Acta Astronautica 173 (2020) 145–154

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Utilizing the Analytical Hierarchy Process to determine the optimal lunar habitat configuration

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ARTICLE INFO

Keywords:
Lunar habitat
Inflatable habitat
Analytical Hierarchy Process
Multi-criteria decision making

ABSTRACT

Discussion over how to construct a sustainable lunar base has been ongoing since before the Apollo program, with no clear answers emerging. In this study, a decision support tool known as the Analytical Hierarchy Process (AHP) is used to narrow down what the optimal characteristics of a lunar habitat would be. The mathematical basis for AHP, as well as its criticisms, are briefly detailed. AHP is subsequently applied to lunar habitats after the central design characteristics and judging criteria for such characteristics are determined. Ultimately, we determined that inflatable habitats should be slightly favored over rigid habitats for lunar applications and greatly favored over other habitat concepts. Hybrid structures may provide an appropriate compromise between inflatable and rigid habitats. AHP also suggested that utilizing a Vectran restraint layer and deploying the habitat using columnation and compartmentalization are much more desirable than their alternatives. Further, it also suggested that an inflatable habitat should be cylindrical and pressurized to sea level pressure. A sensitivity analysis is conducted on these results. Through this study, the use of AHP to make quantitative, impartial decisions, given complex aerospace problems with many influential criteria and potential options, is demonstrated.

1. Introduction

Exploration and development of the Moon are appealing for many reasons. Lunar manufacturing, mining, and tourism have become more attractive economic opportunities as the cost of launching cargo into space decreases. The Moon may also provide a long-term solution to Earths growing energy needs by acting either as a source of materials for a massive solar array that would beam power to Earth or as a source of helium-3 for fusion reactors [1]. Laboratories and telescopes on the Moon could have immense scientific benefits [2]. Additionally, it is highly likely that advanced technologies developed for lunar use could see much practical use on Earth and application on future Mars missions [3].

Despite these possibilities, advances in lunar development have slowed to a crawl since the Apollo era. While this can be attributed to a vast array of reasons, a few are worth highlighting. Space has never been cheap; the Apollo program itself cost tens of billions of dollars in the 1960s and 1970s without adjusting for inflation, and the Constellation program would likely have cost hundreds of billions of dollars. Investor and constituent interest in lunar missions have historically not been high enough to justify the necessary spending [4]. Institutional changes within NASA have also caused a scaling back of human exploration initiatives at several points in the past few decades, and changes between presidential administrations have forced NASA to modify their internal goals frequently [5].

Given this reality, it is essential that the finite resources available for the development of lunar habitat concepts - money and time - are granted to groups with concepts that have a high likelihood of success. To allocate resources efficiently, however, the optimal framework for a lunar habitat must be determined. This framework will inevitably draw upon our current understanding of the lunar environment and the most recent technological developments.

1.1. Historical background

Lunar habitats have been seriously proposed for over 50 years. DiLeonardo [6] suggested that the first lunar settlers could use a combination of prefabricated tension members and lunar rock to construct a base. DeNike and Zahn [7] proposed pressurizing an excavated tunnel underneath the lunar surface soon after. The Lunar Exploration System for Apollo (LESA), which would have included a lunar base, was seriously considered by NASA as a follow-up to the initial Apollo missions before being canceled [8]. Humanity took a major step towards a lunar base with the successful launch and occupation of the first orbital space

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https://doi.org/10.1016/j.actaastro.2020.04.012
Received 31 January 2020; Received in revised form 4 April 2020; Accepted 6 April 2020
Available online 18 April 2020

station, Salyut 1, in 1971. Following this was years of improvement to space stations, which proved that humans could live for extended periods outside of the confines of Earths atmosphere. An inflatable lunar habitat was first proposed in 1989 by NASA [9].

1.2. Challenges of the lunar environment

Due to the lack of atmosphere on the Moon, habitable structures will need to be pressurized, likely to a level between 69 kPa and sea level pressure (101.3 kPa). They will also need to incorporate airlocks [10]. These characteristics create more complicated loading conditions for pressurized structures when compared to unpressurized structures. Any construction materials must also have low outgassing [11]. Loading conditions are further influenced by the fact that lunar gravity is approximately 1/6 of the Earth's. The lower gravity reduces the load necessary for lunar structures to support. It also suggests that mass, as opposed to weight, be used when designing structures [10]. Additionally, prolonged exposure to low gravity can cause bone loss in astronauts.

Radiation, however, potentially poses the most significant risk to humans living outside of the protective magnetic field of Earth, as long-term exposure to radiation can have many adverse health effects. Solar particle events (SPEs) can release a dangerous amount of radiation, especially around solar maximum [3]. It has been suggested that polyethylene and lunar regolith could be used to shield against solar radiation. Notably, using regolith would create additional loading conditions on a lunar structure [12].

Rapid fluctuations in temperature also characterize the lunar surface. This variation necessitates the incorporation of a radiative thermal control system into any habitable lunar structure [3]. Thermal cycling will inevitably cause a significant amount of structural fatigue, which can be combated through the proper choice of materials used for external structural components. Lunar regolith can fulfill this role, as it is a good thermal insulator [13].

