation would be necessary to maintain a certain order there (Köpping Athanasopoulos 2019).

ECONOMIC ISSUES

One cannot ignore the exciting economic issues that arise as regards expansion to other planets.

In case of tremendous and extremely capital-intensive investment projects such as Moon expeditions, the return rate is a critical issue. As Benaroya writes, according to recent studies the return rate of great research and development enterprises and investments is quite high. These projects incentivise the investors' R&D activity and give them a significant technological advantage in the global economic competition. Furthermore, an extraordinary and unique undertaking such as the colonisation of the Moon can provide access to new natural resources and can open a completely new market, the economy of lunar settlements for investors (Benaroya 2018: 22).

To finance expeditions to colonise the Moon, experts say it is essential to bring together public and private capital in some kind of PPP structure. Recent examples of private capital in the space industry have highlighted the limitations of this type of financing (more limited amount of money, shorter expected payback period), making it clear that public funding will be essential in the future. The plans for cooperation for lunar deployment also envisage a combination of both types of capital and a strong predominance of public funding, while maintaining the possibility of a more mixed financing landscape for lunar investments in the future (Benaroya 2018: 22).

One of the most interesting economic and organisational suggestions of recent years as regards extraterrestrial settlements is a framework called Lunar Development Cooperative (LDC), which is worth noting in a little bit more detailed way.

In their article, the authors of the LDC concept describe their vision for a company–cooperative organisation called Lunar Development Cooperative (LDC) which would operate as a public–private partnership. The LDC's main goal is the fair and sustainable development of the Moon during its human colonisation. By functioning as a joint-stock company, LDC would be open for public and private actors of the world's economy. Any of them could buy a share in the LDC above the minimum price of 1 $. Fifty-one percent of the stocks would be opened for private actors such as companies or individuals, so the states could receive an aggregated share of 49%. None of the shareholders could have a share bigger than 10%. The developing countries could buy special options which are reserved directly for them. As a result, monopolisation and too dominant national interference could be avoided (Castle-Miller et al. 2020).

During the first phase of lunar colonisation, the LDC would operate as an actor which provides all the crucial services (heating, electricity, energy, security etc.) for the growing settlements at a nominal price. Besides the individually accessible services, the LDC would sell site utilisation licences.[6] (Later, by lowering the prices of the individually accessible services, these site utilisation licences would provide the majority of the LDC's income). The owners of these licences would be entitled to use the LDC's services for a certain fee on the designated investment sites for a certain period. At the end of this period (40 years at most) the licences would be sold again, but the former owners would hold their property connected to the licenced site in any case. Those who do not buy LDC licences could use the sites too, but the LDC's services would not be available for them. However, it would not be obligatory to be a shareholder of the LDC or buy its licences, the authors predict that the company's efficiency and wide range of supply will mean tremendous advantages for the shareholders and customers. It might persuade the other actors to join them (Castle-Miller et al. 2020).

The main decision-maker organisation of the LDC is the board of directors which would be elected by the shareholders. Besides the board of directors, the board of advisors would have a significant role in the company's functioning. To this board, every nation and indigenous group could send deputies to provide worldwide control over the LDC's activity. Anybody could claim against the LDC at any court on the Earth or on the Moon. The company's inspector general would have special access to any documents related to the LDC's work. The company's internal rules are determined by the shareholder's agreements which guarantee that the company will function according to the principles of good governance and that its work will be in humanity's best interests. The LDC would strongly support the implementation of the Outer Space Treaty of 1967 and provide equal conditions for any state to access the possibilities of the Moon's exploration (Castle-Miller et al. 2020).

By providing its services, the company could become an indispensable component of the investment and development processes on the Moon. By founding the LDC, the serious conflicts of the colonial era would not occur

[6] Of course the authors' suggestion would imply a change of the international legal environment as regards the Moon. But instead of current regulations, their focus is on practical solutions that could be followed by lawmaking processes.

again on the Moon. The LDC would endorse the development of clusters and settlements with strong, diverse and resilient economies. Moreover, as the LDC is strongly interested in the thriving and attractiveness of the Moon's investment sites, the company would force the investors and developers to work by preserving the local environmental values and using natural resources sustainably. In summary, the LDC or a cooperative similar to it could provide us with the possibility to explore and populate the Moon efficiently, sustainably and fairly (Castle-Miller et al. 2020).

THE PRINCIPLES – HOW TO DESIGN A PERMANENT SETTLEMENT ON MOONS AND OTHER PLANETS?

As we can read in the literature above, the thought of habitats, settlements, colonies and towns on other planets does not fail to fascinate researchers all around the world. Based on these works, human history, lessons learned from habitats in extreme environments and our own experience in the Hungarian Urban Development Association, we can identify and suggest essential principles that can be applied to any planned settlements on other celestial bodies. These principles could help with creating and maintaining thriving settlements.

