Multiobjective Optimization for Structural Design of Lunar Habitats

Valentina Sumini[1], Sam Wald[2], Caitlin Mueller[1], Claudio Chesi[3], Olivier L. de Weck[2]

[1]Digital Structures Research Group, Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA, U.S., email: vsumini@mit.edu; caitlinm@mit.edu
[2] Department of Aeronautics and Asronautics, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA, U.S., email: swald@mit.edu; deweck@mit.edu
[3]Department of Architecture, Built environment and Construction engineering, Politecnico di Milano, piazza Leonardo da Vinci, 32, 20133 Milano, Italy; email: claudio.chesi@polimi.it

ABSTRACT

Much like their Earth-based counterparts, the requirements of future space habitat structures can be defined by their ability to protect their occupants and provide usable space to live and work in an extreme, isolated environment. Due to the high cost of transporting resources off of Earth's surface, recent efforts focus on developing increasingly Earth-independent structural designs. These new designs use local regolith-based materials as a possible solution for long-term extraterrestrial sustainability. With a focus on an Earth-independent habitat, this research looks at architectures that use spherical regolith-based concrete shells with carbon fiber polymer reinforcement. The research approach is to formulate the structural design problem as a multi-objective optimization of the habitat shell. The objectives that apply to the shell geometry and cross section include the minimization of transportation and construction costs, and the minimization of the probability of loss due to radiation and micrometeorite events. Direct trade-offs arise. The multi-objective optimization applies Pareto optimization to determine which design elements or options afford the greatest effectiveness or efficiency. The authors examine candidate design solutions based on priorities and performance thresholds which indicate that ISRU-based reinforced concrete may be a valuable future investment. While the cases presented here are limited to lunar surface systems, both the general architectures and the methodology for analysis and design are applicable to future Mars settlements.

INTRODUCTION

Humans have relied on structures to house and protect them and their valuables for many thousands of years. These structures may be found in the local environment (e.g. caves), constructed from improved local materials (e.g. igloos), or made mobile and moved from place to place (e.g. yurts) [Horning 2009]. The design of these structures has been often driven by resource availability, transportation capacity, the need for mobility. This tradition continues and has been greatly expanded across many scales to include modern rammed-earth homes, integrated mobile-homes, and steel skyscrapers enabled by global supply chains [Easton 2007] [Wallis 1997] [Leslie 2010].

In the potential futures of the human species, it may prove desirable, or even necessary, to move beyond Earth to other bodies in the solar system. However, we will require protection from the harsh extraterrestrial environments. Much like their Earth-based counterparts, these future shelters will have requirements that can be defined by their ability to protect their occupants and provide usable space to live and work [Kennedy 2002]. Preliminary research have highlighted the high cost of transporting resources from Earth's surface. Therefore recent efforts have focused on developing Earth-independent structural designs that use local regolith-based materials as a possible solution for long-term extraterrestrial sustainability [Werkheiser 2015] [Mueller 2016]. With this in mind, we investigated the impact of material geometrical variables on reinforced concrete shells in five figures of merit in an effort to generalize the habitat design space. These shells are compared to a baseline aluminum shell case. By identifying the Pareto-optimal result for each it is possible to provide recommendations on final solutions for both typology and design details.

PRIOR STUDIES ON LUNAR HABITAT STRUCTURAL OPTIMIZATION

Pressurized, aluminum, dome-type habitat structure considerations were investigated in detail by Ruess, including geometric relationships between interior volume and enveloping exterior shell used in this research [Ruess 2006]. Benvenuti presented a habitat structural concept using a pressurized inflatable structure inside of a protective catenary shell using a specific lunar regolith-based material under development [Benvenuti 2013]. Tripathi has investigated optimal radiation shielding materials and thickness based on mission profiles [Tripathi 2001]. A multi-objective trade study of ten different, feasible, integrated construction approaches was performed by Bodiford resulting in a final ranking based on a composite function of thirty-five evaluation criteria [Bodiford 2006]. San Soucie has successfully used genetic algorithms applied to dome-type shells through multi-objective optimization using weighted sum method for thermal, radiation, structural integrity, micrometeorite, and structural up-mass [San Soucie 2007].

The research presented here builds upon these prior studies by applying multi-objective evaluation to the design of pressurized domed habitats constructed from regolith-based concrete reinforced with material from Earth. By considering the objectives of material volume, crew protection, and interior volume, the method provides transparency on the trade-offs between construction effort, technology development and implementation, and operations and human safety.