This lunar regolith - the top layer of surface material on the Moon - is composed of highly abrasive, charged dust particles primarily composed of silicates and oxides [14]. Lunar dust can impair astronaut vision during EVAs and cause instrument failures [15]. It also poses a danger to the operation of mechanical joints in lunar machinery by potentially clogging moving parts [16]. For crewed missions, the greatest danger that lunar dust poses might be its effects on the human body; exposure to regolith is known to cause cell death and DNA damage [17]. Despite the problems that it poses, lunar regolith may be a necessary evil, as it can be used as micrometeorite shielding. Micrometeorites - meteoroids that are less than 0.05 mm in size - can reach speeds up to 70 km/s. Coupled with their high flux over the lunar surface, they pose a significant risk to pressurized structures, as a puncture can lead to the rapid depressurization of a structure and the loss of the crew housed within.

1.3. Lunar habitat features

In order to confront the challenges previously outlined and ensure astronaut safety during the entirety of the mission duration, any lunar structure must meet stringent requirements. A lunar habitat must be light and low volume while, paradoxically, providing the most useable volume upon deployment to maximize efficiency and astronaut comfort. The structure must be manufactured with strong, ductile, durable materials with low thermal expansion characteristics. The structure should be low maintenance and require little initial construction time in order to minimize astronaut EVA time. Excavation should be minimized, and foundations should be small or nonexistent. On top of all of this, a lunar structure must be designed with a high safety factor; a design code for such a project does not exist, and our experience with the lunar environment is lacking [10].

1.4. Habitat concepts

Concepts for lunar habitats are numerous and highly variant. A few general, seriously explored concepts are highlighted.

Rigid structures are metallic structures fabricated on Earth and launched as a complete structure. They are relatively simple, and engineers have much experience with them. Their behavior under various loading conditions is relatively easy to model. Rigid structures have some severe drawbacks, however. They are expensive, have a high mass-to-volume ratio, and inherently possess no packing advantage [3].

Cable structures use cables as the main support structure for a pressurized enclosure. A cable-based habitat would have a relatively low weight and high versatility regarding packing arrangements. A significant downside of cable structures is that any structure of this sort would likely require an extensive anchoring system. Installing this system would require additional work on the part of astronauts [18].

Several types of ISRU structures have also been proposed. One application of this particular structural concept has materialized in the form of a habitat made out of regolith concrete. A structure of this type would theoretically require relatively little energy to construct, have favorable heat transfer properties, and provide its own resistance to radiation and MMODs. A considerable disadvantage of lunar concrete is that it would likely require water, one of the main ingredients in concrete production. This water would have to come from costly rocket launches or regolith excavation [10]. The latter option may not even be less expensive, as water on the Moon is scarce [19].

Well-mapped lava tubes with an easily accessible entrance could provide natural radiation- and MMOD-protected locations for astronauts. A lava tube could be lined with a material that renders it airtight, providing a large living and working space [20]. Similarly, a lunar crater could be enclosed to form a large habitat [21].

2. Inflatable structures

Inflatable structures are a type of prefabricated, fabric-based structure that expand in size upon deployment. This basic premise lends many advantages to the use of inflatables. They are light, strong, and relatively inexpensive. They have a low mass-to-volume ratio, which, when coupled with their high packing advantage, allows for large structures to be launched for less payload mass and a smaller payload size. Some inflatables can be deflated and inflated repeatedly, which allows for structure mobility [3]. Further, they can be configured to deploy themselves automatically, reducing EVA risk [13]. As such, inflatable structures have great potential for future aerospace applications.

Of course, inflatable structures are not perfect. Inflatable structures may be more sensitive to radiation exposure than rigid structures. There is also considerable concern regarding the effect of both abrasion from lunar regolith and non-static loads [3,11]. Inflatable structures will need to interface with rigid structures - an airlock, for example - which provides a potential point of failure for the habitat. Inflatable modules may also be harder to maintain and service than rigid modules, especially if a regolith load is placed on the structure [11].

2.1. Geometry

Concepts for inflatable structures are dominated by four general geometries: spheres, tori, cylinders, and irregular. Spheres have the most efficient volume to surface ratio but are difficult to outfit once deployed [22]. Tori require much less excavation than other shapes but complicate rigid structure integration. Cylinders simplify this integration, allow for easy compartmentalization, and are less risky than other shapes. On the other hand, they have a higher mass-to-volume ratio than spherical structures, partially negating one of the main advantages of inflatable structures. Irregular shapes, such as the tuft-pillow structure, tend to fall victim to higher stresses but are more specialized for their purpose [23]. Derivatives of these shapes, specifically hemispheres and semicylinders, are also often proposed.

2.2. Materials

Organic polymers are extremely light and can be folded easily, allowing for the formation of complex shapes [24]. As such, the main load-bearing layer of modern inflatable aerospace structures is usually woven out of Vectran or a variation of Kevlar. The designers of the Bigelow Expandable Activity Module (BEAM) opted to use Kevlar, which has a high Young's Modulus and is relatively inexpensive. Vectran, on the other hand, has low outgassing and is more abrasion resistant than Kevlar 49 while having similar UV degradation rates [25]. Vectran is also more resistant to atomic oxygen than Kevlar [26].