Each principle is followed by a short explanation in the following section. Due to the complex nature of human dwellings and settlements, some of the principles might overlap to a certain extent. Of course, it is unavoidable in this field but we believe that distinguishing between the focuses of the principles will help to better understand.

SUSTAINABILITY

Becoming a multi-planet species gives humanity the possibility to avoid mistakes of the past on Earth, such as the building of unsustainable settlements and urban structures that overuse natural resources, and foster social tensions and economic declines. Therefore, we suggest the concept of sustainability as a stepping stone.

A great responsibility of humanity during the colonisation of a planet is to make it as sustainable as possible for both the Earth and the planet in question, paying attention to all three pillars of sustainability. The concept of sustainability – especially its environmental pillar – is often connected to biological ecosystems, but in the context of planet colonisation, it is also important to take into account the mindset of sustainable development. The economic pillar is important even in the short term because the colonisation of a planet is only likely to be successful if it is profitable in the first habitats. As an already existing example, the term 'space sustainability' first appeared in the second half of the 20th century, when it referred to the lifetime of the different hardware and technologies sent into space, and to the financial and political difficulties of space programs, as illustrated by the cancellation of the Apollo lunar program (Newman–Williamson 2018: 31). Environmental sustainability is also important because those who arrive later should have the same variety and quantity of resources (at least roughly) as the first settlers. Additionally, this pillar is also important if we take into consideration the complexity of the consequences of discovering and meeting with extraterrestrial organisms (aliens). Researchers have already highlighted the importance of planetary protection, which includes "forward contamination" (the contamination of other solar system bodies by Earth microbes and organic materials) and "backward contamination" (the contamination of Earth systems by potential extraterrestrial life) (Conley–Rummel 2010: 792). Finally, social sustainability is not considered in current space programs, but in the long term, if we want to build independently functioning colonies, social cohesion and diversity will become a major factor (Table 1).

Table 1
The sustainability of planet colonising regarding its three pillars

Pillars of sustainability	Economic	Environmental	Social
What does it mean in case of colonising planets?	The colonisation produces enough financial value to cover the expenses, so it does not set back any future colonising projects.	The latecomers or second generation of settlers have the same resources available as the first settlers.	A society that is diverse enough to be able to function and reproduce itself isolated.
When is it important?	Short-, mid- and long-term	Mid- and long-term	Long-term
Main benefits it gives	It enables keeping up the support from Earth and other colonies to the new colony, it enables new colonising projects and expeditions in space.	Makes sure that there will be a liveable planet for humanity even if Earth becomes unliveable.	Avoiding ghost space colonies, enabling the support of the project(s) of the whole population of Earth, the colony(ies) can survive (and grow) without new people coming from Earth (or space).
Challenges of achieving it	Most of the current technologies are far from profitable, they are usually supported by governmental programs and accidents can cause the shutdown of whole programs.	We do not know what needs to be conserved, or even what is going to be the reaction of the planet to the first colonies, societies, pollution.	It requires cooperation from different Earth nations, not every person will be able to travel in space.
Possible solutions	Better technologies, non-governmental companies investing and making profit in the sector.	Defining the neutral environment on a planet, finding and monitoring the key aspects.	Making the groups–crews of the missions diverse in different aspects (social background, profession, gender, nation, age).

Pillars of sustainability	Economic	Environmental	Social
How can working on the solutions help life on Earth?	Developing more cost-efficient solutions encourages innovation and can lead to technologies that can solve the problems of people living on Earth.	Inventing methods and technologies that minimally damage the environment of different planets could help in saving the Earth's ecosystem.	Populating a different planet would significantly increase the survival chances of the human species and our civilisation.

Source: Compiled by the authors

Just to give an example, let us see what the principle of sustainability would mean in practice: planners of these settlements must emphasise the prospects and needs of shared public transportation modes instead of energy and place consuming individual transportation, so they have to elaborate the master plans accordingly.

THE IMPORTANCE OF LOCATION

History teaches that settlements with a monoculture economy are fragile and are prone to abandonment. That was the fate of ghost towns after the gold rush era or the reason behind the urbanistic depression in Detroit. Successful and sustainable towns and cities are built and developed on more advantages and perks. That is why the choice of the location must be carefully considered well before the landing of the first habitat module.

Requirements of the settlement location:

- Possibility of producing water. This would primarily mean ice, groundwater, water attached to regolith or water reserves in deeper layers. Water is an essential part of the life support system and a possible resource for propellant.