LUNAR HABITATS: CONCEPTS AND MATERIALS

Lunar Concrete for Habitats. The idea of Moon colonization originated long before the age of actual space exploration, as the Moon is the Earth's only natural satellite. Recent discoveries of considerable amounts of water close to the Lunar poles as well as the need to optimize space exploration by exploiting Moon bases [Schulze-Makuch 2008] and thus reducing the amount of fuel required for take-off (thanks to the fact that the Lunar gravity is far lower than the Earth's one) makes this opportunity more concrete and appealing [Ramachandran 2008 and Raval 2011]. However the establishment of a manned human colony on the Moon (or on Mars) will need some form of infrastructure to shelter the astronauts and scientific instrumentations from a very harsh environment.

Designing a structure for construction on the lunar surface includes several topics, such as: the relationships between severe lunar temperature cycles and structural and material fatigue (this problem is related to exposed structures); the structural sensitivity to temperature differentials between different sections of the same component; the very low-temperature effects and the possibility of brittle fractures; the out-gassing for exposed steels and other effects of high vacuum on steel, alloys, and advanced materials; the factors of safety; the reliability (and risk) which must be major components for lunar structures as they are for significant Earth structures; the dead loads/live loads under lunar gravity; the buckling, stiffening, bracing requirements for lunar structures, which will be internally pressurized; consideration of new failure modes such as those due to high-velocity micrometeorite impacts and the selection of a proper site for a lunar astronomical facility (for example, choosing a polar location would include the possibility to have half sky continuously visible). Many factors affecting system life cannot be predicted due to the nature of the lunar environment and the inability to realistically assess the system before it is built and utilized.

Moreover, due to the virtual absence of atmosphere and magnetic field, space radiation on the Moon is far higher than on Earth. In order to protect the inner core of the outpost from solar wind, solar flares and Galactic Cosmic Rays (GCR), a regolith shelter is considered the most meaningful solution.

In literature, several examples of lunar habitat with an outer layer in regolith for micrometeoroid and radiation shielding can be found. One the most interesting one was designed by Foster + Partners [Cesaretti 2014] [Benvenuti 2013] in which a combination of inflatable and regolith layer is considered. The overall shape of the inflatable should presents a continuous curvature to most effectively withstand the internal pressures while the outer layer of regolith has a catenary configuration in order to span the internal pressurized volume in a way that ensures that mostly compression forces act on the structure itself. Moreover, the overall structure of the outpost has been designed also by trying to minimize the amount of regolith to displace (that will be 3D printed in situ thanks to the D-Shape technology developed by Enrico Dini). Also the NASA Innovative Advanced Concepts Fellow, Neil Leach, is involved in a research project that aim to develop a robotic fabrication technology capable of printing structures on Moon and Mars using the lunar dust. One of the analyzed techniques is the Contour Crafting, that is a digitally controlled construction process, developed by Behrokh Khoshnevis, that fabricates components directly form computer models. The material used is a form of rapid-hardening cement that gains sufficient strength to be self-supporting almost immediately after extrusion. At the moment, also other 3D printing technology are taken into account from other private companies such as Made In Space and Redworks.

The importance of using local materials is due to the high transportation into space cost that could be up to US$ 2 million for a single brick to be shipped to the

Moon. Moreover, the idea of building a robotic fabricated habitat would reduce the risk of radiation exposure for construction workers.
Therefore, the present paper describes the outcome of an optimization study in order to explore the possibility to build structures on the Moon through In Situ Resources Utilization and comparing them with an aluminum solution that is the one used for the actual International Space Station.

Aluminum Shell. The case of the aluminum shell is analyzed as it represents the typical the system used for the walls of the International Space Station habitation modules.

Reinforced Concrete Shell. The reinforced concrete case considers a spherical dome structure in regolith as construction material. However, instead of having a inner inflatable structure totally separated from the concrete shell, as in the literature examples mentioned above, we are considering an inner bladder layer that is in contact with the concrete shell [Toutanji 2005] that, therefore, has to resist also to the internal pressure. Being the main load acting on the structure, reinforcement is required inside the concrete shell in order to resist tension stresses. The type of reinforcement considered in the analysis is made of carbon fiber reinforced polymers (CFRP). Moreover, the use of CFRP will increase the structural performance in case of micrometeorite impact. Figure 1 shows the aluminum shell and the reinforced concrete ones considered in the analysis.

