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Research Article

# A Review of Structural Systems to be Built on Planets

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ABSTRACT

The architectural construction process on planets is an architectural issue that develops day by day due to extreme environmental conditions and uncertainties. Architectural design needs structural systems to survive.
Structural systems on planets encounter load factors that are different from the load factors on Earth. Choosing the optimum structural system is important for the structures planned to be built on planets to survive under the effects and loads of the environment and to adapt to human physiology. Some of the different types of structural systems used on Earth are featured in the literature for building a structure on planets. An evaluation system has been created to determine the correct system type for the first settlements on planets among the prominent structural system types and to narrow down the selection area of these system features. In line with this evaluation system in this study, a structural system model that stands up to harsh environmental conditions and protects human health is proposed for the first settlements on the planets. It is aimed that the evaluation system will be developed in the light of research emerging from developing technologies and can be used in future studies.

## 1. Introduction

Due to the rapid depletion of Earth's resources and advancements in technology, the search for life on other planets has introduced the concept of planetary architecture. Planetary architecture, which encompasses the design and construction of structures, aims to enable livings to work and live healthily on planets for extended periods.

On Earth, structures protect living beings from potential environmental effects. However, planetary environmental conditions are significantly harsher and more unusual than those on Earth. The goal is to shield the occupants of buildings constructed in these harsh conditions from environmental impacts.

The extreme environments of planets profoundly influence the architecture and structural systems of buildings. While on Earth, structural systems are designed with conventional factors such as dead and live loads in mind, on other planets, factors such as gravity, radiation, pressure, dust, temperature, and cost are critical in selecting the structural system.

There are numerous studies being updated daily on the types of structural systems that can withstand the harsh environmental conditions of planets and the materials that compose these systems. With continually advancing technological developments, discussions about the selection of structural systems suitable for planetary conditions will persist. Creating an evaluation system to determine the optimal structural system for planetary structures accelerates the decision-making process among options, facilitates understanding the behavior of structural systems under environmental influences, and highlights the superiority of different systems.

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## 2. Harsh Environmental Conditions of Planets

While Mars, where life is predicted to exist, is on average millions of kilometers away from Earth, the Moon is on average 384,400 kilometers away from Earth (Figure 1) [1, 2]. Transporting materials, workers, and equipment over these vast distances is quite costly [3]. When determining the structural system for planned constructions, it is important that the structural elements transported from Earth to these planets are small in volume and light in weight. Additionally, it is crucial that the materials used in the construction are locally sourced.

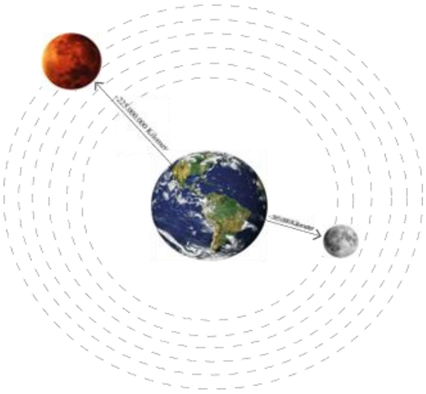

**Figure 1.** Distance between Earth and planets

The gravitational force, which is considered constant on Earth at an average value of 9.80665 m/s², varies on other planetary surfaces [4]. On the Moon, this value is one-sixth of Earth's gravitational acceleration (1.62 m/s²), while on Mars, it is one-third of Earth's acceleration [5, 6]. Structural system design in different gravity environments is a concept for which knowledge and experience are limited on Earth. However, with decreasing gravity, the weight of structures built on other planets will be less than those built on Earth (Figure 2). Consequently, much thinner and lighter structures can be designed, and larger spans can be achieved [7]. This is because the load-bearing capacity of structures will be greater than on Earth  [6]. As the load-bearing capacity increases with decreasing gravity, the materials used in the design of structural systems do not need to be as high-strength as those used on Earth [8].

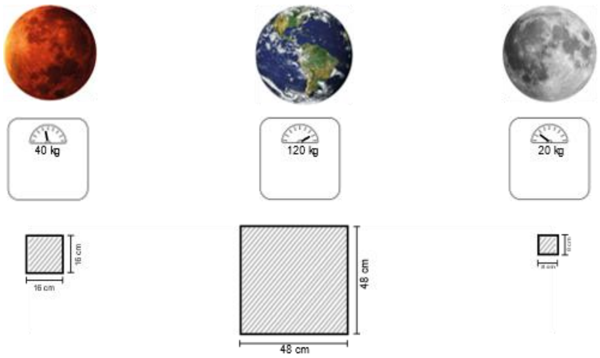

**Figure 2.** Comparing the gravity of planets

Radiation that harms human health and electronic equipment is limited on Earth by the atmospheric layer. However, since the atmospheric layers surrounding other planets are very thin or non-existent, they cannot limit these harmful rays. There is no atmospheric layer on the Moon, while Mars has a very thin atmosphere (Figure 3) [5, 9]. To build a livable structure in a planetary environment that cannot limit harmful radiation, the radiation effect on the building's structural system must be mitigated. Although radiation does not create a direct load on structural systems, radiation protective layers added to structures for human health can create an additional load [5].

