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Concept of a 3D-Printed Voronoi Egg-Shaped Habitat for Permanent Lunar Outpost

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Abstract: The article presents a concept of a lunar base that would take advantage of the natural shape of an egg. Several versions of egg-shaped habitat structures characterized by different sizes are presented. Possible locations of habitats both on lunar surface and in craters were discussed. Advantages and disadvantages of particular locations were also pointed out. The proposed in the paper concept of an egg-shaped structure is characterised by a spatial character based on Voronoi diagram and would be implemented using a 3D-printed method. The presented 3D-printed structure was designed to be light and suitable to be covered by lunar soil. As a necessity in the developed concept, in situ resources utilization was addressed in order to generate products using local sources to reduce the number of materials that would be required to be transported from Earth. At the end of the paper, future areas of research and tests are highlighted.

Keywords: the Moon; lunar outpost; space; 3D printing; Voronoi structure

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1. Introduction

Looking to the starry sky, man has always longed to stand on the surface of the Moon. However, starting from 4 October 1957, the dream began to become a reality. A new era of space exploration began, when the Soviet Union sent the first artificial satellite Sputnik to the Earth's orbit [1,2]. Man stepped on the surface of the moon on 16 June 1969 as part of American Apollo 11 mission. No one thought at the time that the last step taken by the crew of Apollo 17 on 19 December 1972 would be the last for the next decades. Currently, NASA plans to return and land a human crew by 2024 and permanently inhabit the Moon in the future. However, NASA is not the only institution or country which has such intentions. China (among other countries) and private companies such as SPACEX and BLUE ORIGIN also strive for the Moon [3–6].

European Space Agency developed Terrae Novae 2030+ Strategy Roadmap [7], whose main long term goals for Europe are defined as follows: capability to launch and deliver payloads to ISS as laboratory for technology demonstration, and to be able to deliver these technologies to the Moon and Mars. Poland is an example of a relatively small country with lunar ambitious. The Polish Space Agency is a part of the Artemis Accord program and has its own plans for Moon exploration. Polish scientists are working on different aspects related to prospective exploration and further utilization of lunar surface. The investigations of future orbiter payload able to detect troilite on lunar surface are described in [8]. The developed surface payloads are presently able to detect mechanical properties of lunar soil with the capability to reach 5 m depth in lunar regolith [9]. The technology of lunar surface exploration is based on drilling systems [10] and sampling systems [11]. The latter is currently under investigations to reach technology readiness level 6. In this context, several campaigns were organized in Poland to better understand the lunar regolith [12]. From the perspective of future lunar surface utilization, economic aspects, intellectual property issues, and space law questions are of great importance [13].

Ideas for establishing a base on the Moon have been around since the early days of the space program. Many questions arose regarding the functionality, use, shape, and transport of the material, and assembly of the habitat [13]. A big breakthrough happened recently when 3D printing technology appeared, which completely opened up new possibilities for working with the shape and processing of material on site.

NASA's ultimate goal is to get to Mars. In order to achieve this, many procedures and technologies need to be tested on the nearest neighbour—the Moon. The Artemis mission is to test new technologies, land a man on the Moon, and establish a base there. The base would also serve as a transfer station and actively provide support for missions to Mars. The major components of the program are the Space Launch System (SLS), Orion spacecraft, Lunar Gateway space station, and the commercial Human Landing Systems, including Starship HLS.

The entire lunar surface is covered by regolith, which is the unconsolidated layer of granular material and has been generated over time due to the pulverization of rocks by meteorite and micro-meteorite impacts [14]. To create a permanent base, strategic raw materials (e.g., water, metals, and oxygen) are needed. Possible water deposits were found in the regions of the South Pole [15]. Metals and oxygen can be extracted from regolith at the lunar South Pole [14]. There are more craters in these places, and due to their position and depth, sunlight never reaches the bottom of craters. At the same time, this location is advantageous for long-term foundations thanks to the constant sunshine. Even though the Sun moves just above the horizon in these regions, its radiation is not weakened, as is the case on Earth where it is limited by the atmosphere.

Among the main goals of creating the concept of the 3D-printed habitat for permanent lunar outpost was to explore ways of depositing the habitat both on the surface of the Moon and in the craters. Furthermore, the way to ensure safe and relatively comfortable entrance to the habitat by the most direct route possible, through the pressurized room was also analysed. In the next phase of conceptualisation, properties of the egg-shaped habitat (and its realization) were of key interest. Due to low lunar gravity, astronauts are forced to move on the Moon by small jumps instead of ordinary walking. Taking this fact into consideration, one should come to the conclusion that the shape of the future lunar base should have more of a vertical than horizontal shape. The vast majority of proposals of future lunar bases harness the shape of the traditional dome. This type of structure is very efficient on Earth but is questionable on the Moon. People who are walking on Earth need structures which provide "horizontal space". On the Moon, astronauts will need much more "vertical space". In authors' opinion egg-shaped habitat would provide more vertically focused space which would be much more practical to use by astronauts. Of course, it is necessary to ensure the lightness of the structure and proper (from architectural and ergonomic points of view) layout of the internal space. Another problem that long-term (or permanent) missions will face with is the danger of radiation and falling meteorites. Therefore, variants using inflatable membranes that would be covered with regolith were analysed as a possible solution.

Greenhouses with the possibility of growing plants have become another focus for sustainable accommodation. In this regard, several variants have been created, which include a transparent membrane [16], and use mirrors to direct and regulate light radiation into an otherwise covered and therefore protected environment [17].

In order to create lunar habitats, it is necessary to provide components which could be used to rise such structures characterised by sufficient mechanical strength. The most common construction material on the Earth is concrete which, in its simplest form, consists of aggregate, water, and cement. On the Moon, there is a possibility to create alternatives. The most promising seem to be sulphur concrete [18] and geopolymers [19–21].

3D printing technology is the cornerstone of the extra-terrestrial construction, which involves harsh and remote locations and very limited resources [22]. Geopolymer, as a type of non-conventional construction material, is one of the options with the greatest potential for implementation in lunar civil engineering 3D technology [23]. Additionally, sulphur concrete is one of the options for lunar construction programme. Sulphur as a binding agent is readily available on the Moon, no water is needed for the concrete production, and it can be produced under cold temperatures [22].

3D printing gives a unique opportunity to create complicated structures such as Voronoi structures. Georgy Voronoi was a mathematician of Ukrainian descent living at the turn of the 19th and 20th centuries, famous for extending a diagram also known as Dirichlet tessellation. A Voronoi diagram is, in the simplest case, a partition of a plane into regions close to a given set of objects called seeds (see Figure 1). Voronoi diagram decomposes an area or a volume into smaller pieces, and each resulting Voronoi cell consists of the points that are closest to the given Voronoi site [24]. If the seeds are placed in a 3D space, the partition is limited to the fixed space. One of the most significant advantages of using a Voronoi structure is to save material while maintaining mechanical properties. The Voronoi structure provides a reduction in stiffener mass up to 67% [25]. A Voronoi diagram has many applications in many fields of science and art. One of the earliest uses of this tool was the analysis of the cholera epidemic in London, which occurred in 1854. A physician, John Snow, determined a heavy correlation of deaths with proximity to infected water pumps, creating a Voronoi diagram map [26].