- Presence of mineable metals and rare metals. These elements are also dual-purpose. They can be used as in-situ resources for the structures or equipment of the colonies and they will also be export products to Earth or other colonies. The source of income generated can be used to finance the founding and maintenance of the settlement.
- Enough sunlight. Like almost everything in isolated extreme environments sunlight also serves more than one vital cause. First, a settlement should not rely only on nuclear power (see redundancy principle later[7]). Instead, it needs to be able to utilise solar power, too both for critical infrastructure and mobile equipment (e.g. rovers, machines, drones). Second, places without sunlight are extremely cold environments both on the Moon and Mars (this is true for an overwhelming part of the Solar System), therefore, creating and maintaining habitats in these dark places would mean disproportional costs. Third, we humans psychologically need to see natural light from time to time to keep our sanity in the long run.
- Places where mountains and hills meet plains and flatlands are preferred. Different geological formations usually mean more possibilities such as resources, observation and communication points and natural shelter. Shelters can provide further protection from heavy storms, dust storms, radiation or an attack. Later when the process of civilisation advances and there are more settlements and mining outposts, these locations at the foot of the hills and mountains can serve as trading hubs as well because spacecraft are more likely to be able to land on flat lands.
- Presence of natural caves or suitable locations for artificially built caves and tunnels are preferred. In the first era of extraterrestrial settlements, it is crucial to utilise these caves and tunnels to provide enough protection from radiation. Parts of the first colonies will likely be located underground, protected by a thick layer of regolith.

7 The basic principle is that the settlement must have more than one source of energy, water, food and communication method.

- Lack of dangerous seismic activity. Planners have to minimise the risks to the integrity of the structures because the possibility of rescue missions and resupply of materials and equipment is considerably limited.
- The presence of deep canyons is preferred. This is an optional requirement but it is worth paying attention to the opportunity. With proper radiation and impact shielding on the top, these canyons can be transformed into auxiliary habitats because they provide better protection from nearby meteor impacts, surface blasts and shockwaves than surface structures.

It follows from the location principle that careful examination and evaluation of the potential settlement spots are essential. This long process should start way before the first spacecraft would be able to be commissioned for the first phase of the establishment of an outpost. The process involves a great deal of exploration missions, scanning of the area with probes and beginning of constant monitoring as soon as possible. The more data we have the higher the chance that we can minimise the risks by choosing a secure location. This is crucial because a poor choice results in loss of life and a tremendous amount of resources.

REDUNDANCY AND PROTECTION

Given the impossibility of immediate rescue and resupply missions, these settlements must be resilient against a lot of effects.

The literature agrees that every colony must have shelters against extreme radiation, storms or meteor impact events; therefore, it is likely that some parts of these habitat structures will be located underground. We have to remember that equipment malfunctions, fires, etc. are also risks we cannot ignore.

The designs must take into account that parts of the colony have to be able to work even if others do not. Therefore, settlements must have more than one energy source (moreover, solar panels, reactors and other energy sources should not be in the same place) and should also have alternate cable roots to consumer buildings. The same is true for oxygen, food and water producers, storage and transporter facilities. The underground part of the colonies should have life support and other systems that can remain functional even if the surface modules–domes are lost or have to be cut from the grid.

Hygiene and isolation capabilities are also vital parts of urban planning because a pandemic could cause severe problems. The colony must be able to function and operate even with one part locked down.

Planners should not forget about connection–date resiliency either. Not only because of the obvious reason that humans can communicate with each other on that planet or with other planets, but because construction, repair and maintenance will be partly robotised, and a lot of data exchange will be needed to coordinate the robot swarm. For these reasons Internet–Lunarnet–Marsnet is necessary, possibly with satellite technology that helps geolocation as well. The net has to have reserve satellites and reserve ground facilities.

RECYCLING

History shows that great civilisations cannot thrive if they are not able to handle their waste. That is why recycling and waste management are a main pillar of successful and healthy settlements. This is especially true in case of settlements outside Earth due to the scarcity of resources. The literature also agrees that recycling water, waste, nutrients and oxygen is key for the survival of these outposts.

RESEMBLANCE

Humans are not robots. Besides the basic life functions, we have recreational, mental and spiritual needs to preserve our health. This implies that the design of successful long-term settlements must reflect our needs as human beings.

This means that the settlements have to remind people of the features they love about their home on Earth. Nowadays every experienced urban planner knows that humans need different kinds of spaces in order to feel comfortable. Therefore, the designs have to contain community places where residents can have a chat, relax or have parties and feasts. Parties and feasts are not typical words to occur in space science literature, but having these festive gatherings is one of the most ancient traditions of humankind and as such it cannot be ignored because it is rooted so deep in our culture. We also need the sight of nature and plants of some kind. Research proved that it enhances both mental and physical health. What is more, people need to see wide horizons, scenic views and the sight of the sky from time to time. We also need spaces of spiritual recreation for a completely soothing and comforting environment. It follows that soulless base designs with only purely functional modules for work, research, maintenance, sleep and nutrition are going to ultimately fail in the long run.