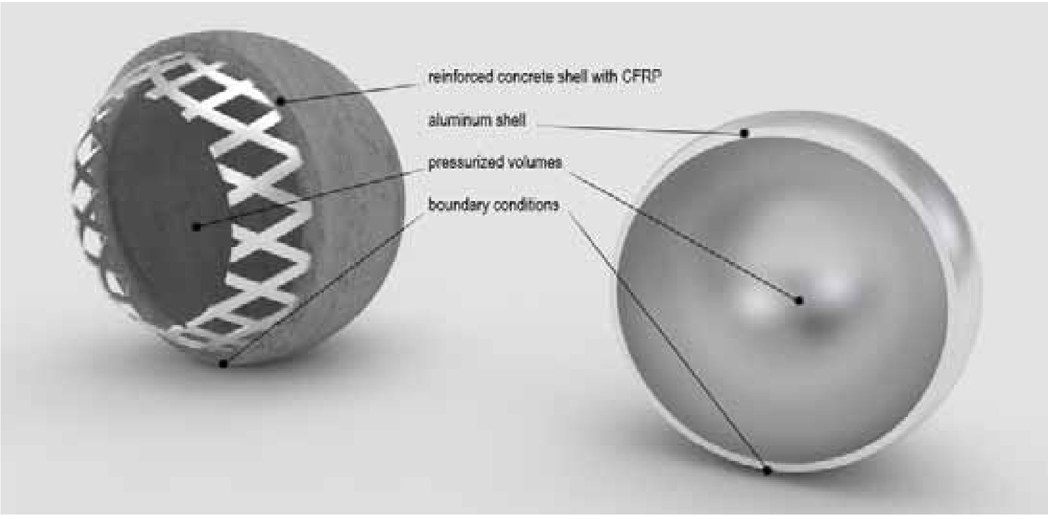

Figure 1. Spherical lunar habitat layouts considered in the analysis.

Material properties. This project aims to identify optimum structural shell geometries for habitat structures built on site with local material. To that end, the authors have limited the trade-space to represent likely materials that can be created with lunar regolith. While no structures of this type have ever been built in practice, much work has been accomplished in development of required technologies and testing with regolith simulants. These include cast regolith [Happel 1993], sintered regolith [Taylor 2005], lunar concrete [Cesaretti 2014] [Toutanji 2005, 2006] [Happel

1993]. An excellent and more comprehensive summary of technologies and techniques is available in Mueller (2016).
Based on potential materials of interest in the family of ceramics, the expected material strength for the regolith is assumed to be between 10 and 100 MPa with a density between 1000 to 3000 kg/m^3 based on prior work by Cesaretti and Happel [Cesaretti 2014] [Happel 1993]. A summary of all the material parameters is given in Table 1.

Table 1. Material properties

Property	*Units*	*Value*
Concrete density	Kg/m^3	2200
Concrete allowable stress	Pa	33.8* 10^6
Aluminum density	Kg/m^3	2700
Aluminum tensile allowable stress	Pa	280*10^6

METHODOLOGY

Primary Structure Generation and Evaluation Process. Each of the spherical geometries is defined by a set of three variables, which describe the interior radius of the sphere, the thickness of the shell tensile layer and the thickness of the concrete layer. A set of parameters defines fixed assumptions regarding material properties. The possible geometries are screened by a set of inequality constraints that ensure that the structural concept is feasible. The constraints considered here are geometry of the payload shroud during launch and the material stress due to atmospheric pressure.

The feasible geometries are evaluated on five objectives: internal pressured volume, material from Earth, material from the Moon, radiation protection provided, and meteoroid protection provided. Together, these objectives represent some of the most significant concerns for habitat structural designers at the early-phase concept development stage. Finally, the non-dominated solutions are filtered from the set, leaving only those solutions that are Pareto efficient. A solution $\boldsymbol{X}_k$ is defined as Pareto optimal if [Censor 1977]

$$J_k \leq J_l \; for \; all \; l \neq j, \quad and \; J_k < J_l \; for \; at \; least \; one \; point. \tag{1}$$

The benefit of identifying this set is to give decision makers options that cannot be improved in any dimension without sacrificing performance in another.

Design Variables. Below the list of the design variables considered in the analysis.

1. *Interior Radius X_1*

The interior radius of the spherical habitat primary structure defined in meters, defines the overall size of the habitat. It is measured from the center of the sphere to the internal wall of the primary structure.

2. *Tensile Layer Thickness X_2*

The tensile layer thickness is measured in cross-sectional area of the tensile material per linear length of the shell's circumference. For a shell with constant cross-section, such as in the baseline case, the thickness of that layer is equal to *X_2*. When the tensile layer is made up of discrete reinforcing members, *X_2* represents the effective thickness of those members if the material were distributed, or smeared, continuously across the shell cross section.

3. Concrete Layer Thickness X_3

The thickness of the concrete layer of the shell is represented with the third variable. This is the depth of the concrete measured from the interior to the exterior of the habitat. In the case when there may be reinforcement embedded within the concrete, this variable represents only the concrete material, with *X_2* accounting for the tensile members as defined above.