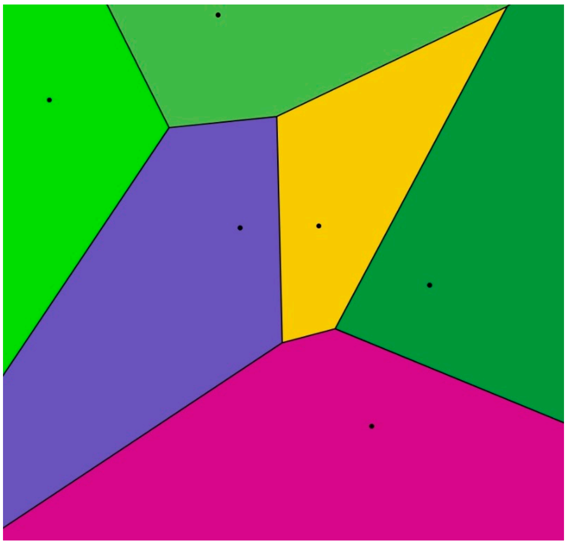

Figure 1. An example of a Voronoi diagram in 2D dimensions.

The aim of this paper is to present a concept of a Moon habitat that would take the advantage of the natural shape of an egg. An egg shape is an example of a structure created by nature itself. It is resistant to a number of mechanical factors and optimized regarding material needed for its creation. In addition, the walls of the egg are closer to the vertical axis in its cross-section than the walls of the sphere. For this reason, the structure can be more effectively divided into functional spaces for people living there. In the authors' opinion, such a habitat should be created in situ on the Moon as a 3D-printed Voronoi egg-shaped structure. The questions concerning the possible location of such an object on the Moon surface, ways of accessing the structure, and its stiffness characteristics are addressed. Several variants of the solution were presented, focusing finally on the selected variant. Among other issues, the way in which the object would be realized was presented, and finally, visualizations were created.

2. Principal Concepts

2.1. Lunar Habitat Placing Concepts

There are four types of possible placement of the habitat on the lunar ground. Possible access to the habitat is directly associated with the type of habitat's placement (see Figure 2):

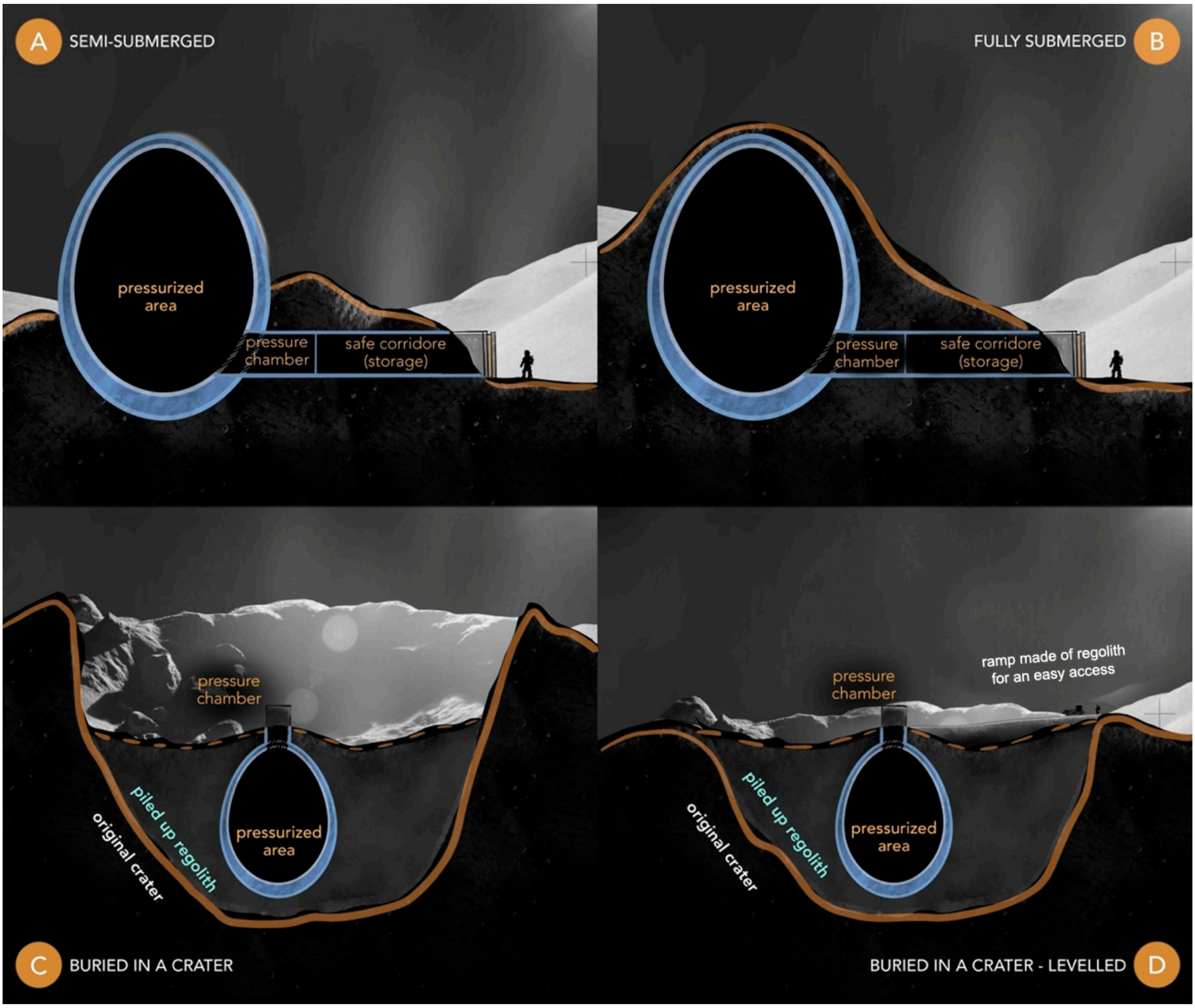

Figure 2. Concepts for placing an egg-shaped habitat on the surface of the Moon: cross-section view. (**A**) Semi-submerged, (**B**) fully submerged, (**C**) buried in a crater, (**D**) buried in a crater (levelled).