FINANCIAL RETURN

Any space mission, especially the establishment of permanent habitats on other planets costs a huge sum of resources. We have to accept that these costs cannot be sacrificed only from taxpayers' money and donations. Earth's history taught us that financial incentives lead to the involvement of the private sector and as a result, the whole process of expansion becomes a lot faster (enough to think about the history of trading outposts of the Dutch East India Company). We argue that these settlements have to have competitive yields and return on investment in accordance with the economic sustainability principle above. To reach this, a special economic zone system is unavoidable, partly for incentive purposes and partly because other planets are special areas in international law as well.

What could generate income in or for these settlements and communities in the first decades far away from Mother Earth that can be incentives for investors?

- government subsidy
- research time and facilities
- intellectual property rights
- mining
- video streaming and ads
- tourism

We think it is likely that in the first years, the main product of these settlements will be the results of scientific activity such as patents and intellectual property rights. That is why – like in the case of every successful civilisation – only a small portion of the population's task shall be the providing of basic needs (food, life support system). This also creates the need for the intense use of technology and AI in maintaining, repairing and monitoring structures and machinery because communication with Earth for instructions is time consuming and in the first years there will not be enough people in the colony to have professionals for every situation imaginable.

In case of the Moon, high-end tourism can also generate a significant amount of income that would contribute to economic sustainability. Tourism on Mars is only realistic if technological advancements make it possible to reduce travel time significantly.

CAREFUL SELECTION OF SETTLERS

Becoming a multi-planet species is one of the greatest endeavours of humankind. The survival of our species and civilisation depends on it and it requires the use of almost unimaginable amount of resources. Simply put, there is too much at stake and we have to conduct a careful and rigorous process of choosing crews and settlers. Populating other planets is not a place for uncontrolled migration or amnesty–prison camp like colonisation as we saw in Earth's history earlier. Successful training, useful skills, mental stability and a clean criminal record are basic requirements for would-be inhabitants. The selection process should be based on merits gained during training on Earth. Besides the common skills and knowledge, members shall have diverse individual skill sets that help with keeping thriving settlements. The groups shall be balanced in terms of social background, nationality, gender and age (to a certain extent).

NO WEAPONS

At present, according to the best knowledge of the scientific community, we do not know any species on other celestial bodies in the Solar System that endangers humans and can be fought with weapons besides humankind itself. It follows that if there were weapons in these settlements they would probably only harm humanity and these settlements, not protect them from an unknown threat. Considering the stunning costs weapons can cause in these extreme environment settlements we argue that international cooperation should ensure that these settlements remain free of weapons. The issue must be revisited if new species appear that are a direct threat to human life and are vulnerable to weapons. We emphasise this principle from a practical point of view as we are sceptic to a certain extent as regards the long-term compliance with any international space treaties on the peaceful use of space and celestial bodies. History shows that compliance with this kind of international treaty is rather a matter of technological possibilities and balance of power among the actors than the rule of law due to the lack of effective international bodies to enforce them.[8]

[8] We have to note that the weaponisation of space has already started. For example, modern military reconnaissance and guidance systems rely on devices in orbit to a great extent. Nevertheless, further military researches also seek the possibility of conducting attacks from or in space partly against these devices controlled by hostile forces.

EVOLUTION

As time passes and one generation follows the other, the effects of biological evolution will also appear in these settlements. According to our knowledge of the history of evolution, we are certain that the genome of the inhabitants will transform even without genetic engineering. At some point, this transformation will cross the point where we can call these people new species. This implies that the needs and requirements for these people's settlements can be very different from the principles we design settlements. Therefore, designs and thinking should have the possibility for flexibility and be open to changes from time to time.

CLOSING REMARKS

Becoming a multi-planet species seems unavoidable if humankind intends to survive. We are at the dawn of the era which marks the beginning of this transformation process. The enormous technological and biological challenges tend to eclipse the questions that need discussion as regards the way of human life and society in the long term outside planet Earth. That is why we think it is important to have a discussion about design principles, societal and economic viability of the settlements and environment that humans will call home in the future. Based on other authors' expertise and our experience in urban planning, we offer some basic principles that could help with designing resilient settlement structures on other celestial bodies. These principles are:

- sustainability
- location
- redundancy and protection
- recycling
- resemblance
- financial return
- careful selection of settlers
- no weapons

We believe that keeping these principles in mind will help create the experience of home for the generations to come.

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