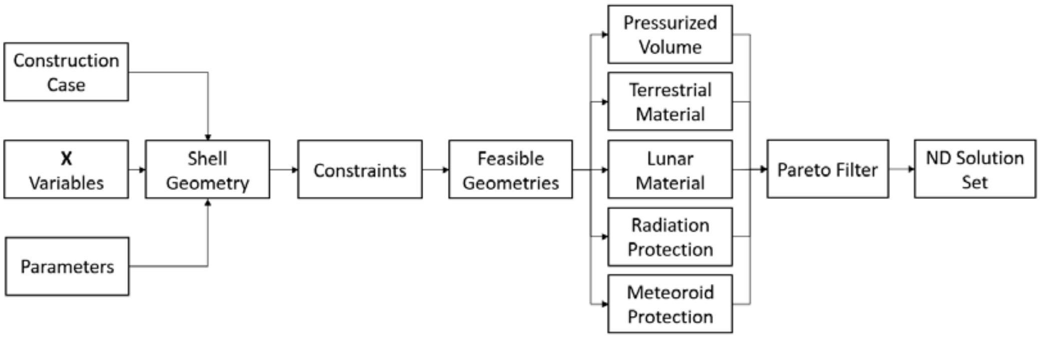

Figure 2. Block diagram of habitat structure multi-objective generation and evaluation process to identify Pareto optimal (non-dominated) solution set.

Objectives Used for Evaluation. The five primary objectives - material volume, radiation protection, impact protection, and interior layout – define a multi-objective vector, ***J***, and corresponding objective space in which habitat designers can locate and compare a population of designs.

1. Pressurized Volume

The pressurized volume provided by the primary structure is a valuable resource provided by the habitat. Hardware within this volume is protected from the harsh lunar environment and can be accessed by the crew. The volume also set limits on the number of crew, the mission duration, and the types of subsystems and research equipment that could be used. The objective is formulated to maximize this volume (or minimizing its negative) given the spherical geometry,

$$\text{Minimize:} \qquad J_1(X) = -V_{press} \tag{2}$$

where $V_{press} = \frac{4}{3}\pi X_1^3$

Due to the gravity at the lunar surface, the useful floor area is also an important metric for evaluating the habitat's ability to provide a useful environment for the crew to operate.

2. Terrestrial Material Mass

The mass brought from Earth is an important consideration for habitat design evaluation as it represents a significant cost for the mission in terms of 1) the development, testing, and fabrication of the system, and 2) the transportation infrastructure and propellant needed to deliver the mass out of Earth's gravity well to the Moon. The objective is formulated as,

(3)

Minimize: $J_2(X) = M_{terr}$

where $M_{terr} = V_{tens}\rho_{tens} + V_{EarthCem}\rho_{EarthCem}$
For the baseline case of an aluminum shell, there is no concrete and thus no cement required and the tensile volume is that of the primary shell.
For the reinforced concrete case, the material brought from Earth may include both the reinforcement tension members (carbon fiber reinforced polymers) as well as any inorganic addictive that cannot be produced on the lunar surface and is used to generate a concrete made of in-situ resources (regolith).

3. Lunar Material Mass

The lunar material mass includes the final processed material masses of both concrete aggregate and cement originating on the Moon. The mass is used as proxy measure of the costs and complexity of finding, collecting, processing these materials and constructing the structure in-situ.

(4)

Minimize: $J_3(X) = M_{lunar}$

where $M_{lunar} = V_{LunarAgg}\rho_{LunarAgg} + V_{LunarCem}\rho_{LunarCem}$
The material properties of aluminum shell, concrete, and reinforcement used in the analyses were presented in Table 1.

4. Impact Protection

Lunar surface habitats and crews must be protected from micrometeoroid hazards along a 'As Low As Reasonably Achievable' (ALARA) criterion. With regard to micrometeoroids, the goal is to afford a 0.993 "Probability of No Penetration" (PMP) over a 5 year period. The objective here is to find the maximum meteoroid mass that the structure could resist in both cases: aluminum and reinforced concrete.

(5)

Minimize: $J_4(X) = -M_{impact}$

where M_{impact} is the mass of meteoroid impacting the structure.
In the aluminum case, the mass of the impacting meteoroid impacting a solid aluminum has been derived by the Fish-Summers single-plate equation [Hayashida 1991]:

(6)

$$P = K m_p^{0.352} \rho_p^{0.167} (V_p \cos\beta)^{0.875}$$

where: P is the depth of penetration (cm), K a material-dependent constant, m_p the mass of the projectile, ρ_p the density of the projectile (0.5 g/cm^3), V_p the velocity of the projectile (20 km/s) and β the angle of impact (zero-degree angle).
The material constant can be defined through the following equation [Jex 1973]:

(7)

$$K = \frac{0.816}{\epsilon^{\frac{1}{18}}\sqrt{\rho_T}}$$

where ε represents the elongation and ρ_T the target density.
In the reinforced concrete case, one of the most common formulas used to predict various components of local impact effects of hard missile on reinforced concrete structure was modified Petry formula. It is the oldest of available empirical formulae, and developed originally in 1910 [Rahman 2010]. This equation was derived from the equation of motion that states that the component of drag-resisting force depends upon square of the impacted velocity, and the instantaneous resisting force is constant. According to Petry's equation (in S.I. units), the penetration depth x can be predicted as:

$$\frac{x}{d} = k\frac{M}{d^3}log_{10}\left(1 + \frac{V_0^2}{19.974}\right) \quad (8)$$

where M is the mass of the projectile, d its diameter and V_0 its velocity while k represents the penetrability coefficient and depends on the strength of the concrete and its degree of reinforcement. Its value varies from 0.000339 for normal reinforced cement concrete, to 0.000226 for special reinforced cement concrete, and 0.000636 for massive plain cement concrete.