A semi-submerged habitat was built on a flat plain and its sides were secured with accumulated regolith. A significant part of it was in direct contact with the external environment and is therefore directly exposed to solar radiation and meteorites. However, it was foreseen that its structural envelope will be produced by 3D printing, which is largely made of regolith, which, together with its greater thickness, will have a certain effect on reducing these external influences. Access to the building was then solved using a 3D-printed corridor under the embankment to ensure safe and direct entry. It can also include storage areas for materials and equipment protected from the influence of radiation but was stored in a vacuum environment so as not to unnecessarily fill up the valuable interior space of the habitat. A disadvantage of this solution is the thickness of the outer printed envelope, which would have to be considerable to sufficiently reflect external influences, causing a manufacturing problem due to difficult access at higher levels above the ground.

A fully submerged habitat has almost the same characteristics as the semi-submerged version. The main difference is associated with the solution to the problem of protection from the influence of the cosmic radiation. The protective layer of regolith covers the entire habitat. As a result, it creates an additional (adequately thick) layer over the entire volume of the habitat. Subsequently, it is unnecessary to have a large thickness of the outer walls. On the other hand, erecting such a habitat will be more complicated and work-intensive. The prepared building materials would be in danger of sliding down. At the same time, the entrance corridor would have to be long to avoid possible lunar soil slides.

A habitat buried in a crater is a concept working with pre-existing irregularities on the surface of the Moon, which are caused by meteorite impact. Their size varies greatly, and many have a diameter of several tens of kilometres. The idea is to gradually 3D print the habitat and pile up the regolith. The result will be flat terrain in the immediate vicinity of the habitat, with vertical access to it from the edge of the crater and vertically towards the habitat itself. The advantage of this system is no soil sliding problems, which can also fall from the edge of the crater during construction. Burying a habitat in a crater will create relatively stable conditions inside. The thick layer of regolith covering the habitat will significantly ease maintaining room temperature. The negative influence of cosmic radiation and impacts of meteorites will be significantly limited. Moreover, such habitats are likely to be used for the purpose of deep mining directly from the habitat. The disadvantage of this solution is the transport of material, equipment, and people to a less-accessible construction site. At the same time, in most cases, a huge amount of regolith will be needed for backfilling, which is also a disadvantage for future expansion of the base. Another major disadvantage is the vertical approach, which is impractical for transporting material.

A buried habitat in a crater with fully levelled ground is a proposal based on the previous concept, where access to the entrance to the object is simpler. An ideal crater (regarding size and location) will be harnessed. An erected habitat will be placed in the crater. The habitat will be covered with regolith up to the level which will form an almost flat plain. The access to the habitat could be realized through a ramp made of lunar aggregate [27] filling a 3D-printed geopolymer spatial structural layer. However, this variant also suffers from the same problems as the previous one.

The main advantage of the buried habitat in a crater with fully levelled ground is the possibility to easily create a complex made up of several egg-shaped units of different sizes (see Figure 3). Such a complex brings new aspects of use. It utilizes a mirror to reflect sunlight into the semi-open large space of the central building, where it is collected and reflected for the purpose of growing plants, creating a special type of greenhouse. At the same time, the mirror collector can be used for the purpose of reflection and conversion of radiation into heat, which would support the whole complex. It should also be possible to extract ice from an ice deposit located under the crater. Heating ice and storing created water in a reservoir would take place at the bottom of the egg-shaped structure.

2.2. A Voronoi Structure Concept

To create an egg-shaped light-weight structure, a Voronoi pattern was proposed. Thanks to its variability, it can be worked with in different ways with many additional parameters, which can be evaluated during future static assessment and design of its ideal density, size, etc.

One of the ways is to apply the Voronoi pattern directly to the surface of the object. The achieved network enables to generate a structure with a thickness between individual cells and with a thickness in the third dimension (i.e., the thickness of the object's wall). Moreover, it is possible to round the generated shapes, which brings many manufacturing and mechanical advantages (see Figure 4a). The way to implement this shape for a regolith-filled structure is shown in Figure 5a (using a wall section). In order to prevent lunar soil from spilling through the openings into the interior space, a partition will be 3D-printed at the same time, which will withstand only this load. The resulting pockets, which are filled with regolith, serve as a lock for the settled object. On the inside there is an inflatable membrane, which is locked in place in the same way.