2.3. Deployment

Optimally, during deployment, an inflatable structure can be expanded slowly and predictably to control the rigidity and stress of the structure at all times. There are three common mechanical deployment/rigidization techniques. Compartmentalization involves staging the inflation process through the use of burst disks, pressure relief valves, or orifices. Often, this method is used in conjunction with another deployment method, columnation, which allows for a structure to grow linearly from a fixed base. Roll-out devices utilize a mechanism to inflate and unravel a structure simultaneously [24]. Several self-strengthening materials can aid in or be the primary component of a structure rigidization process, including thermosetting and thermoplastic composites, UV cured composites, and rigidizing foam [24].

2.4. Internal pressure

The air pressure within a habitat affects both its structure and the health of the astronauts within it. NASA recommends that launch vehicles should operate at a standard sea level pressure of 101.3 kPa given the long-term health effects of lower air pressures [27]. Other pressures have been utilized in the past, with Skylab utilizing an oxygen-rich atmosphere at 35 kPa.

3. The Analytical Hierarchy Process

The Analytical Hierarchy Process (AHP) is a quantitative multi-criteria decision-making (MCDM) process that was first proposed by Saaty [28] in order to solve problems that can be modeled by a hierarchical or network structure. The hierarchical structures evaluated with AHP tend to take the form of a central question that has several choices, which can each, in turn, be judged using several different criteria. AHP is useful for determining the relative weight that each criterion should have when a decision needs to be made. As such, it is used for a variety of applications such as supply chain management [29], risk assessment [30,31], and environmental management [32].

AHP includes the following steps:

1. Define the central question, choices, and judging criteria
2. Create a pairwise comparison matrix based on the fundamental scale, found in Table 1
3. Normalize the comparison matrix
4. Calculate the average of each row of the normalized comparison matrix to determine the criterion weight vector
5. Calculate the consistency index (CI) of the comparison matrix using Equation 1
6. Determine the random consistency index (RCI) value for the comparison matrix
7. Calculate the consistency ratio (CR) using the CI and RCI
8. Compare the calculated CR to the value considered acceptable for consistency

In short, AHP revolves around the creation and manipulation of a pairwise comparison matrix. A pairwise comparison matrix allows a user to compare the relative importance of one criterion as compared to another. Relative importance is determined according to a scale Saaty proposed in 1980 [33], which converts qualitative relations into quantitative relations. These quantitative relations form the backbone for AHP. Saaty's scale is still used today and reproduced in Table 1.

AHP has proven to be an extremely useful tool. It shifts the subjectivity within the decision-making process from the central question to a set of related judging criteria. This shift is beneficial. Deciding between different alternatives within an engineering project can be extremely difficult, as there are so many influencing factors, both technical and non-technical. This difficulty can easily lead to misinformed decision making and costs companies and organizations millions of dollars and thousands of working hours. AHP takes an extremely complex central question and creates many simpler questions that directly relate to how the decision should be made. For this particular study, the question "What is the optimal lunar habitat?" shifts into "What factors are most important for the success of a lunar habitat?". Creating simpler questions also allows for a more thorough and objective analysis, as deciding whether a particular judging criterion is more important than another is much easier than attempting to determine the best alternative straightaway. Ensuring that these simpler questions are answered as accurately as possible will ultimately lead to a decision that is as objective and accurate as possible, even if it is in response to a complicated question.

By shifting where the subjectivity is applied in the decision-making process, AHP can minimize potential biases that may be present. One would have to bias the comparison matrix while keeping it internally consistent without knowing exactly how the biased values would propagate throughout the criteria weight calculation. This biasing would also become more difficult when taking into consideration that comparison matrices would optimally not be an individual decision, especially within a large company or organization. A comparison matrix should be subjected to peer review and scrutiny.

For these reasons, AHP can be a useful starting point during the preliminary design of a system. It can suggest that a particular direction is most appropriate when beginning a project. It may also show that an optimal choice is more apparent than previously thought, saving precious time and resources.

With these things said, the shortcomings of AHP should not be ignored. Despite being classified as an MCDM process, AHP should be used as a decision support tool, not a decision-making tool. In other words, the outcomes of AHP should be used in conjunction with other MCDM tools or subjected to a sensitivity analysis, especially when the differences between the final weights and weighted sums are small. AHP is still, at its core, a subjective process. Though it shifts where subjectivity is applied, the outcome of AHP is still dependent on how the judging criteria are compared with one another. Different people or groups are unlikely to agree on the proper relative importance of every pair of criteria, which can lead to different results. The most knowledgeable individual within a particular field should not have the only input on comparison matrices, however. Many parties should have input; reaching a consensus or "middle ground" is a necessity.

When differences are small, AHP and other MCDM methods can sometimes suggest that a non-optimal alternative is the best alternative. Increasing the number of criteria taken into consideration can help to make the differences between weights and choices larger, increasing the likelihood that the theoretical optimal choice as determined by AHP lines up with the actual optimal choice [34]. Further, rebuttals of criticisms directed towards AHP can also be found [35], and AHP has grown to be one of the most popular and prevalent MCDM methods.