However, even if this equation relates to reinforced concrete structures doesn't seem to represent properly the behavior of an r.c. structural element when impacted by a hyper-velocity object. As a consequence other model has been analyzed in order to better define the maximum impactor mass on the lunar habitat built with elements made from in situ materials. The adopted model is the one defined by [Evans 2006] where a hydrodynamic code was used to simulate impacts was validated against hypervelocity impact test results. The Smooth Particle Hydrodynamics impact simulation Code (SPHC) was used to examine penetration and fracture of walls following impact. The meteoroid dimension has been derived from the following equation:

$$D = 4.34\ d \quad (9)$$

where D is the crater depth in cm (the thickness of the reinforced concrete dome) and d is the particle diameter in cm, assuming meteoroid impacts with velocity 20 km/s and density 0.5 g/cc (stony meteoroids). The resulting particle diameter has been checked with the diagram representing the design curved for meteoroid assessments [Evans 2006]. However this model doesn't represent the presence of steel rebars embedded in the concrete.

5. *Radiation Protection*

The habitat structural material must shield the crew from radiation while they are on the lunar surface including radiation from SPEs and GCR, both posing a danger to the crew. The effect on the crew can be measured using the Radiation Dose Equivalent and compared to career dose limits for a one-year mission [NASA STD-3001 2015] [NASA HIDH 2010], Figure 3. The shielding effect based on material properties and geometry of the habitat was accomplished using dose equivalent values calculated by Cucinotta using the HZETRN/BRYNTRN codes at solar minimum (see Figure 3) [Cucinotta 2005]. The objective is formulated such that this value is minimized, thus minimizing the risk to the crew and can be used to identify opportunities for implementing an ALARA principle [Tripathi 2001]. The results given here only consider effects from GCR, but future work should also address SPE limits as well.

$$\text{Minimize:} \qquad J_6(X) = D_{rad} \tag{10}$$

where D_{rad} is found by using the equivalent shielding depth of shell layers and internal geometry.

Regolith and aluminum have similar responses to radiation [NASA HIDH 2010]. The analyses presented here assume that lunar concrete and the CFRP reinforcement also follows the same trends. In addition, it is assumed that the lunar surface completely blocks half of the solid angle of potential radiation to the crew. The internal geometry of the shell is also considered, with the dose equivalent through reinforced concrete as the solid-angle weighted sum of 1) cross sections with concrete only, and 2) cross sections with concrete and reinforcement. This is a function of both the amount of reinforcement and its spacing and provides a better estimate of the radiation effects than using an assumption of smeared tension layer.

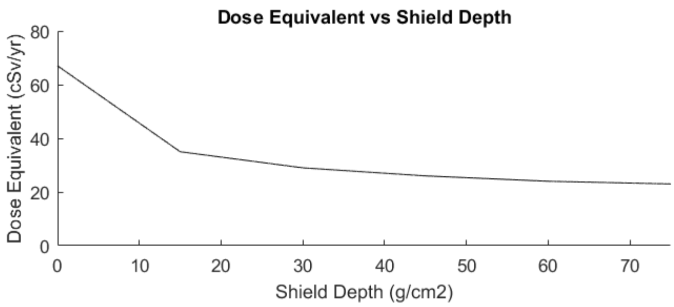

Figure 3. Annual dose equivalent in cSv/yr from GCR as a function of shielding depth for regolith and aluminum. Based on data from [Wilson 1997] with linear interpolation.

CONSTRAINTS

In the case of the reinforced concrete design, it is assumed that a nonstructural bladder provides airtightness, but that the tensile stresses due to pressurization are resisted by the CFRP reinforcement.

Tensile stresses. The tensile stress of the material used to contain the atmospheric pressure is used to constrain designs to those that are structurally feasible. The stress within a spherical shell under internal pressure loads can be found as:

$$\sigma = \frac{Pr}{2X_2} \tag{11}$$

where r is the radius of the sphere formed by the tension members and is a function of X_1 [Gill 2016]. A safety factor of 2 is used on top of the material yield strength.