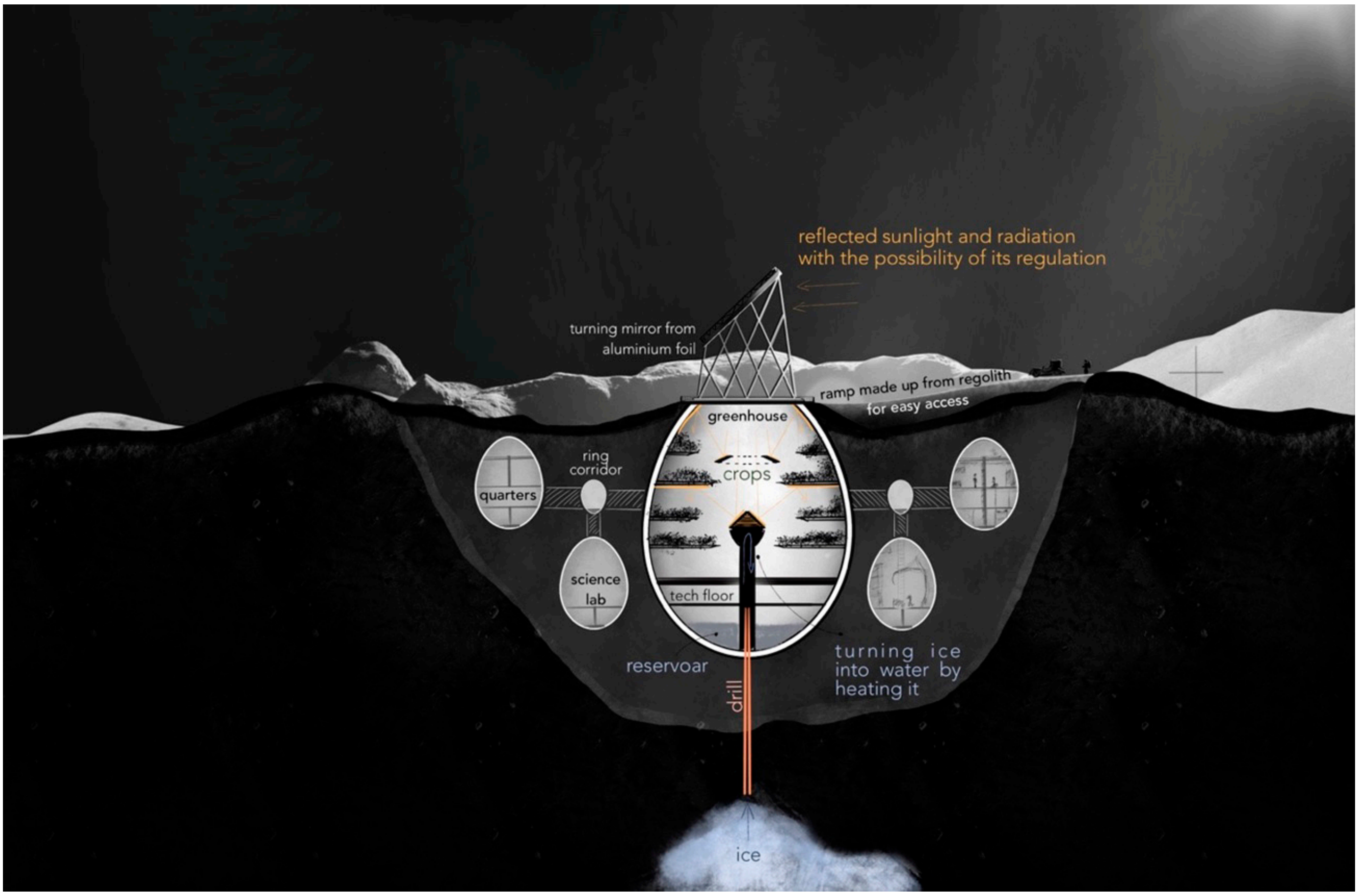

Figure 3. Concept for grouping several habitats of different size in a crater: cross-section view.

Figure 4. Generated model of the Voronoi structure: (**a**) implemented single-layer Voronoi structure on an egg-shaped surface, (**b**) cut-out of the 3D Voronoi structure that can be used for the entire outer wall thickness envelope.

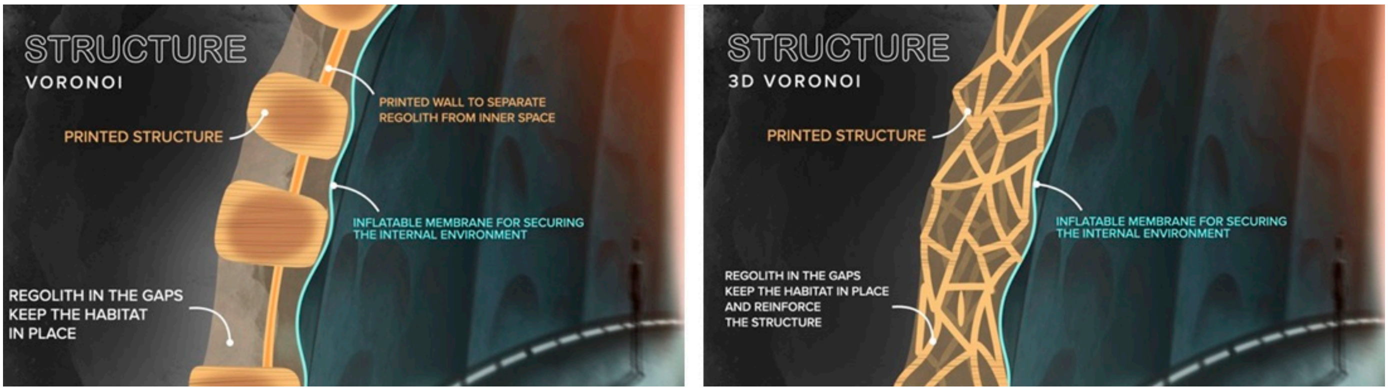

Figure 5. Schematic representation of the use of a Voronoi structure in cross-section view: (**a**) single-layer Voronoi structure with a partition wall, (**b**) 3D Voronoi structure with regolith infill.

Another solution is to apply a 3D Voronoi structure in the wall thickness of the object (see Figure 4b). This creates a complex network system (Figure 5b) which can also be used extensively (but requires more computing power to generate the model). The fundamental difference in comparison to the previous variant is the possibility of directly filling its structure with regolith.

For the future full scale design of the lattice cell structure, the principle of finite element analysis (FEA) should be used to read the properties of that design. FEA for a single-layer Voronoi structure on an egg-shaped surface, and a cut-out of the 3D Voronoi structure, can be used for the entire outer wall thickness envelope. The methodology proposed by Tahseen A. Alwattar and Ahsan Mian [28,29], based on the principle of equivalent lattice cell structure idea to solve the problem, should be very useful.

3. Materials and Methods

3.1. Materials

Because of transportation issues between the Earth and the Moon, building Lunar habitats should be solely based on an in situ resource utilization (ISRU) approach. Thanks to the Apollo missions, the composition of Lunar regolith is fairly well known. The fifth and last lunar mission (Apollo 17) brought back 111 kg of lunar soil [30]. On Earth, on the basis of samples brought from the Moon, materials called lunar simulants (imitating the properties of lunar regolith) were created [12]. This enables an understanding of the behaviour of material similar to the lunar regolith under different conditions [9]. The result was the development of regolith mining equipment [10,11]. On the other hand, ISRU should provide materials for construction, life support, and energy. Lunar regolith contains ferromagnetic fractions which, after separation, could be used as the protective layer against meteorites and radiation and as an aggregate of 3D printable geopolymer concrete.

3.2. Method of an Egg-Shape Calculation

The shape of an egg has many forms and has already been described in many articles [31,32], along with its mechanical properties. For the purpose of this study, a formula introduced by German engineer Fritz Hügelschäffer was used. Hügelschäffer proposed an oviform curve shaped like egg by moving one of two concentric circles along its *x*-axis, constructing an asymmetric ellipse. The equation was adapted in relation to the main measurements of the egg [32]:

$$y = \pm\frac{B}{2}\sqrt{\frac{L^2 - 4x^2}{L^2 + 8wx + 4w^2}}, \ [m] \qquad (1)$$

According to the scheme (Figure 6): L is the length of the egg, B is maximum width, w is the parameter that shows the distance between two vertical axes corresponding to the maximum width and the half length of the egg. The parameter x is the x-axis value where the corresponding y-axis value is to be calculated.

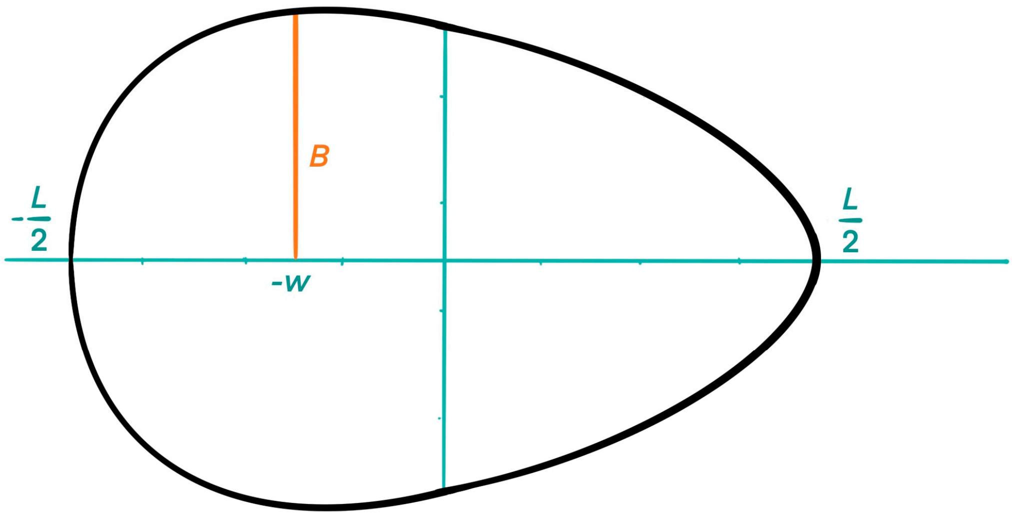

Figure 6. Scheme of an egg curve with marked parameters.