In various studies carried out for planets, the shielding method is used to provide protection from radiation [10]. Different materials are considered for shielding to protect the building from radiation. Regolith, the soil covering the surface of planets, is the local material considered for radiation protection [11]. To provide radiation protection equivalent to Earth's atmosphere, the structural system must be covered with a 5-meter thick layer of regolith [12]. Another material planned for shielding on planets is water. Water is considered an effective radiation shield due to its chemical properties. For protection equivalent to Earth's atmospheric standards, a 10-meter thick water column is required [8].

The temperature factor, which is evaluated in structural system design on Earth, is crucial in the high temperature difference environments on other planets.

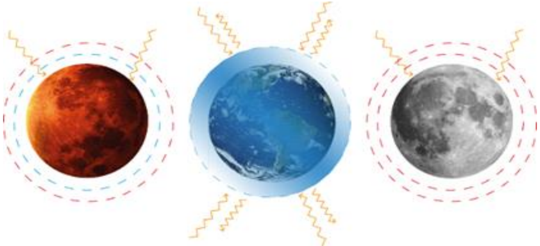

**Figure 3.** Radiation effect on Earth and Planets

On the Moon, where life is predicted to exist, the temperature varies between -310°F (-190°C) and +279°F (137°C), while on Mars it ranges between -89°C and -31°C (Figure 4) [13]. Such extreme temperature differences can cause effects on structural systems such as thermal stress, expansion, contraction, and fatigue, impacting the strength and durability of the structure. Therefore, various precautions must be taken during and after the construction phase. Large temperature differences also affect the material selection and form of the structural system. For this reason, in selecting materials for the structural system, it is important to use materials that have low thermal expansion properties, do not exhibit deterioration, shrinkage, or expansion within a certain temperature range, and can adapt to large temperature changes. This is essential for building habitable structures on planets [8, 13].

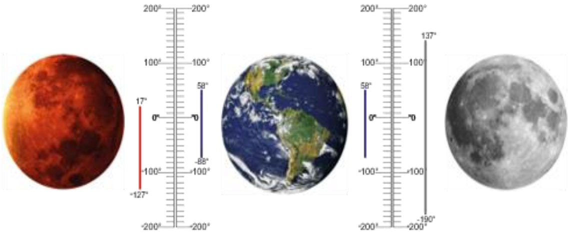

**Figure 4.** Temperature values of the Earth and planets

The pressurized environment required for livings to survive is maintained on Earth by the influence of the atmospheric layer [14]. However, the open air pressure on Mars and the Moon, where habitable structures are planned, is significantly lower [15]. To avoid the negative effects of low pressure on humans and to establish long-term living habitats on these planets, pressurized living spaces (Pressure Vessels) must be created. These structures will need to maintain a sea-level pressure of 101.3 kPa [16]. In pressurized structures, tensile forces will occur on the outer surface due to the internal pressure (Figure 5) [17].

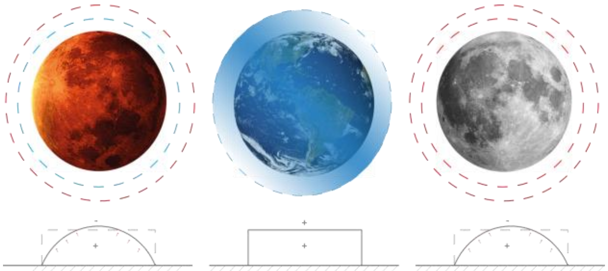

**Figure 5.** Pressure effect on Earth and planets

Unlike the Earth's environment, the surface of planets has a layer of fine particles. These fine particles adhere to surfaces, causing permanent damage to construction equipment and exposed surfaces [6].They accumulate on the surface and lead to the corrosion of structural system elements and electronic equipment [8, 18].This factor is crucial in determining the form of the structural system. As the surface area of the structure increases, the impact surface of these particles also increases [19]. Circular forms that reduce the accumulation of dust particles on the surface can be utilized in planetary structures [20].

## 3. Structural Systems Planning on Planets

To establish long-term settlements in the harsh environmental conditions of planets, the structures must ensure the safety of their users and create healthy environments. To determine the structural system of these structures, various suggestions have emerged that can adapt to the challenging variables of planetary conditions.

### 3.1. Steel systems

Steel, which is used on Earth as a high-performance, lightweight, ductile building material that can span large spans, can also be used for the structural systems of structures on planets. Iron-nickel (FeNi) meteorites found on Mars remain on the surface of Mars without oxidation due to the existence of an atmosphere consisting of carbon dioxide (CO2) and the absence of water [21].Studies on the use of steel systems with high tensile strength under planetary conditions continue.

Research continues to ensure that steel systems with high tensile strength can be used under planetary conditions. It is important how steel, which can be produced from local resources on Mars, responds to the planet's environmental conditions. Steel production on the Moon is also an issue that needs to be investigated. Designed by ABIBOO Studio (A global design company) and SONet (The Sustainable Offworld Research Network), the Mars City named “NÜWA”, which is planned to be built in 2054, is a self-sufficient sustainable city. This city is intended to be built using steel obtained by processing iron-nickel meteorites, the local material on Mars, with carbon dioxide. Steel will be the main material in the structure to be built with the lava tube system (Figure 6-7) [22, 23].