Payload Volume. The maximum stowed diameter of a shell brought from Earth is also limited by the launch vehicle payload shroud of the SLS (10 m) [Boeing 2014]. This value may change significantly if one allows for alternative launch vehicles, or fabrication and deployment of the structure after launch (e.g. lunar concrete case, inflatables).

RESULTS

Using the variables, objectives, and constraints defined above, a range of feasible designs can be evaluated for a mission scenario. Figure 4 shows the objective values for a 180 day mission on the lunar surface with both the aluminum and reinforced concrete case. The variable ranges were restricted to:

$$X_1 = [2, 6]m, X_2 = [0.01, 0.1]m, X_3 = [0, 0.3]m. \quad (12)$$

In order to view the five dimensional objective space, the results are shown using parallel coordinates plots in Figure 4. This gives the relationship between each objective – represented along the horizontal axis – for each possible configuration – represented by an individual line. The colors are used to make it easier to read the trends in the results and corresond to habitat volume. The value of each objective has been normalized by its maximum value for each case, aluminum or concrete.
The results show some general trends which match with recommendations from the lunar concrete literature. For one, the maximum payload from Earth is reduced due to the increased strength and reduced density of the CFRP compared to aluminum for a give volume. Second, the increase in lunar mass required to build the concrete habitat greatly increases both the meteoroid and radiation protection over the aluminum case.

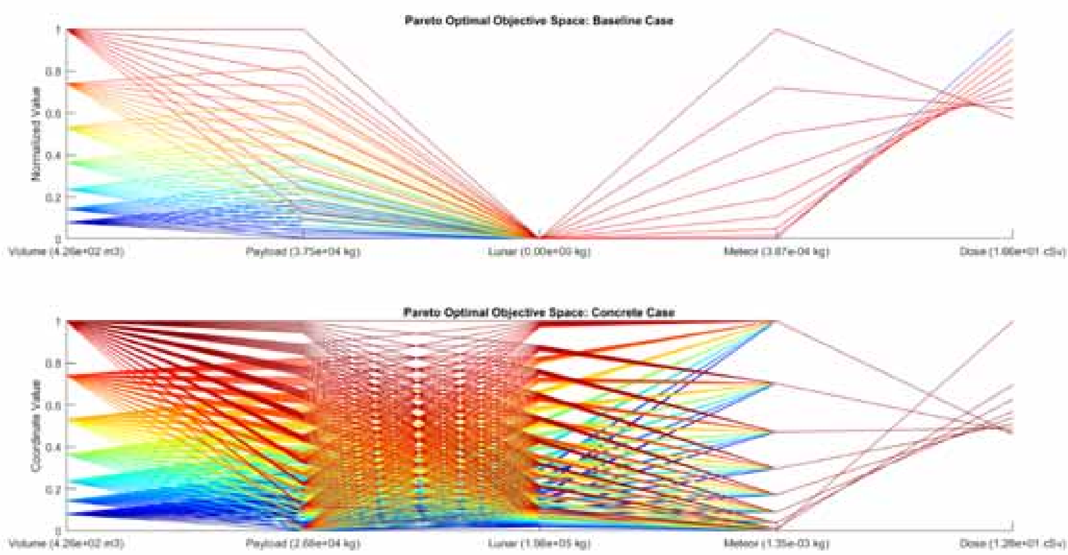

Figure 4. Pareto optimal objective space normalized by maximum value attained (value in parentheses). Variable ranges: x1=[2, 6], x2=[0.01, 0.1], x3=[0, 0.3].

The minimum dose from GCR in the aluminum habitat – around 7.5 cSv - is limited by the tensile thickness range, while the concrete case minimum is reduced from the concrete thickness up to 0.3 meters. However, due to the GCR penetration through the material, this value is only 5.8 cSv. A significant benefit of the reinforced concrete is seen in its ability to stop the penetration of meteoroids of masses with orders of magnitude greater than that possible with the aluminum shell for analyzed ranges.

DISCUSSION

Given all of this information, the decision maker must determine which configuration to choose if the habitat is to be refined and analyzed further. Looking at a subset of configurations, it will be possible to meet the performance requirements of the system.

Performance Goals. The pressurized volume required to enclose all of the necessary hardware, accommodations, logistics, and habitable volume for the crew to work and live. Lunar architectures for the Constellation program recommended 226 m^3 for 4 crew on the surface for 180 days [Kennedy 2010]. The maximum payload able to be delivered to the lunar surface should be considered. The Space Launch System under development was used with a low lunar orbit payload capacity of 12,000 kg [Boeing 2014]. The maximum payload mass to the surface was then determined under single stage propulsive decent stage. Under assumptions of delta-v (2 km/s) structure ratio (0.15), and specific impulse (320 s), the maximum possible payload to the surface is approximately 5,500 kg for a single launch and lander [Larson and Pranke 1999].