The egg-shape has many forms. The parameter w is determined by the relationship (2) using the values of L and B together with the coefficient n, which defines the resulting shape of the egg [32]:

$$w = \frac{L - B}{2n}, \ [m] \quad (2)$$

For the paper purposes of the current study, the value $n = 1.5$ was chosen, corresponding to the shape of chicken egg. The designed length of the structure was $L = 18$ m and width $B = 12.6$ m. The equation was compiled in the parametric program Rhino with the Grasshopper programming add-on. The curve and, subsequently, the area of the entire object was drawn up. It served as a basis for further work.

3.3. Possible Construction Method of a Lunar Habitat

The construction process described below is a conceptual consideration, but just like the Artemis mission, the use of robotic technology is also expected here. In this regard, it is possible to consider preparing the base, or a large part of it, even before the landing of the human crew. All the stages described below are also depicted in Figure 7.

Phase A—Finding a suitable place for the future habitat and transporting construction equipment and materials. At this stage, it is necessary to evaluate the actual conditions and possible complications of the given place. Subsequently, preparations for the base at the bottom of the crater and the surrounding area, for easier transportation, were conducted. At the same time preparations are being made for the production of printable geopolymer mixture from regolith.

Phase B—Laying and anchoring of the basic building block. It is a critical part of the building, which is followed by 3D printing of the external and internal supporting part of the structure. At this moment the printable mixture is already prepared, together with a robotic arm and other supporting equipment.

Phase C—Layer after layer of the future habitat is now being continuously 3D-printed. At the same time, regolith is constantly being sprinkled to the same level at which the printing is currently taking place.

Phase D—Once the structure reaches the ground floor level and the access area (with a retention wall) is 3D-printed, the connection module with the pressure chamber and space suit chamber will be installed. Regolith will continue to be piled up around it.

Phase E—The entire retention wall protecting the entrance and habitat structure is printed. Once the connecting ring of the habitat on top is in place, work will begin on the internal structure. Firstly, the membrane is inflated (only with a small pressure), which completely adheres to the walls, to which it is anchored at points. The internal structure is assembled from collapsible beams and columns, and a frame is prepared for the installation of the modular floor. At the same time, the light tube is assembled and ready to be used. All equipment is installed, and the habitat can be fully pressurized.

Phase F—The connecting ring and the mirror are installed. The regolith embankment is complete. The lunar base is fully operational.

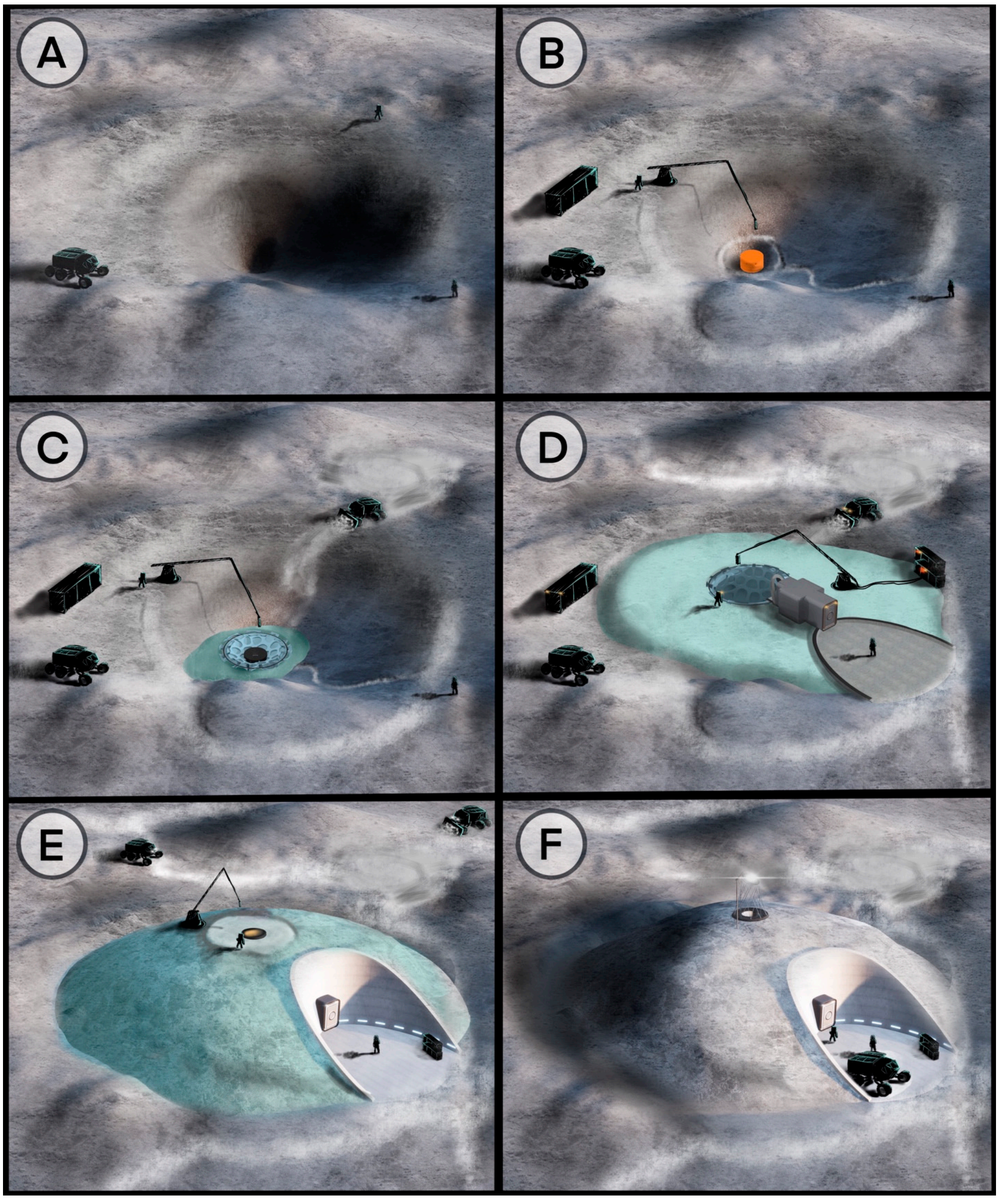

Figure 7. A view of a Lunar habitat construction procedure divided into six phases (**A**–**F**).