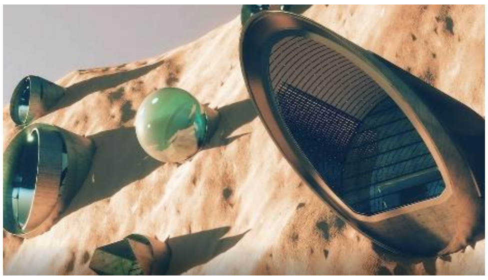

**Figure 6.** Nüwa City [22]

**Figure 7.** Nüwa City [23]

### 3.2. Concrete, regolith and reinforced concrete systems

Concrete consists of mineral materials such as aggregate and gravel combined with cement and water as binders. Reinforced concrete systems are created by reinforcing concrete, known for its high resistance to compression, low cost, and proven methods, with steel elements. To be used as a building material in harsh planetary conditions, concrete requires special modifications to maintain its bearing strength under extreme conditions. The durability, continuity, vapor permeability, tensile and compressive strength, thermal expansion, and UV resistance of a habitable structure built with concrete on planets must be evaluated and designed for these harsh conditions [8]. The low gravitational force of planets affects the load on the structural system. High temperature fluctuations increase the thermal stress on the concrete, and the high radiation environment complicates construction conditions and may affect the integrity of the structure. Harsh environmental conditions will require rethinking processes such as pouring, curing, and compaction of concrete [24].

To produce concrete in planetary environments, it is important to utilize local materials found on planets. For standard concrete to be produced, aggregate, water, and cement must be sourced or manufactured. Producing waterless concrete is crucial to ensure that the concrete made from local resources is not affected by temperature differences [8].Three types of concrete stand out for use on planets.

Sulfur concrete (Figure 8) is a type of concrete made from sulfur aggregates and plastic, without water and cement [25, 26]. Compared to standard concrete, it offers “Fast curing time, waste management, recycling opportunities, high resistance to acids and radiation, the possibility of concreting at sub-zero ambient temperatures, fast setting time, low electrical and thermal conductivity, water resistance, high freezing resistance, and high wear resistance" [27]. Since Mars and the Moon are rich in sulfur, the use of sulfur concrete is recommended. Sulfur concrete is twice as strong as standard concrete and has a much shorter curing time [3]. However, like standard concrete, sulfur concrete has weak tensile strength. The use of elements that can absorb the tensile force of concrete under planetary conditions, which is reinforced with steel elements for tensile strength on Earth, has yet to be discovered.

Magnesium concrete is not widely preferred as a structural system material on Earth due to its high cost. However, it can be used on planets. It is suitable for the extreme conditions of planets due to its properties of not conducting heat, cold, or electricity [26].

**Figure 8.** Sulfur concrete [28]

Polymer concrete (Figure 9) uses polymer materials as binders. “Polymer concrete materials are used in various applications due to their superior properties such as fast curing, high compressive strength, high rigidity and strength, resistance to chemicals and corrosion, ability to form complex shapes, and high vibration damping properties" [25, 29]. It has 2-4 times the compressive strength and 3-6 times the tensile strength compared to conventional concrete [25]. However, to produce this concrete on planets, polymer materials would need to be transported from Earth [8].

**Figure 9.** Polymer Concrete [30]

### 3.3 3. D printed systems

The 3D printing system creates three-dimensional shapes from a malleable material [31]. Applications using 3D printing systems take less time than traditional methods. Structures created with these systems have no restrictions on span or length, allowing for unlimited building forms. Since robots construct the structure in this system, the need for labor decreases significantly. However, this technology is still evolving. Although material and labor costs are low with 3D printing, the equipment is costly. By using this developing system with concrete materials, the 3D concrete printing (3DCP) method has emerged [20, 31]. In structures built with the 3D printing system, vertical elements are created by spraying concrete material with the help of a pump and layering the material.

Different studies have been carried out to build habitable structures on planets with the 3D printing system. Designed by Al SpaceFactory (A company developing manufacturing technologies for space exploration), "Marsha" is planned to be built on Mars with 3D printing systems. The structure, rising in an egg-like vertical form, is printed with printing material derived from natural materials (Figure 10) [32, 33]. A different study, the "Mars Ice House" project, which envisions creating a habitable structure by printing water ice with 3D printing systems, was designed by SEARch+ (Space Exploration Architecture) and Clouds Architecture Office (Figure 11) [34].

**Figure 10.** Marsha [32]

**Figure 11.** Mars Ice House [34]

### 3.4. Pneumatic (Inflatable) systems

Pneumatic (Inflatable) systems are created by using membrane materials to absorb tensile forces on the structure, which are then inflated with air supports. The basic working mechanism of this system relies on the membrane material becoming structural through the pressure difference on its surfaces. To withstand the stress on the membrane material, it is additionally supported by different structural systems such as columns and cables [35].

Considering the harsh environmental conditions of planets, pneumatic structural systems are suitable for transportation from Earth to planetary environments due to their low mass-to-volume ratio and foldable feature [36]. They are resistant to the tensile forces that occur when the structure is pressurized in low-pressure environments [37]. This system, which is suitable for spherical geometric forms, can also be configured into free forms such as cylinders, cones, and tori [36].