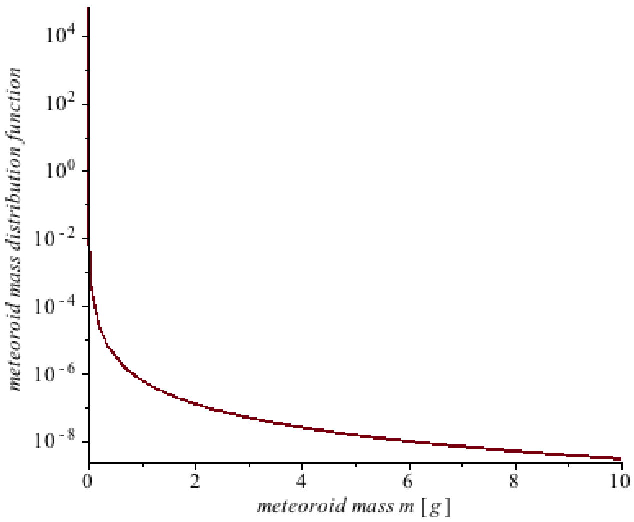

Figure5. Probability distribution function for micrometeoroid impactor mass for square meter and year. Based on the model discussed by Anderson et al. (1994) and used by San Soucie (2007).

The cost of processing of regolith into a given amount of concrete aggregate and cement was not examined in detail in this paper. The authors assume a goal of ten kilograms of concrete mass per kilogram of infrastructure on the surface annually based on other concepts for ISRU systems [Drake 2009]. Allowing one full lander to be dedicated to this infrastructure, a reference mass of 55,000 kg of concrete can be produced in-situ.

We can determine a level of protection based on meteoroid mass distribution presented by SanSoucie (2007) and Anderson et al. (1994). Assuming worst-case radius of ten meters and habitat lifetime of one year, there is only a 5% chance that a meteor of mass 0.0028 grams or greater will impact the habitat. Protection for this impact mass can be used as a minimum level.

The career effective dose limit for a one mission 95% confidence level limit for a 30-year-old female crew is approximately 0.124 Sv [NASA HIDH 2010]. This can be used to set an initial goal for the radiation shielding from the primary structure.

Figure 6 shows the Pareto optimal solutions normalized by all five of these performance goals. The final configurations satisfy each of the goals individually with different performances. Direct trade offs between each objective are required to choose a set of possible solutions in the early design phase of the habitat.

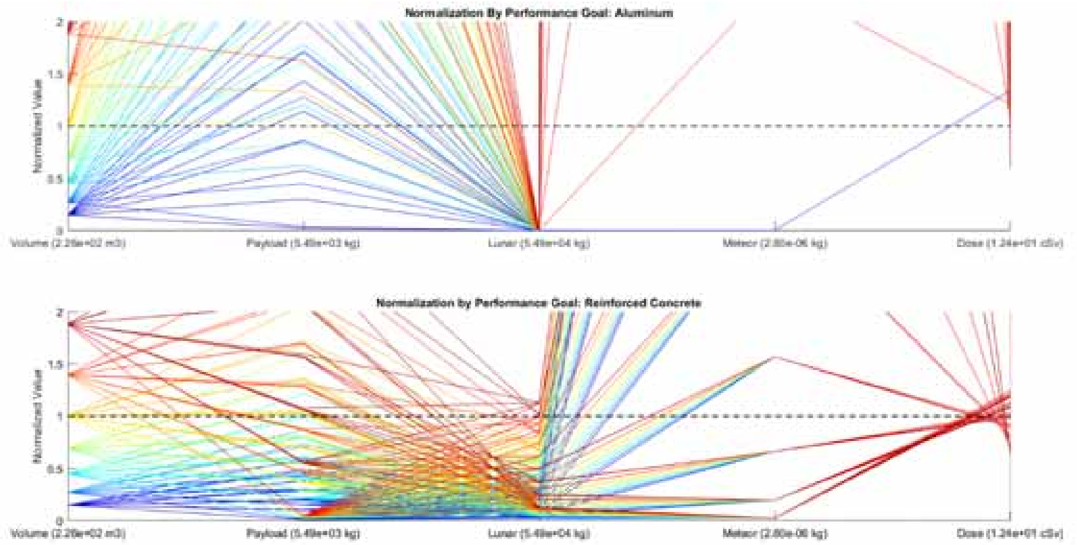

Figure 6. Pareto optimal solutions normalized by performance goals (J1=226 m3, J2=5,490 kg, J3=54,900 kg, J4 = 0.056 g, J5=124 cSv).

Possible Solutions. Based on these performance goals and an assumed mission scenario, a solution can be recommended. Figure 7 has screened for configurations, which could be brought to the surface in a single lander, brought from SLS by filtering for both Earth payload and lunar material mass. From these results, a reduced subset of configurations is still possible with direct trade offs between each objective. In the baseline aluminum shell case it is not possible to satisfy all of the objectives with a single configuration. However, in the concrete case the designer has options, which can satisfy all the goals.