4. AHP with lunar habitats

With the benefits of AHP established, it is applied to the selection of an optimal lunar habitat. The subsequent analysis outlines how AHP was used to determine several optimal characteristics of a lunar habitat. These characteristics include the habitat concept, its shape, its deployment method, its internal pressure, and the restraint layer material. In order to assist in the explanation of this process, a focus will be placed on the selection of the habitat concept. The comparison matrices and unweighted results for the other habitat features can be found in the appendix.

It is important to note that these habitat characteristics are not independent of each other. For example, a deployment method is only relevant if the habitat concept is able to be deployed in some fashion. When applying AHP to a design with multiple systems and subsystems, it is necessary to apply AHP at the top of the operational hierarchy and work downward.

After selecting the central question, the evaluation criteria for the problem must be defined. This selection is made through an extensive literature review in the field of interest. For lunar habitats specifically, the criteria can be derived from how important certain features are to a particular aspect of a lunar habitat. The criteria considered for this particular study, adapted from a number of works [3,10,13,16,36,37], are listed in Table 2. The alternatives considered are also included alongside their corresponding habitat feature.

The easiest way to make a quantitative decision regarding the optimal lunar habitat concept is to equate qualitative features of a lunar habitat concept to numerical values and take an unweighted sum. From this, a determination can be made as to how well each particular habitat concept addresses all of the relevant judging criteria.

In order to accomplish this, each criterion was defined on a scale from 1 to 5. The criteria definitions for evaluating a habitat concept are shown in Table 3. Assigning a value of 1 to a particular concept for a particular criterion indicates that the concept is less desirable because the manner in which it addresses the criterion is disadvantageous for any number of reasons. Assigning a value of 5 to a particular concept for a particular criterion indicates that the concept is more desirable because it addresses the criterion in a way that is relatively advantageous for the construction of a lunar habitat. 2, 3, and 4 are intermediate values between these extremes. They can be specifically defined, as in the case of the “Experience with System” criterion, or not. In the case of the latter, it is left to the judgment of the person carrying out this procedure to determine what particular intermediate ranking should be assigned to a particular habitat concept.

Each potential habitat concept was ranked 1 through 5 for each criterion using these definitions. For example, the inflatable habitat was given a rating of 5 for expandability since it, by its very nature, is designed to increase significantly in size. The rest of the rankings for each habitat concept criterion can be found in Table 4. A sum was also calculated for each habitat concept based on these rankings.

From this matrix, one might be tempted to conclude that an inflatable habitat would be the optimal choice for a lunar habitat. This conclusion, however, assumes that all of the criteria that were used to judge the habitat concepts are equally important, which is clearly not the case. Therefore, the logical thing to do would be to assign a weight to each criterion. These weights could then be multiplied by the rankings given to each concept and summed to give a more accurate representation of the optimal habitat concept. In order to do this, a comparison matrix was created in the manner outlined by AHP. This comparison matrix is shown in Table 5.

The right principal eigenvector of this comparison matrix was then calculated to derive the weights for each habitat concept evaluation criterion. As demonstrated by Saaty [38], given the properties of the right principal eigenvector, it can be shown that it becomes the only device for representing priorities using a near consistent pairwise comparison matrix. In order to find the right principal eigenvector, the comparison matrix was normalized. The normalized comparison matrix is shown in Table 6.

Finally, the weights for each criterion can be calculated by averaging the values in each row of the normalized comparison matrix. These weights are shown in Table 7.

To verify the methodology for obtaining these weights and the AHP

Table 2
Habitat features evaluated with corresponding judging criteria and alternatives.

Feature	Judging Criteria	Options
Habitat Concept	• Launch Mass/Volume • Ease of Construction • Experience with System • Expandability • Excavation • Foundations • Maintenance • Recycling/Mobility • Environment	• Inflatable Structure • Cable Structure • Lunar Crater • Rigid Structure • Lava Tube Base • Concrete/ISRU
Habitat Shape	• Stress • Mass to Volume Ratio • Manufacturability • Modularity • Risk • Excavation	• Spherical • Tuft Pillow/Irregular • Cylindrical • Torus • Hemisphere • Semicylinder
Deployment Method	• Fold Stress • Storage Volume • Risk • Deployment Time	• Columnation and Compartmentalization • Roll-out Method • Material Rigidization
Internal Pressure	• Stress • Astronaut Health • EVA Compatability • Noise • Emergency Response Ability • Fire Hazard	• 101.3 kPa • 55–69 kPa • 35 kPa
Restraint Layer Material	• Experience • Abrasion Resistance • UV Degredation • Creep Rate • Cost	• Kevlar • Vectran

Table 1
Scale of relative importances [33].

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgement favor one activity over another
5	Essential or strong importance	Experience and judgement strongly favor one activity over another
7	Very strong importance	An activity is strongly favored and its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values	When compromise is needed
Reciprocals	If activity *i* has one of the above numbers assigned to it when compared to activity *j*, then *j* has the reciprocal value when compared with *i*	

Table 3
Habitat concept ranking definitions.