It is crucial that the membrane material, the main element of pneumatic systems, is suitable for the harsh conditions of the planet and has the strength to carry the loads imposed on it. Simple membrane fabrics are not suitable for use in planetary conditions, so layered or composite solutions are preferred [8]. Organic polymer materials are lightweight and can be easily shaped [38]. Aramid fabrics composed of organic polymers are used in aerospace applications [39]. Different types of aramid fabrics, known for their high strength, lightness, durability, and heat resistance under planetary conditions, are listed in Table 1 along with their properties.

**Table 1.** Characteristics of Different [40-43]

| | ***Kevlar*** | ***Vectran*** | ***Nomex*** | ***Twaron*** |
|---|---|---|---|---|
| ***Temperature Resistance*** | -40°/429° | -40°/330° | -40°/250° | -40°/300° |
| ***Thermal expansion*** | Low | Low | Low | Low |
| ***UV Resistance*** | Available | Available | Not available | Available |
| ***Tensile Strength(MPA)*** | 2800-4100 | 1100-3200 | 400-500 | 2500-3500 |

In the studies carried out, there are suggestions for structures with pneumatic structural systems that are intended to be used on planets. A cylindrical structure with a pneumatic system was designed by Kriss Kennedy and his team [35]. The “Space Nomad” project, created from three-layer membrane materials, was designed for Mars [44]. The “Mars Ice Home” project was created with pneumatic systems and was achieved by filling the pockets of the membrane material with water (Figure 12) [45]

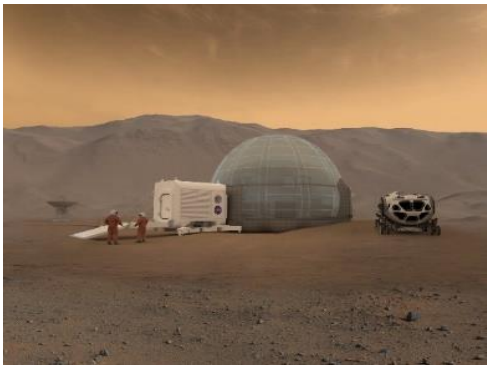

**Figure 12.** Mars Ice Home [45]

## 3.5. Mixed systems

The systems intended to build structures against the harsh environmental conditions of planets have both advantages and disadvantages. To mitigate these disadvantages, hybrid systems have been developed, combining rigid and flexible systems for planetary construction. Flexible structures are vulnerable to environmental effects such as meteorite impacts and radiation. While rigid structures are more effective against these environmental effects, flexible structures are more resistant to the loads created by internal pressure compared to rigid structures [46]. By combining these systems, which have complementary strengths and weaknesses, mixed structural systems for buildings can be created.

Different design suggestions have emerged to create livable spaces on planets for buildings with mixed structural systems. “TransHab”, which is one of the examples of mixed structural system buildings, is a design model with an inflatable outer shell and a rigid core inside [47]. Another mixed structural system structure proposed for planetary settlements is the "Hive Mars" project. It is formed by pressurizing an egg-shaped pneumatic system into the outer shell built with 3D systems (Figure 13) [48, 49]. The "Lunar Habitation ESA" project, which is planned to be built on the lunar surface and designed by Foster and Partners, was created by adding the regolith layer on top of the dome-shaped pneumatic system with 3D printing systems (Figure 14) [50, 51].Another construction proposal using hybrid systems "Mars X-House V1", was created by covering two pneumatic (Inflatable) systems in the inner center with a 3D-printed protective radiation shield (Figure 15) [52, 53].

**Figure 13.** Hive Mars [48]

**Figure 14.** Lunar Habitation ESA [50]

**Figure 15.** Mars X-House V1 [53]

## 4. Evaluation of structural systems

To determine the structural system of a structure to be built on planets, a building material that can safely carry loads, withstand environmental conditions, is cost-effective, has a suitable modular geometric form, and possesses high strength with low thermal expansion is needed [17]. Understanding the different environmental conditions of planets is essential to creating a suitable environment for users. When determining the structural system of buildings, important variables include the structure's function, geometry, loads, material, and cost.

Using a scoring system to choose a structural system in planetary environments, where there are various variables and alternatives with respective advantages and disadvantages, facilitates the decision-making process. This evaluation system aims to select an appropriate system by assessing numerous sub-variables to decide on the structural system suitable for planetary conditions. As information about planets is continually developed and updated, the structural system alternatives and factors in the scoring system will evolve over time. In the scoring system, structural system types are compared against factors affecting their selection, and as a result of the comparison, the systems are rated from 1 to 5. A rating of 5 indicates that the structural system is efficient and preferable against the factor, while a rating of 1 indicates that it is weak and not advisable. Ratings of 2, 3, and 4 are intermediate evaluation scores. These scores for the factors will be explained specifically for each structural system.

### 4.1. Cost of the structure

Various variables affect the cost of a structure planned to be built on planets. Transporting building materials from Earth to the planetary environment and the construction process on the planet itself significantly impact the cost. The types of structural systems prominent for use on planets are evaluated according to the factors shown in Figure 16.