Two possible options are highlighted below. The variable and objective values of each are given in Table 2.These results indicate that reinforced concrete should be investigated further as a construction material for lunar habitat structures. More importantly, it shows the benefits of providing multiple configurations to the decision maker. Depending on flexibility of trading requirements and costs of technology development, alternative configurations may also prove to be valuable.

Table 2. Possible habitat configurations with design variables and objectives for aluminum and concrete typologies.

	Aluminum	*Concrete*	
Radius	4.22	4.67	m
Tensile Thickness	0.009	0.012	m
Regolith Thickness	0	0.059	m
Volume	316	426	m^3
Payload	5435	3059	kg
Concrete	0	36283	kg
Meteoroid	2.94e-6	1.04e-5	kg
Dose	15.3	9.7	cSv

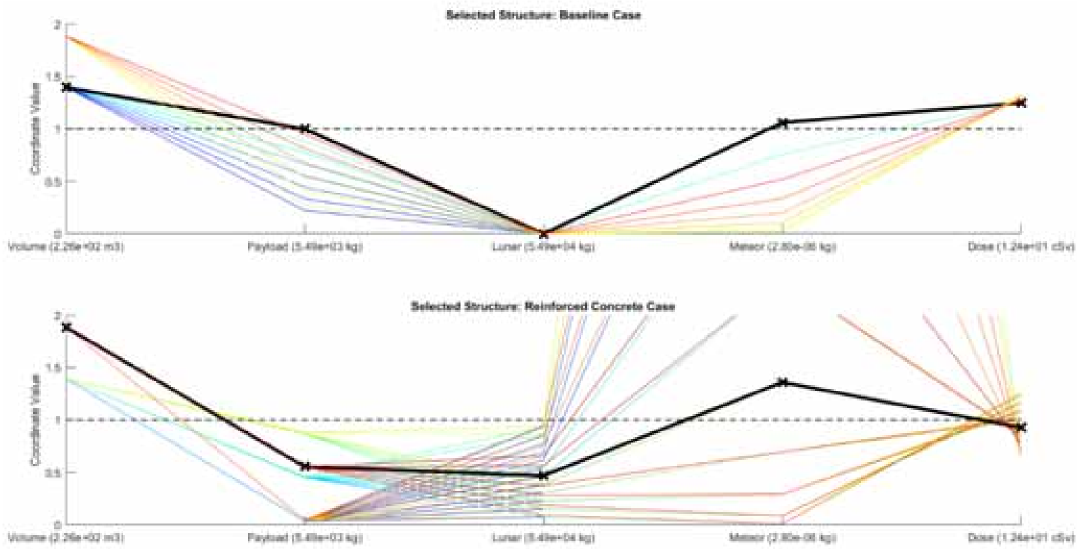

Figure 7. Highlighted options from Pareto optimal solutions. Normalized by performance goals (J1=226 m3, J2=5,490 kg, J3=54,900 kg, J4 = 0.056 g, J5=124 cSv).

LIMITATIONS AND FUTURE WORK

The results presented are useful in both understanding the trends in the multi-objective trade-space of a habitat primary structural shell. However, the analyses used have been simplified in a number of areas and can be improved upon in future iterations.

- Sensitivities to Parameters – the authors will investigate the sensitivities of optimal solutions on parameters including atmospheric pressure, material properties, and reinforcement geometry.
- Increased Fidelity of Objectives – the quantification of objectives, particularly those of meteoroid and radiation protection can be greatly improved by incorporating radiation transport codes directly, capture effects of SPEs, calculate bending moments on the shell, and include options for Whipple bumpers and dedicated water or polymer shields.
- Shell Geometry – co-optimizing the structure geometry beyond a sphere will help to expand the trade-space to include pressure shells which provide additional surface area and are better suited to unique layouts as well as exterior interfaces.
- Implementation of in-situ construction – in order to better evaluate reinforced concrete as an option for construction it is necessary to understand the costs in additional infrastructure and time needed to process the lunar regolith mass.
- Visualization of Design Space – alternative visualization of the possible configurations will help decision makers to understand

These modifications will greatly improve the confidence in recommendations for technology development that can be made as a product of these results and will be a focus of near-term work.

CONCLUSION

Space habitat structures must serve multiple functions to enable safe and successful missions. Pareto optimization allows decision makers to understand the trade-offs between the performances of these functions and to make more informed decisions without having to apply a priority weighting to them. By looking at how the example results presented here indicate that reinforced concrete could be a valuable material to investigate further. Future work will improve on the quantification of habitat performance and costs and the presentation of results for habitat concept development.

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