Criteria	1	2	3	4	5
Launch Mass/Volume	Prohibitively heavy and extremely low volume	Heavy and low relative volume	Moderate relative mass and medium relative volume	Low realtive mass and high realtive volume	Minimal transport volume
Ease of Construction	Much outfitting necessary; much care must be taken				Little relative outfitting necessary; little specialized care necessary
Experience with System	No experience	Little Earth experience	Some Earth experience; little aerospace experience	Much Earth experience; some aerospace experience	Much aerospace experience
Expandability	Finite size; modules cannot be added	Modules difficult to add			Modules easily added
Excavation	Much excavation necessary				No excavation necessary
Foundations	Extensive foundations necessary			Small foundations necessary	No foundations necessary
Maintenance	Difficult to maintain		Somewhat hard to maintain		Easy maintenance
Recycling/Mobility	No movement/reoutfitting possible	Reoutfitting possible, but immobile	Hard to move/repurpose		Easy to move/repurpose
Environment	Cannot be outfitted with environmental protection				Environmental protection built in

Table 4
Habitat concept ranking.

Criteria	Inflatable	Cable	Lunar Crater	Rigid	Lava Tube	Concrete
Launch Mass/ Volume	4	4	3	2	4	5
Ease of Construction	4	3	1	4	1	1
Experience with System	4	4	1	5	1	2
Expandability	5	3	1	5	1	3
Excavation	4	5	5	4	2	1
Foundations	4	3	2	4	4	4
Maintenance	5	3	1	5	5	1
Recycling/Mobility	5	4	2	3	2	2
Environment	3	2	3	3	5	5
Sum	38	31	19	35	25	24

carried out, the comparison matrix must be checked for internal consistency. Each value in the comparison matrix is multiplied by the weight for the criteria in that particular row of the matrix, creating a mean matrix. This mean matrix is shown in Table 8.

The eigenvalues of this mean matrix are then calculated. These eigenvalues can be found in Table 9.

These eigenvalues are then used to compute the consistency index (CI) value for the comparison matrix using Equation (1).

$$CI = (\lambda_{max} - n)/(n - 1) \quad (1)$$

λ_{max} is equal to the average of the set of eigenvalues, and n is the number of criteria that were compared in the original comparison matrix. The CI is equivalent to 0.120 for the habitat concept comparison matrix. This value must be divided by the appropriate random consistency index (RCI) value, as provided by Saaty [39], to obtain the consistency ratio (CR). Since nine criteria were compared in the consistency matrix, the CI value is divided by an RCI value of 1.45. The resulting CR is equal to 0.083 or 8.3%, which is less than the 10% necessary to assert consistency [39]. Therefore, the internal consistency within the comparison matrix for lunar habitat concepts is high enough for the weights calculated from it to be confidently utilized.

After the calculated weights are verified, they can then be multiplied by the original ranking matrix to obtain a new, weighted matrix. As with the original ranking matrix, the values for each option can be summed to determine the best option for that particular habitat feature. This summation is how the best habitat concept was chosen; the corresponding matrix is shown in Table 10.

Since the inflatable habitat has the highest weighted sum out of all of the habitat concept alternatives, it is the theoretically optimal habitat concept.

5. Sensitivity analysis

As stated previously, the results of AHP are inherently dependent on how the ranking criteria are defined, which can vary from person to person or group to group. Therefore, it was essential to determine how resilient the results of AHP were by conducting a sensitivity analysis.

The method chosen involved changing the weights of the highest and second-highest criteria while proportionally changing the weights of the other criteria until a new concept, shape, pressure, deployment method, or restraint layer material was determined to be the most optimal. These two criteria were chosen because a change in them would be most likely to create a change in the optimal habitat characteristics.

To illustrate how this manipulation of weights works, consider an example where there are three criteria: A, B, and C. They are weighted 0.5, 0.4, and 0.1, respectively. To find the lower bound - the percentage that the highest weighted criteria could be decreased without changing the set of optimal habitat characteristics - criterion A's weight would be

Table 5
Habitat concept comparison matrix.

Criteria	Launch Mass/ Volume	Ease of Construction	Experience with System	Expandability	Excavation	Foundations	Maintenance	Recycling/ Mobility	Environment
Launch Mass/Volume	1	3	1/5	1	3	3	7	9	1
Ease of Construction	1/3	1	1/7	1/3	1	1	5	7	1/3
Experience with System	5	7	1	3	5	5	7	9	1
Expandability	1	3	1/3	1	1	1	7	9	1/3
Excavation	1/3	1	1/5	1	1	1	7	9	1/3
Foundations	1/3	1	1/5	1	1	1	5	7	1/7
Maintenance	1/7	1/5	1/7	1/7	1/7	1/5	1	1/3	1/7
Recycling/Mobility	1/9	1/7	1/9	1/9	1/9	1/7	3	1	1/9
Environment	1	3	1	3	3	7	7	9	1

lowered to, for example, 0.3. Since the difference between the original weight and the new weight is 0.2, and the weights must still add up to 1, this difference is added proportionally to the weights of B and C. Criterion B's new weight would become 0.56. Criterion C's new weight would become 0.14.