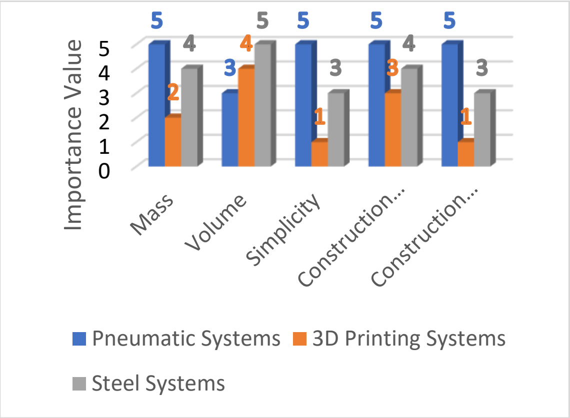

**Figure 16.** Evaluation of structural systems according to cost factor

- Mass: Pneumatic systems are the lightest (5 points). Steel systems carry less material from Earth (4 points). 3D printing systems are rated intermediate (2 points) due to the size of the equipment that must be transported to the planets (Figure 16).

- Volume: 3D printing systems can create unlimited volumes (5 points). Steel systems can span large areas (4 points). The volumes that pneumatic systems can create are limited (3 points) (Figure 16).

- Simplicity: Pneumatic systems are the simplest in construction (5 points). Steel systems are more complex than pneumatic systems in terms of material production (3 points), and our experience with them is limited. 3D printing systems are the most challenging (1 point) (Figure 16).

- Construction Time: Pneumatic systems arrive from Earth to the planets almost ready (5 points). 3D printing systems, built through robots, are faster than steel systems (4 points). Steel systems are slower (3 points) (Figure 16).

- Construction Equipment: Pneumatic systems can be constructed almost without the aid of equipment (5 points). Steel systems require equipment for material production (3 points). Bringing 3D printing system robots from Earth is challenging (1 point) (Figure 16).

## 4.2. Loads of the structure

Loads refer to the forces acting on a structure. A building withstands these loads thanks to its structural system. The environmental conditions of planets affect the load characteristics acting on the structure.

The durability of structural systems depends on environmental conditions, structural loads, and material properties. When choosing a structural system, the differences in environmental conditions between Earth and other planets affect the loads on the structures. For example, wind formation is not very common on the Moon and Mars due to the lack of a significant atmosphere [9]. Therefore, wind load can be ignored when creating structures on these planets. However, dust storms that affect the structure similarly to wind are a significant consideration. This dust load is important for ensuring resistance to external influences. Dust should not accumulate on the structure, and designs that protect structural system elements should be considered. The form of the building and any indentations on the structure influence the structural system's exposure to dust load. Additionally, the durability of habitable structures is crucial to prevent them from being affected by the dust load. Rigid structural systems are more resistant to this load compared to flexible systems.

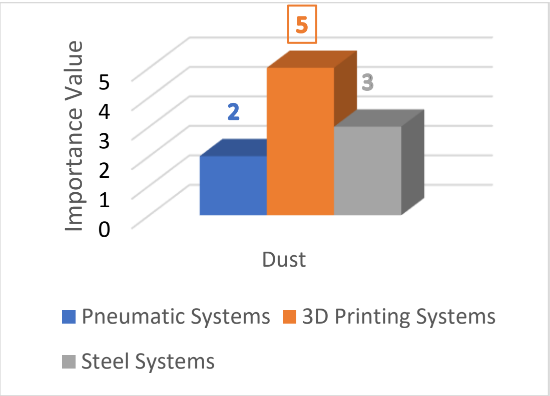

**Figure 17.** Evaluation of structural systems according to dust load factor

- Dust: Since 3D printing systems are rigid systems, they are resistant to wear (5p). Since steel systems are rigid systems (3p). It is more durable compared to pneumatic systems (2p) (Figure 17).

Gravity load, which determines the amount of dead load on the structure on Earth, dominates the choice of structural system. Unlike on Earth, on planets, the pressure load is the determining factor, not the gravitational load. Tensile forces occur on the surface of the structure, which must be pressurized in order to create a healthy environment for its users.

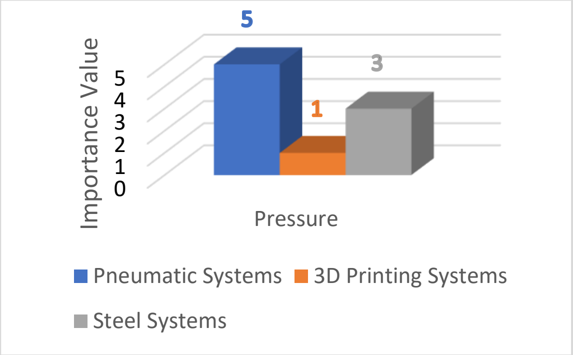

**Figure 18.** Evaluation of structural systems according to pressure load factor

- Pressure: It is usable because it is resistant to the tensile forces of pneumatic systems (5p). The steel material used in steel systems is resistant to tensile (3p), however, 3D printing systems are not efficient without additional supports (1p) (Figure 18).

Flexible structural systems are more affected by radiation compared to rigid structural systems. Proposed methods of protection from radiation on planets will create an additional load mass on the structure [16]. It is important that the structures to be built can bear this load.