4. Results

To create the concept of 3D-printed habitat for a permanent lunar outpost, only one egg-shaped habitat with an entrance and external lighting solution was considered (see Figures 8–12). It uses an existing crater into which the habitat is embedded to a third or half of its height. The entire complex is covered with regolith. Thanks to this, the problem of access during construction will be minimized and the resulting embankment will not be large. However, a large number of cubic meters of material still needs to be moved. The design envisages a 3D-printed main structure of the habitat, including a paved access area with a retaining wall preventing regolith from sliding to the entrance of the facility. This solution shortens the required length between the entrance and the habitat. At the same time, it is possible to transfer material more easily on a reinforced (by spatial 3D-printed geopolymer) surface, or to partially use it for storage. Additional modifications can be made for this purpose. In the connection between the exterior and the habitat, there is a pressure chamber and a changing room with stored spacesuits. This is the only element of the proposed lunar outpost which will not be 3D-printed.

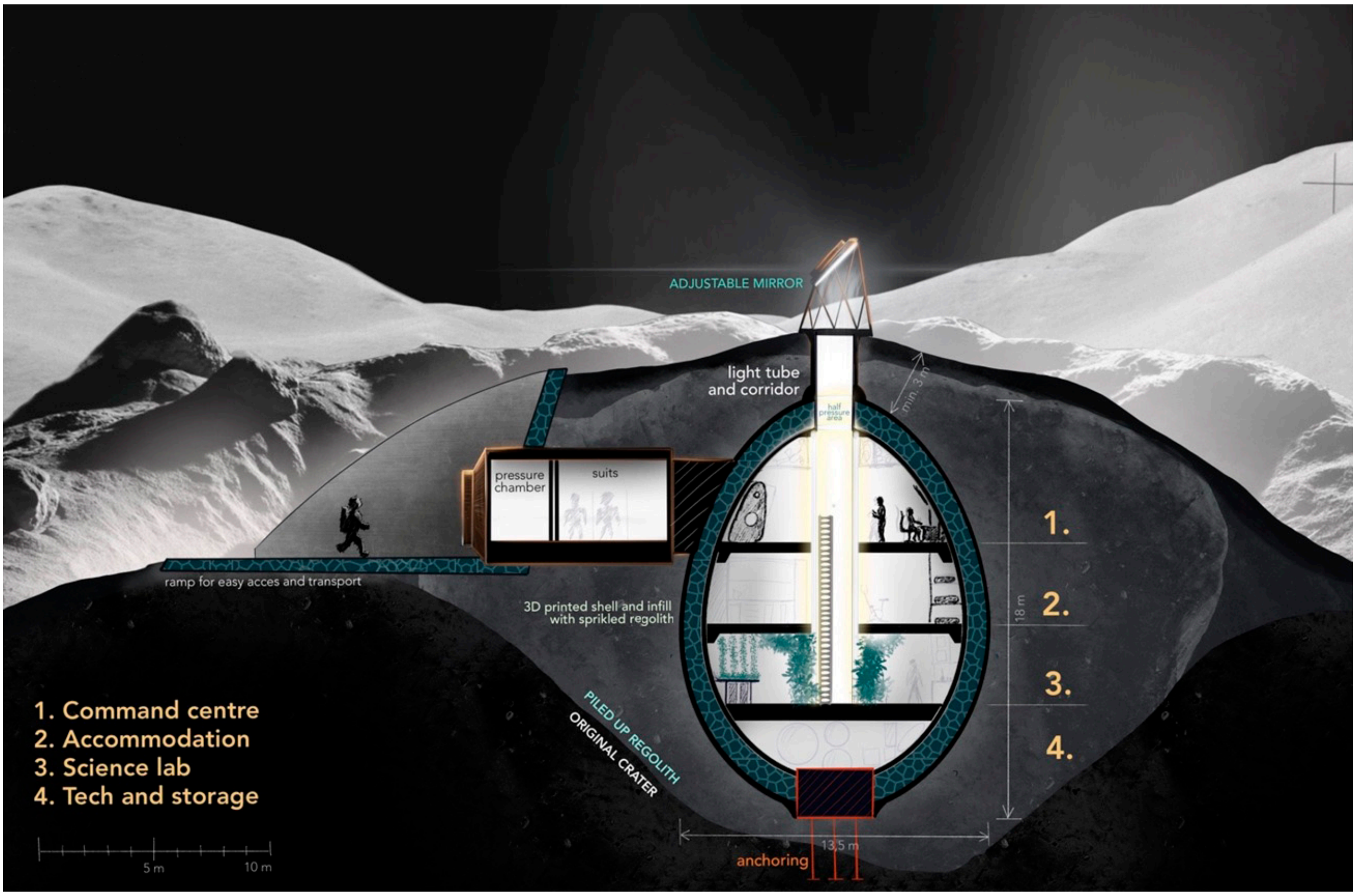

Figure 8. Cross-sectional view of the final variant of one egg-shaped habitat, semi-submerged to an existing crater with a piled-up regolith.

The 3D-printed egg habitat is 13.5 m in diameter and 18 m high, so that the minimum clear height of one floor is 3.5 m. Due to the low gravity (one sixth of the Earth's gravity), it is possible to use equipment with a larger height preventing possible injuries when moving in inside. The main element of the design is an adjustable mirror at the top of the entire structure. It reflects sunlight into a vertical tube that permeates through all floors. Thanks to reflective surfaces and optical guidance, it transmits the light to all rooms, especially to the floors where plants are grown. The mirror makes it possible to regulate the amount of light and radiation that enters the habitat and (if necessary) it is possible to completely block the light inlet. Therefore, simulating the 24 h day-night cycle is enabled. This property is essential for the well-being of astronauts, due to the location of the outpost at the lunar South Pole. The sun is low on the horizon there, but it never sets. The light tube also serves as a communication hub across the individual floors. If larger pieces of material need to be moved, the folding part of the floor can be used for this purpose. However, there is a need to assess the effectiveness and safety of the communication method through this tube, precisely because of the concentration of reflected sunlight through the mirror.