A's weight would be decreased until the optimal habitat features change, with the percentage decrease representing the lower sensitivity bound. Similarly, the upper bound for A - the percentage that the highest weighted criteria could increase without changing the set of optimal habitat characteristics - could be found by increasing its weight and proportionally changing the weights of the other criteria until a new set of optimal habitat characteristics are found. The range between the lower and upper bound, which is representative of the sensitivity of that particular criterion, could then be calculated as the difference between the two. The process for finding the upper and lower bounds was then replicated for the criteria with the second-highest original weight. In this example, it is criterion B, with a weight of 0.4.

The bounds calculated for the two highest weighted criteria for each habitat feature are reported in Table 11.

The first row of values can be used to reach the following conclusions. When deciding between lunar habitat concepts, the weight of the “Experience with System” criterion can increase by 2.7% while proportionally decreasing the weight of each of the other judging criteria before a new optimal habitat concept arises. In this case, the new optimal habitat concept is a rigid structure. The weight of this criterion can be also be decreased by 28.8% while proportionally increasing the weight of each of the other judging criteria before a habitat concept other than the inflatable structure is determined to be the optimal choice. This results in a range of 31.5% within which the weight of the “Experience with System” criterion can change before a new optimal habitat concept arises.

6. Results

According to AHP, inflatable habitats are the optimal habitat concept, but not by a large margin. The difference between the weighted sums for inflatable structures and rigid structures is less than 0.04, a small difference. The sensitivity analysis results, however, indicate that both the “Experience with System” and “Environment” criteria can change by over 30% before the weighted sum for the rigid structure overtakes the weighted sum for the inflatable habitat. This range is considerable but indicates that the result is not quite robust enough to be extremely confident that the inflatable habitat is indeed the optimal choice.

Table 7
Habitat concept criteria weights.

Criteria	Weight
Launch Mass/Volume	0.143
Ease of Construction	0.064
Experience with System	0.288
Expandability	0.105
Excavation	0.081
Foundations	0.068
Maintenance	0.018
Recycling/Mobility	0.020
Environment	0.214

This particular result can be interpreted in two ways. First, while inflatable habitats are more attractive than rigid structures and should garner more attention, they are not unequivocally the best habitat concept. The lack of experience with inflatable structures is cause for concern, especially given the risk inherent to a lunar habitat. Legacy technology is much preferred in the aerospace community for this reason, and understandably so. Nevertheless, the low mass to volume ratio and potentially mobile nature of an inflatable habitat make the concept worth pursuing even further than has already been done.

Second, this result may suggest that an alternate habitat concept should be seriously considered: hybrid structures. These habitats combine the characteristics of rigid and inflatable habitats, utilizing the best aspects of both concepts. Hybrid structures were intentionally not considered in AHP due to their highly variable nature; differences in

Table 6
Habitat concept normalized comparison matrix.

Criteria	Launch Mass/ Volume	Ease of Construction	Experience with System	Expandability	Excavation	Foundations	Maintenance	Recycling/ Mobility	Environment
Launch Mass/Volume	0.108	0.155	0.060	0.094	0.197	0.155	0.143	0.149	0.227
Ease of Construction	0.036	0.052	0.043	0.031	0.066	0.052	0.102	0.116	0.076
Experience with system	0.540	0.362	0.300	0.283	0.328	0.258	0.143	0.149	0.227
Expandability	0.108	0.155	0.100	0.094	0.066	0.052	0.143	0.149	0.076
Excavation	0.036	0.052	0.060	0.094	0.066	0.052	0.143	0.149	0.076
Foundations	0.036	0.052	0.060	0.094	0.066	0.052	0.102	0.116	0.032
Maintenance	0.015	0.010	0.043	0.013	0.009	0.010	0.020	0.006	0.032
Recycling/Mobility	0.012	0.007	0.033	0.010	0.007	0.007	0.061	0.017	0.025
Environment	0.108	0.155	0.300	0.283	0.197	0.362	0.143	0.149	0.227

Table 8
Habitat concept mean matrix.

Criteria	Launch Mass/ Volume	Ease of Construction	Experience with System	Expandablity	Excavation	Foundations	Maintenance	Recycling/ Mobility	Environment
Launch Mass/Volume	0.143	0.191	0.058	0.105	0.242	0.203	0.125	0.181	0.214
Ease of Construction	0.048	0.064	0.041	0.035	0.081	0.068	0.089	0.141	0.071
Experience with system	0.716	0.446	0.288	0.314	0.404	0.339	0.125	0.181	0.214
Expandability	0.143	0.191	0.096	0.105	0.081	0.068	0.125	0.181	0.071
Excavation	0.048	0.064	0.058	0.105	0.081	0.068	0.125	0.181	0.071
Foundations	0.048	0.064	0.058	0.105	0.081	0.068	0.089	0.141	0.031
Maintenance	0.020	0.013	0.041	0.015	0.012	0.014	0.018	0.007	0.031
Recycling/Mobility	0.016	0.009	0.032	0.012	0.009	0.010	0.053	0.020	0.024
Environment	0.143	0.191	0.288	0.314	0.242	0.474	0.125	0.181	0.214

Table 9
Habitat concept mean matrix eigenvectors.