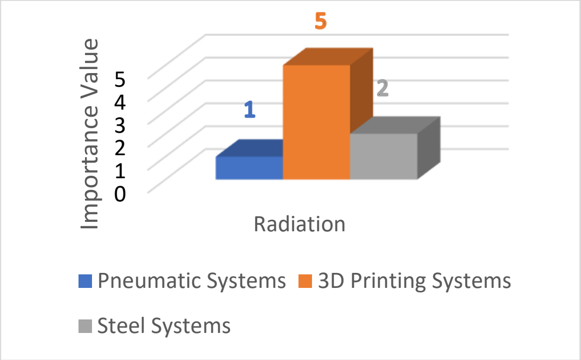

**Figure 19.** Evaluation of structural systems according to radiation load factor

- Radiation: 3D printing systems carry the incoming load to protect from radiation (5p). The strength of steel systems without coating with additional coatings is low (2p). Pneumatic systems cannot handle the shielding load even without support elements (1p) (Figure 19).

### 4.3. Material of the structure

It is important to determine the structural system before considering system materials on planets. The evaluation system used to propose a structure for the first settlements on planets suggests that economical (inflatable) flexible systems are advantageous according to cost and load factors. However, it will be important to compare this system with the ready-made capsule systems sent from Earth to planets for construction. The different effects of these two systems have been evaluated.

- Cost: Capsule systems (2p), created with high technological possibilities, are much more costly to produce compared to pneumatic structural systems (5p) (Figure 20).

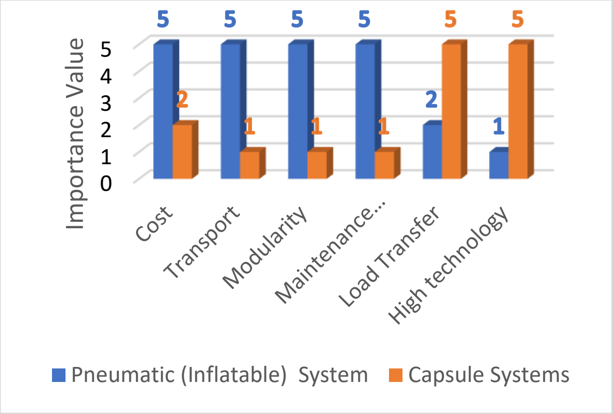

**Figure 20.** Comparison of Pneumatic Systems and Capsule Systems

- Transport: Transport and installation of capsule systems (1), which are planned to be sent ready-made from Earth to the planetary environment, are quite difficult and costly compared to pneumatic systems (4p). According to Dr. İbrahim Güven, an associate professor in the Department of Mechanical and Nuclear Engineering in the VCU College of Engineering, the cost of transporting 1 pound of weight to the moon is currently around $100,000 (Figure 20).
- Modularity: In the planetary environment, which is quite open to developments and changes, capsule systems (1p) are closed to adaptations compared to pneumatic systems (5p) (Figure 20).
- Maintenance and repair: Repair and maintenance of high-tech capsule

systems (1p) are quite complicated compared to pneumatic systems (5p) (Figure 20).

- Load Transfer: Capsule systems (5p) are advantageous compared to pneumatic systems (2p) in carrying heavy loads (Figure 20).

- High Technology: Capsule systems (5p), produced with advanced technological systems, are more resistant to harsh conditions compared to pneumatic systems (1p) (Figure 20).

As a result of the evaluation, pneumatic systems are advantageous compared to capsule systems. In this regard, when material selection is made, it is important that the membrane material, which is the structural element, is selected in accordance with the environmental conditions of the planet. Studies have shown that aramid fabrics consisting of organic polymers are used on planets [54]. Aramid fabrics recommended for use were also evaluated. (Figure 21).

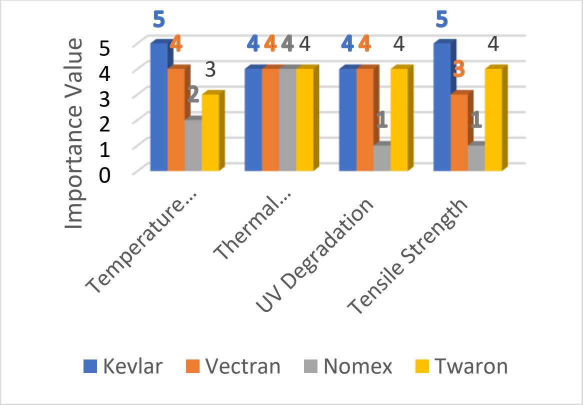

**Figure 21.** Evaluation of the properties of materials

- Temperature resistance: Kevlar fabric material has the widest temperature range (5p) as it can withstand -40°/429°. Vectran (4p) based on -40°/330° range respectively. Twaron (3p) based on -40°/300° range. Nomex (2p) is rated based on the -40°/250° range (Figure 21).

- Thermal expansion: Since the thermal expansion feature of the membrane fabrics intended to be used is at a low level (4p), they are scored equally (Figure 21).

- UV degradation: Kevlar, Vectran and Twaron (4p), a membrane with uv degradation resistance. Nomex that does not have this resistance is rated as (1p) (Figure 21).

- Tensile strength: Kevlar (2800-4100 mpa) has the highest tensile strength of the membrane fabrics that become structural by pressurization (5p). Tensile strength value respectively twaron (2500-3500 mpa) (4p). vectran (1100-3200 mpa) (3p). nomex is rated as (400-500 mpa) (2p) (Figure 21).