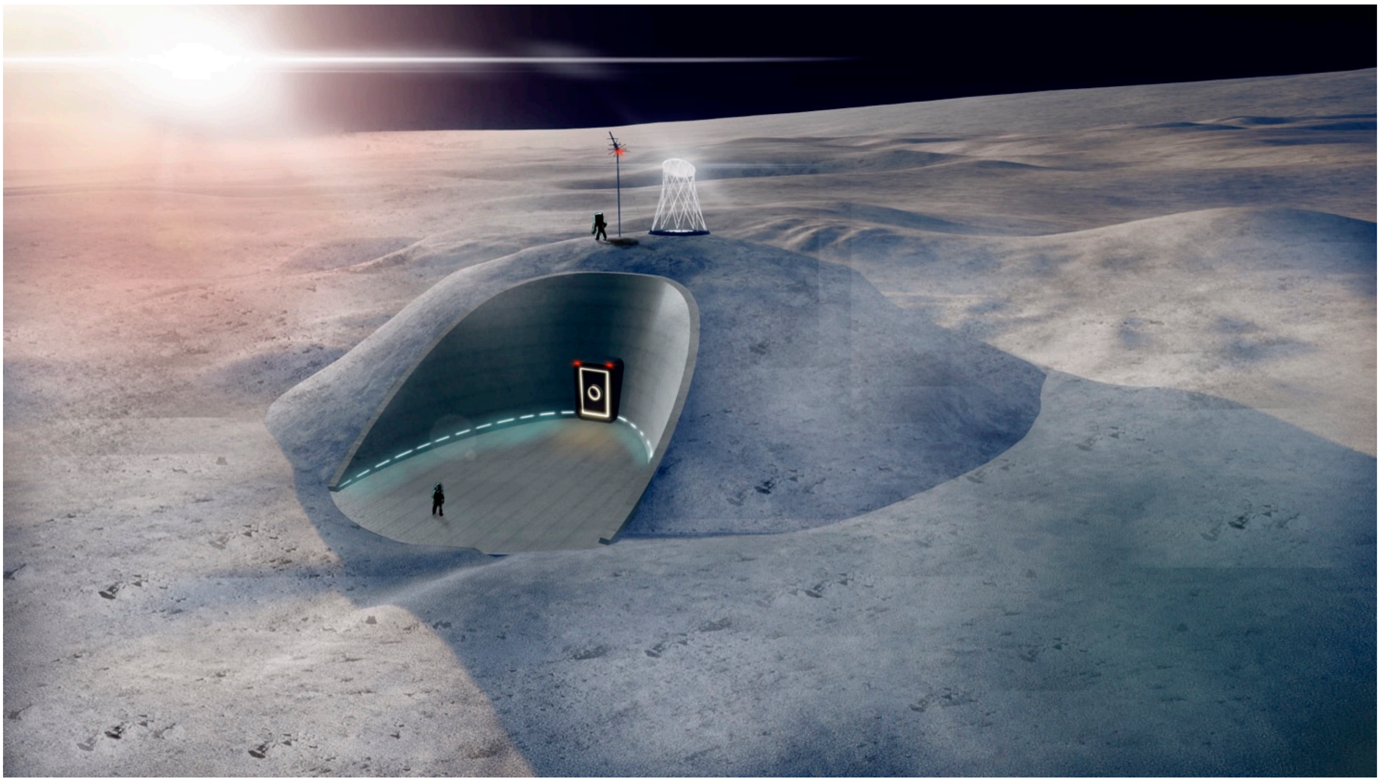

Figure 9. View of the complex with the entrance from the outside.

Figure 10. A view of a 3D section in the perspective of a semi-submerged habitat.

Figure 11. Perspective view of the first floor (command floor) of the habitat. A light tube can be seen in the image.

Figure 12. Perspective view of the third underground floor (greenhouse and laboratories) of the habitat.

The first underground floor is almost flushed with the external access area for easy movement. This floor also serves as a command and operations planning floor.

The second underground floor is dedicated to the crew as accommodation, dining room, gym, and relaxation room. It is clear that it will need to be divided into individual sections with movable partitions for greater privacy.

The third underground floor serves as a greenhouse and laboratories.

The last (fourth) floor is for storing supplies, technical equipment, and containers for oxygen, water, and others.

5. Discussion

Today, it is clear that in the very near future we will see a human landing on the Moon again. The planned missions aim at enabling a permanent stay at this location and thus allow other missions to go even further to Mars.

Several basic variants of the solution were presented regarding designing a lunar base concept using the shape of an egg and 3D printing. A seemingly more ideal variant was created from them. It turned out that it is possible to create a single object or an entire complex. Although it seems an impractical shape at first glance, it is possible with the rapidly progressing 3D printing technology. It has been proven that placing this object in the field ensures convenient and direct access and provides enough light for each floor, with all this under the protective layers of regolith.

Further development of the variant should bring a solution for variable layouts and equipment. Another variant of using the shape of an egg could be a printed part of it in the form of a protective shelter with a free layout, under which a habitat made of an inflated membrane will be freely placed. This would provide an advantage for future easy base expansions and access for repairs. On the other hand, it provides less protection and additional support for the membrane due to internal pressure.

The goal was to check this variant of the solution and thus bring an incentive to consider the method of solving the construction of a base. As this is just a proposal, its feasibility needs to be checked. Firstly, scaled models of the outpost and lunar soil simulants (LSS) [33] should be used to test the main concept. Subsequently, the development and thorough tests of printable lunar geopolymer should be conducted.

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References

1. Siddiqi, A. Sputnik 50 Years Later: New Evidence on Its Origins. *Acta Astronaut.* **2008**, *63*, 529–539. [CrossRef]
2. Kuznetsov, V.D.; Sinelnikov, V.M.; Alpert, S.N. Yakov Alpert: Sputnik-1 and the First Satellite Ionospheric Experiment. *Adv. Sp. Res.* **2015**, *55*, 2833–2839. [CrossRef]
3. Witt, M.; Rowe, J. *As Artemis Moves Forward, NASA Picks SpaceX to Land Next Americans on Moon*; NASA: Washington, DC, USA, 2021.