Criteria	Eigenvalue
Launch Mass/Volume	10.208
Ease of Construction	10.004
Experience with System	10.511
Expandability	10.124
Excavation	9.891
Foundations	10.073
Maintenance	9.515
Recycling/Mobility	9.180
Environment	10.160

Table 10
Habitat concept weighted results.

Criteria	Inflatable	Cable	Lunar Crater	Rigid	Lava Tube	Concrete
Launch Mass/ Volume	0.573	0.573	0.430	0.286	0.573	0.716
Ease of Construction	0.255	0.191	0.064	0.255	0.064	0.067
Experience with System	1.152	1.152	0.288	1.440	0.288	0.576
Expandability	0.524	0.314	0.105	0.524	0.105	0.314
Excavation	0.323	0.404	0.404	0.323	0.162	0.081
Foundations	0.271	0.203	0.136	0.271	0.271	0.271
Maintenance	0.090	0.053	0.018	0.089	0.089	0.018
Recycling/Mobility	0.101	0.080	0.040	0.060	0.040	0.040
Environment	0.642	0.428	0.642	0.642	1.069	1.069
Sum	3.929	3.399	2.125	3.890	2.661	3.149

Table 11
Habitat concept weighted results.

		Upper Bound	Lower Bound	Range
Habitat Concept	Experience with System	2.7%	−28.8%	31.5%
	Environment	22.1%	−21.4%	43.4%
Habitat Shape	Experience with System	59.8%	−28.9%	88.7%
	Stress	19.5%	−17.0%	36.5%
Deployment Method	Experience with System	42.4%	−27.5%	69.8%
	Fold Stress	21.8%	−22.8%	44.6%
Air Pressure	Astronaut Health	56.5%	−12.0%	68.5%
	Stress	11.4%	−24.0%	35.4%
Habitat Material	Abrasion Resistance	45.5%	−43.9%	89.4%
	Experience	46.9%	−21.3%	68.2%

hybrid concepts far outweigh differences between inflatable or rigid structures. As such, it would be challenging to generalize hybrid structures as a whole. These results indicate that it may be most appropriate to shift more focus and resources towards developing hybrid lunar structures.

After further applying AHP to the other habitat characteristics, taking into account the previous determination that inflatable habitats are the optimal choice for a lunar habitat, several more optimal features emerged with varying levels of confidence in the results.

The relevant matrices utilized for the habitat shape calculations can be found in Table A.1 and A.2, located in the appendix. Cylindrical habitats were determined to be the optimal shape by a weighted sum margin of about 0.4, with sensitivity ranges of 88.7% and 36.5% for the two most heavily weighted criteria. These percentages indicate a high degree of confidence in the results of AHP when considered alongside the margin in the weighted sum. The semicylinder had the second-highest weighted sum due to its higher stress and less frequent use for aerospace applications when compared with cylinders.

Sea level pressure is the most desirable internal pressurization by a weighted sum margin of about 0.3, with sensitivity ranges of 68.5% and 35.4%. The matrices from which these results are derived can be found in Table A.3 and A.4, located in the appendix. These sensitivity ranges, like those for the habitat shape, are high enough to lend a high degree of confidence in the assertion that sea level pressure is the optimal choice. This is likely due to the fact that astronaut health on a crewed expedition is of paramount importance. Since this criterion outweighs all other criteria considerably and sea level pressure results in the best astronaut health, the aforementioned conclusion is reached.

Compartmentalization and columnation was determined to be the optimal choice for the deployment method by a large margin of almost 0.8. The corresponding matrices can be found in Table A.5 and A.6, located in the appendix. When this margin is considered along with the large sensitivity margins and the shape chosen for an optimal lunar habitat, an extremely high confidence level can be placed in this result.

Finally, Vectran was chosen as the optimal restraint layer material over Kevlar, with the relevant matrices found in Table A.7 and A.8, located in the appendix. The margin in the weighted sum of these two, amounting to almost 1.5, is due to the high abrasion resistance of Vectran, which will be integral for a long-term structure on the Moon. An extremely high level of confidence can be placed in this decision, as sensitivity analysis margins were both over 60%.

7. Conclusions

AHP was applied to lunar habitats in order to differentiate between several alternatives for several major characteristics of a lunar habitat: concept, shape, pressurization, restraint layer material, and deployment method.

It was determined that pursuing an inflatable habitat concept would be slightly more favorable than pursuing a rigid habitat concept. Pursuing a hybrid concept might be even more desirable. It was further determined that this inflatable habitat should likely be cylindrical in shape and pressurized to sea level pressure. It can be confidently asserted that an inflatable lunar habitat should use Vectran for its restraint layer and be deployed using columnation and compartmentalization.

The work conducted has shown the incredible value that AHP can lend to the aerospace industry. AHP has taken an extremely complex engineering problem whose solution has been argued over for decades - designing a lunar habitat - and simplified the decision-making process to such a degree that a decision can be made with some quick contemplation and a few calculations. Further, AHP was applied to multiple steps in the design process, unlike previous attempts to apply AHP to lunar habitats [23]. AHP provides mathematical verification of all stages in the design process, avoiding problems with designing systems around a faulty notion that a specific characteristic should be pursued.