In addition to making the membrane fabrics of structures with pneumatic structural systems resistant to radiation, it is important to provide shielding around the structure to ensure the health of living things and the resistance of the structure. In order to provide shielding on planets, the materials that have been highlighted in the research carried out so far have been evaluated (Figure 22).

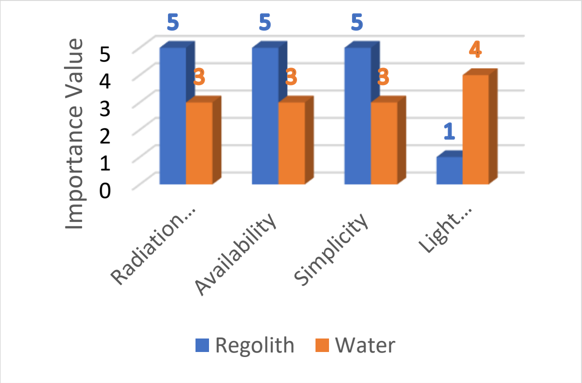

**Figure 22.** Evaluation of the properties of radiation protective materials

- Radiation protection: regolith requires a depth of 5m to provide protection equivalent to the Earth's atmosphere (5p). The water must be 10m deep to provide protection from there (3p) (Figure 22).

- Availability: since the surface layer of the planets is covered with its native material, regolith (5p). Water is not directly present on the surface (3p) (Figure 22).

- Simplicity: regolith found on the surface of planets can be used directly (5p). In order to use water, its form must be transformed into ice (3p) (Figure 22).

- Light transmittance: Water is a material that transmits light (5p). The regolith does not allow light into the structure (1p) (Figure 22).

## 4.4. Geometry of the structure

Geometric form is an important factor in determining a structural system. The harsh conditions of the planets are effective in the formation of the geometric form of the structure. Straight or arch geometries are used in the openings we will pass through to create structures in these harsh environments. Crossing the opening straight is not as effective as arch geometry in terms of load transfer. As seen in the Figure 23, arches are more resistant to tensile and pressure forces than straight opening transitions.

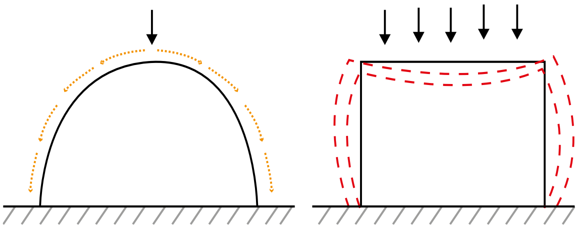

**Figure 23.** Arches and straight opening transitions

There are different geometric forms proposed to build structures in the harsh environmental conditions of the planets. Rectangular, spherical, cylindrical and conical forms intended to be used on planets are evaluated according to their various features in the figure 24.

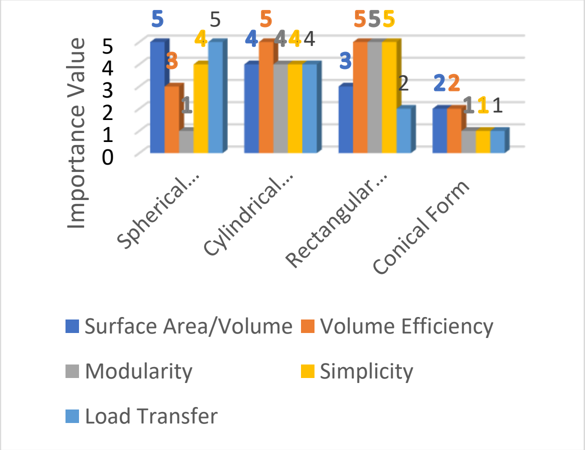

**Figure 24.** Evaluation of building forms

- Spherical form: although its surface area is small, it is large in volume (5p). It is difficult to use this large volume efficiently (3p). It is relatively easy to produce a tested geometry form (4p). It transfers the loads acting on it to the ground evenly (5p). Also, the form is not a good choice when considering modular additions (1p) (Figure 24).

- Cylindrical form: the surface area it covers is quite small compared to the volume (4p). It is very efficient in terms of volume (5p). It distributes the loads acting on it equally (5p). It is a geometric form (4p) suitable for modular additions. It is relatively easy to produce a tested geometry form (4p) (Figure 24).

- Rectangular form: surface area to volume ratio is inefficient compared to other forms (3p). It allows efficient use of the volume it creates (5p). Suitable for modular additions (5p). They are simple because they form symmetrical geometries (5p). Considering spherical forms, charge transfer is incomplete (2p) (Figure 24).

- Conical form: the volume narrows as it rises, making it difficult to use it efficiently (2p). To obtain large volumes, the surface area must increase considerably (2p). It does not allow modular additions (1p). It is a complex structural form (1p). It cannot transfer the load to the ground efficiently (1p) (Figure 24).

## 4.5. Building proposal

As a result of the evaluation, it is important to be able to build fast, simple, and functional structures in the first settlements on planets. The types of structural systems envisaged for use in these initial settlements were evaluated according to cost, load, material, and geometric form criteria. The evaluation concluded that mixed (hybrid) systems, which incorporate 3D systems, would be more appropriate for use in the settlement phase after the first planetary settlements. Transporting capsule structures, planned to be built on Earth using high technological means and then transported to the planet's surface, is very costly. Studies have determined that the cost of transporting 1 pound (0.45359237 kilograms) of weight to the moon is currently around $100,000. and sending it to Mars will cost much more [55].