4. Athanasopoulos, H.K. The Moon Village and Space 4.0: The 'Open Concept' as a New Way of Doing Space? *Space Policy* **2019**, *49*, 101323. [CrossRef]
5. Ferreira-Snyman, A.; Ferreira, G. The Application of International Human Rights Instruments in Outer Space Settlements: Today's Science Fiction, Tomorrow's Reality. *Potchefstroom Electron. Law J.* **2019**, *22*. [CrossRef]
6. Rutishauser, D.; Ramadorai, R.; Prothro, J.; Fleming, T.; Fidelman, P. Nasa and Blue Origin Collaborative Assessment of Precision Landing Algorithms and Computing. In Proceedings of the AIAA Scitech 2021 Forum, Virtual, 11–15 & 19–21 January 2021.
7. Terrae Novae 2030+ Strategy Roadmap. Available online: https://esamultimedia.esa.int/docs/HRE/Terrae_Novae_2030+strategy_roadmap.pdf (accessed on 1 September 2022).
8. Ciazela, J.; Bakala, J.; Kowalinski, M.; Plocieniak, S.; Zalewska, N.; Pieterek, B.; Mrozek, T.; Ciazela, M.; Paslawski, G.; Steslicki, M.; et al. Concept and Design of Martian Far-IR ORE Spectrometer (MIRORES). *Remote Sens.* **2022**, *14*, 2799. [CrossRef]
9. Seweryn, K.; Skocki, K.; Banaszkiewicz, M.; Grygorczuk, J.; Kolano, M.; Kuciński, T.; Mazurek, J.; Morawski, M.; Białek, A.; Rickman, H.; et al. Determining the Geotechnical Properties of Planetary Regolith Using Low Velocity Penetrometers. *Planet. Space Sci.* **2014**, *99*, 70–83. [CrossRef]
10. Zwierzyński, A.J.; Teper, W.; Wiśniowski, R.; Gonet, A.; Buratowski, T.; Uhl, T.; Seweryn, K. Feasibility Study of Low Mass and Low Energy Consumption Drilling Devices for Future Space (Mining Surveying) Missions. *Energies* **2021**, *14*, 5005. [CrossRef]
11. Seweryn, K. The New Concept of a Sampling Device Driven by Rotary Hammering Actions. *IEEE/ASME Trans. Mechatron.* **2016**, *21*, 2477–2489. [CrossRef]
12. Bednarz, S.; Rzyczniak, M.; Gonet, A.; Seweryn, K. Research of Formed Lunar Regholit Analog AGK-2010. *Arch. Min. Sci.* **2013**, *58*, 551–556. [CrossRef]
13. Wachowicz, M.E.; Frąk, P.; Węgłowski, A.; Burdzy, Z.; Bachtin, R.; Bankiewicz, J.; Gołąbek, W. Space mining challenges: Expertise of the Polish entities and international perspective on future exploration missions. In *GeoPlanet: Earth and Planetary Sciences*; Springer: Cham, Switzerland, 2019; pp. 161–195.
14. Guerrero-Gonzalez, F.J.; Zabel, P. System Analysis of an ISRU Production Plant: Extraction of Metals and Oxygen from Lunar Regolith. *Acta Astronaut.* **2023**, *203*, 187–201. [CrossRef]
15. Deutsch, A.N.; Head, J.W.; Neumann, G.A. Analyzing the Ages of South Polar Craters on the Moon: Implications for the Sources and Evolution of Surface Water Ice. *Icarus* **2020**, *336*, 113455. [CrossRef]
16. van Linden Tol, A.; Brandić Lipińska, M.; Foing, B.; Greenwood-George, E. Sky Lake—Moon Environment Design. *Acta Astronaut.* **2022**, *201*, 554–563. [CrossRef]
17. Herzig, T.; Kömle, N.I.; Macher, W.; Bihari, G.; Gläser, P. Site Selection, Thermodynamics, Environment and Life Support Analysis for the PneumoPlanet Inflatable Lunar Habitat Concept. *Planet. Space Sci.* **2022**, *224*, 105595. [CrossRef]
18. Omar, H.A. Production of Lunar Concrete Using Molten Sulfur. In Proceedings of the 4th International Conference on Engineering, Construction, and Operations in Space, Albuquerque, NM, USA, 26 February–3 March 1994; Volume 2, pp. 952–959.
19. Montes, C.; Broussard, K.; Gongre, M.; Simicevic, N.; Mejia, J.; Tham, J.; Allouche, E.; Davis, G. Evaluation of Lunar Regolith Geopolymer Binder as a Radioactive Shielding Material for Space Exploration Applications. *Adv. Space Res.* **2015**, *56*, 1212–1221. [CrossRef]
20. Xiong, G.; Guo, X.; Yuan, S.; Xia, M.; Wang, Z. The Mechanical and Structural Properties of Lunar Regolith Simulant Based Geopolymer under Extreme Temperature Environment on the Moon through Experimental and Simulation Methods. *Constr. Build. Mater.* **2022**, *325*, 126679. [CrossRef]
21. Arnhof, M.; Pilehvar, S.; Kjøniksen, A.L.; Cheibas, I. Basalt Fibre Reinforced Geopolymer Made from Lunar Regolith Simulant. In Proceedings of the 8TH European Conference for Aeronautics and Space Sciences (EUCASS), Madrid, Spain, 1–4 July 2019.
22. Ulubeyli, S. Lunar Shelter Construction Issues: The State-of-the-Art towards 3D Printing Technologies. *Acta Astronaut.* **2022**, *195*, 318–343. [CrossRef]
23. Robayo-Salazar, R.; Mejía de Gutiérrez, R.; Villaquirán-Caicedo, M.A.; Delvasto Arjona, S. 3D Printing with Cementitious Materials: Challenges and Opportunities for the Construction Sector. *Autom. Constr.* **2023**, *146*, 104693. [CrossRef]
24. Özcan, M.; Yaman, U. A Continuous Path Planning Approach on Voronoi Diagrams for Robotics and Manufacturing Applications. *Procedia Manuf.* **2019**, *38*, 1–8. [CrossRef]
25. Bostan, B.; Küsbeci, M.; Çetin, M.; Kırca, M. Buckling Performance of Fuselage Panels Reinforced with Voronoi-Type Stiffeners. *Int. J. Mech. Sci.* **2023**, *240*, 107923. [CrossRef]
26. Brody, H.; Rip, M.R.; Vinten-Johansen, P.; Paneth, N.; Rachman, S. Map-Making and Myth-Making in Broad Street: The London Cholera Epidemic, 1854. *Lancet* **2000**, *356*, 64–68. [CrossRef]
27. Zarzycki, P.K.; Katzer, J. A Proposition for a Lunar Aggregate and Its Simulant. *Adv. Space Res.* **2020**, *65*, 2894–2901. [CrossRef]
28. Alwattar, T.A.; Mian, A. Development of an Elastic Material Model for BCC Lattice Cell Structures Using Finite Element Analysis and Neural Networks Approaches. *J. Compos. Sci.* **2019**, *3*, 33. [CrossRef]
29. Alwattar, T.A.; Mian, A. Developing an Equivalent Solid Material Model for Bcc Lattice Cell Structures Involving Vertical and Horizontal Struts. *J. Compos. Sci.* **2020**, *4*, 74. [CrossRef]
30. Kobaka, J.; Katzer, J.; Zarzycki, P.K. Pilbara Craton Soil as a Possible Lunar Soil Simulant for Civil Engineering Applications. *Materials* **2019**, *12*, 3871. [CrossRef]
31. Narushin, V.G.; Romanov, M.N.; Griffin, D.K. Egg and Math: Introducing a Universal Formula for Egg Shape. *Ann. N. Y. Acad. Sci.* **2021**, *1505*, 169–177. [CrossRef] [PubMed]

32. Narushin, V.G.; Romanov, M.N.; Lu, G.; Cugley, J.; Griffin, D.K. Digital Imaging Assisted Geometry of Chicken Eggs Using Hügelschäffer's Model. *Biosyst. Eng.* **2020**, *197*, 45–55. [CrossRef]
33. Damięcka-Suchocka, M.; Katzer, J. Terrestrial Laser Scanning of Lunar Soil Simulants. *Materials* **2022**, *15*, 8773. [CrossRef] [PubMed]