Finally, and most importantly, utilizing AHP to determine these habitat characteristics has limited the internal bias present in the decision, with consistency checks and quantitative assignment of importance for the many criteria considered. This is extremely important in an industry such as aerospace, where decisions are often intertwined with politics. Using a more objective decision-making process such as AHP can directly impact the success rate of projects and the technological advancement of the field as a whole.

The contents of this study do not represent the full potential of AHP. Not only can AHP be further applied to lunar habitats, with a focus on optimizing subsystems, but its flexibility means that it can also be applied to the design of many aerospace systems and structures. AHP can be used to appropriately govern how the funds and resources of aerospace companies flow with regards to specific projects, increasing industry efficiency and expediting its technological progression.

As previously noted, the results of AHP, even this particular study, cannot necessarily be taken as absolute truth. The sensitivity analysis increases the likelihood that the results of AHP can be trusted, but does not definitively prove them. The process is not perfect, and can still lead to two potential options for solving a problem being too close to decide between confidently. As such, it is important for others to revisit the comparison matrices within this study, adjust them according to their knowledge of the subject, and reapply AHP to determine whether the optimal habitat characteristics shift. The comparison matrices should also be updated as various technologies improve and as new alternatives develop. This study provides a platform from which these new technologies can be evaluated.

Ultimately, AHP mirrors science as a whole. Humanity can never be certain about anything, but we can use our best available knowledge to make informed, pragmatic decisions and apply our assumptions to the world around us. Thus, even though AHP is not perfect, that does not mean that its results should be taken lightly.

Future work should also focus on how AHP can be used alongside other quantitative MCDM techniques to more confidently decide between projects and solutions for the benefit of the aerospace industry and humankind as a whole.

Declaration of competing interest

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

Appendix A. AHP Tables

Table A.1
Habitat Shape Unweighted Results

Criteria	Spherical	Tuft Pillow	Cylindrical	Torus	Hemisphere	Semicylinder
Stress	5	1	3	4	2	2
Mass to volume	5	4	2	4	4	3
Manufacturability	1	5	3	1	4	3
Modularity	2	5	5	2	3	5
Risk	3	1	5	1	3	4
Excavation	1	4	4	4	4	4
Sum	17	20	22	16	20	21

Table A.2
Habitat Shape Comparison Matrix, CR = 0.040

Criteria	Stress	Mass to volume	Manufacturability	Modularity	Risk	Excavation
Stress	1	1	5	5	1/3	1
Mass to volume	1	1	5	5	1/3	1
Manufacturability	1/5	1/5	1	3	1/7	1/5
Modularity	1/5	1/5	1/3	1	1/7	1/5
Risk	3	3	7	7	1	3
Excavation	1	1	5	5	1/3	1

Table A.3
Habitat Pressure Unweighted Results

Criteria	101.3 kPa	55–69 kPa	35 kPa
Stress	1	3	5
Astronaut Health	5	3	1
EVA Compatibility	3	4	5
Noise	4	3	2
Emergency Response Ability	3	3	3
Fire Hazard	5	3	1
Sum	21	19	17

Table A.4
Habitat Pressure Comparison Matrix, CR = 0.090

Criteria	Stress	Astronaut Health	EVA Compatibility	Noise	Emergency Response Ability	Fire Hazard
Stress	1	1/3	3	7	5	5
Astronaut Health	3	1	5	7	7	7
EVA Compatibility	1/3	1/5	1	9	3	7
Noise	1/7	1/7	1/9	1	1/3	1/3
Emergency Response Ability	1/5	1/7	1/3	3	1	1
Fire Hazard	1/5	1/7	1/7	3	1	1

Table A.5
Deployment Method Unweighted Results

Criteria	Columnation and Compartmentalize	Roll-out	Material Rigidizaiton
Fold Stress	3	5	5
Storage Volume	4	4	1
Risk	5	3	3
Deployment Time	4	2	2
Sum	16	14	11

Table A.6
Deployment Method Comparison Matrix, CR = 0.068

Criteria	Fold Stress	Storage Volume	Risk	Deployment Time
Fold Stress	1	3	1/5	5
Storage Volume	1/3	1	1/7	7
Risk	3	5	1	9
Deployment Time	1/5	1/7	1/9	1

Table A.7
Restraint Layer Material Unweighted Results

Criteria	Kevlar	Vectran
Experience	5	4
Abrasion Resistance	2	5
UV Degradation	4	4
Creep Rate	2	5
Cost	4	2
Sum	17	20

Table A.8
Restraint Layer Material Comparison Matrix, CR = 0.080

Criteria	Experience	Abrasion Resistance	UV Degradation	Creep Rate	Cost
Experience	1	1/5	1	9	7
Abrasion Resistance	5	1	5	9	9
UV Degradation	1	1/5	1	3	7
Creep Rate	1/9	1/9	1/3	1	1
Cost	1/7	1/9	1/7	1	1

Funding

This work was supported by the New Jersey Space Grant Consortium.

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