Therefore, pneumatic (inflatable) structural systems, which are light, foldable, and can be built very quickly, were deemed suitable for the first settlements on planets. These systems will be transported to planets by folding them into small volumes and built on the planet's surface.

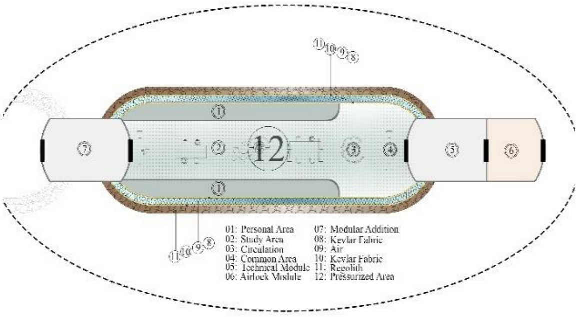

**Figure 25.** Building proposal plan

When evaluating aramid fiber fabrics, which are the main material of pneumatic structural systems, Kevlar Aramid Fiber and Twaron Aramid Fiber, intended for use in the planetary environment, received close scores. To make an evaluation between these two options, their costs were compared, and Kevlar Aramid fabric was deemed appropriate due to its affordable cost [56, 57] . It is recommended to use a hybrid form created with cable support elements to benefit from the advantages of both spherical and cylindrical geometries, which yielded close results in the scoring of the geometric form of the structure.

It is deemed appropriate to cover the Kevlar aramid fabric, which meets the tensile stresses that will occur when the pneumatic system is pressurized to sea level pressure (1013.25 millibars), with a layer of regolith, the surface material of planets, to protect against the negative effects of radiation, meteorites, and temperature. Studies have shown that a three-meter deep regolith layer provides the protection equivalent to Earth's atmosphere [58]. Additionally, the protective regolith layer added to the structural system also creates thermal comfort within the building. The regolith layer surrounding the structural system can keep the temperature inside the structure constant at ±2 degrees [28]. The floor of the structure created with a pneumatic system will be separated from the planet's surface thanks to its air layer feature. There should be a regolith layer on the upper layer of air, providing good insulation with low thermal conductivity, as on all other surfaces of the building. This regolith layer separates the ground of the structural system from the planet's surface.

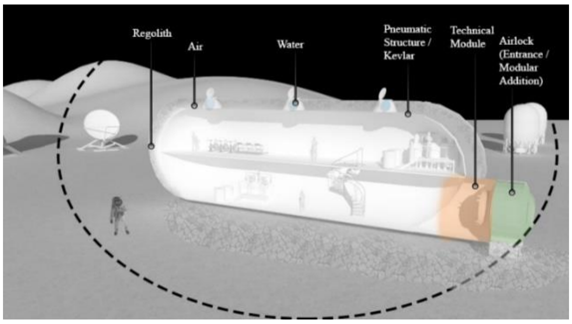

**Figure 26.** Building proposal section

Light does not penetrate the structure covered with regolith, the surface material of planets. To protect the psychological and physical health of users, they need surfaces that allow light transmission. In this building proposal, aimed for use in the first settlements on planets, the regolith layer will be pierced with air-locked systems to allow natural light into the volume. To create a skylight that transmits light while maintaining pressure and radiation control, the space between the double-layered transparent PVC membrane material will be filled with water, which has radiation protection properties, acting as a cushion and sealing the openings [59]. To allow modular joints and increase research on planets, it is recommended to use input and output elements designed specifically for pneumatic systems, ensuring they do not disrupt the pressurization within the structure (Figure 25, 26, 27).

**Figure 27.** Building proposal

## 5. Conclusion

In this study, which aims to create a structural proposal for the first settlements on planets, a scoring system was developed to select and compare criteria. This scoring system aims to mathematically grade all stages in the structural system selection process. Based on this system, it was determined that the primary system to be used in the first settlements should be Pneumatic (Inflatable) systems, transported from Earth to planets. To increase the usable volume area, the proposed structure, combining cylindrical and spherical forms, should be supported with cable elements to bear the loads. It is recommended to cover the structure with regolith to protect the main structural system and living organisms from the damaging effects of the planetary environment.

The building model proposed as a result of the evaluation is still at the conceptual stage. With advancing technological steps, planetary environments need to be tested in more detail. The evaluation system is designed to keep pace with developing technology. Based on further studies, additional criteria can be added to this evaluation system, or obsolete criteria can be removed.

This research simplifies and objectifies the process of determining the structural system for the frameworks of structures to be built on the planets where we plan to travel and settle permanently in the near future. It is intended that this evaluation system can serve as a foundation for future studies on structural system selection on planets.

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The authors of the paper declare that they comply with the scientific, ethical and quotation rules of SAUJS in all processes of the paper and that they do not make any falsification on the data collected. In addition, they declare that Sakarya University Journal of Science and its editorial board have no responsibility for any ethical violations that may be encountered, and that this study has not been evaluated in any academic publication environment other than Sakarya University Journal of Science.

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