

Bringing it Home: Finding Synergies Between Earth and Space Construction and Design

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The highly specific environmental and design constraints of occupied space habitats has often isolated the efforts of systems designers to aerospace applications, leaving traditional terrestrial architects also isolated from the technological developments available in the space industry. Yet recent efforts to consider surface habitation on the Moon and Mars, as well as efforts in the Earth construction community to push for smart, sustainable, and autonomous habitats have emphasized the natural overlaps between design and construction in all built environment applications regardless of location. The same sustainable development objectives of creating safer, healthier, and more circular economies in the built environment on Earth are shared with the development of safe, healthy, and closed loop habitation systems for space. However, while there is widespread belief in these potential values, and demonstration of spin-off technologies subsequent to space applications development, the ability for space and earth systems to be co-developed simultaneously in practice is examined. This paper describes the process of creating value across multiple stakeholders in the space and earth construction and design industries. By understanding the overlaps between the language and ontologies used by the earth sector to define project objectives with those used to describe space design requirements, a series of venn diagram exercises allowed stakeholders to reveal synergies in Construction Means and Methods, Material Innovation, Human Centered Design, and Sustainable Design Strategies. Many of these overlaps are at the surface intuitive, but the formal identification of these shared values and perhaps more critically, their limitations in practice, provides insight on the potential opportunities and challenges for co-development activities across previously isolated design sectors.

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Nomenclature

<i>AEC</i>	=	Architecture, Engineering, and Construction
<i>AM</i>	=	Additive Manufacturing
<i>ECLSS</i>	=	Environmental Control and Life Support Systems
<i>ISHM</i>	=	Intelligent Structural Health Management
<i>ISRU</i>	=	In-Situ Resource Utilization
<i>LaRC</i>	=	Langley Research Center
<i>MSFC</i>	=	Marshall Space Flight Center
<i>M2M</i>	=	Moon 2 Mars
<i>MMPACT</i>	=	Moon to Mars Planetary Autonomous Construction Technologies
<i>OPC</i>	=	Ordinary Portland Cement
<i>SDG</i>	=	Sustainable Development Goals

I. Introduction

A. Current Plans for Human Habitation/Infrastructure

With renewed interest in long-term Mars and Moon planetary surface missions, including more permanent habitation on the Moon and the long duration required for manned Mars mission, the design and technological development required for delivering surface habitat systems is becoming more tangible. NASA is seeking to deploy infrastructure and technologies for a permanent lunar base by 2028, ESA's intended goals for a "Moon Village," among others, there is a clear mandate for sustainable, energy efficient, and potentially locally constructed surface systems which sustain and support human life.

B. Motivations for Linking Space and Earth Design and Construction

At the same moment that we are expanding our human presence in space, the UN forecasts that by 2050 two thirds of humanity's population will live in urban settings (UN 2019). This often implies a disconnect in values, of where development resources should be expended. However, the development of systems necessary for space habitation are happening in parallel with the need for sustainable development on Earth: from smart homes, to net zero operations, from design for dense occupancies to the need for local water, air, and material recycling.

These sectors of human habitat design and development have historically been isolated due to many factors including potentially (1) the siloed disciplines of aerospace engineering and as entirely distinct from traditional architecture and design education, which itself is siloed from other engineering disciplines within the Architecture Engineering and Construction (AEC) industry on Earth, (2) the nature of the space environment in which the structural, mechanical, and material methods required to respond to extreme thermal and pressure conditions and transportation requirements dominate over considerations of human centered design (3) the time, cost, stakeholder network, and length of development of a space mission as compared to any particular building design on Earth, and (4) the perception in engineering culture of architectural design process as largely aesthetic rather than its closer analogy to systems engineering in practice which includes human comfort as a significant, though one of many, drivers of design decisions.

These differences suggest a chasm of difficulty when trying to come together on shared habitation systems development. And yet we might be able to imagine some essential shared goals: a space habitat must operate locally without extended infrastructure, without abundant energy and material resources, and without global supply chains. Physical space is also a scarcity, and the volume of human habitats are small and commensurate with the scale for living space available in increasingly dense urban cities. We may say that in fact, *any experience in creating and demonstrating a place that operates within limited means and resources at scale will have immense promise to return knowledge and provide feedback for earth construction that must also begin to act as though materials, energy, and resources were limited.*

Simultaneously it must be said that the practice of design and construction of Earth has continued with embedded knowledge of successful and less successful human habitats through example through several centuries, and the social, psychological, and physiological principles of creating spaces designed for human life that also react through material and form to the means and methods of production and local environmental principles. This form of knowledge and historic legacy of architecture has a great deal to offer an industry which is, in comparison, relatively novice in terms of its experience with human occupied spaces. (The combined knowledge of the historic legacy of

Earth based Architecture designing for human health and well-being, with the knowledge of the requirements of space habitation exists within the domain of those who might be considered “Space Architects.”)

These common motivations provides a backbone or guiding principle to demonstrate the potential for shared co-development of systems essential to sustainable practice and innovation across the Space and Earth design and construction sectors, and is the jumping off point for an investigation into developing a process for project definition that could potentially find synergistic opportunities for project teams to work on technologies with applications for both Earth and Space.

Furthermore, the degree to which projects for Space and Earth can be genuinely developed simultaneously represents increased interest in funding and development which can serve multiple benefits, compounding the value of each sector. The more a single development effort can have impact for both the advancement of space exploration and sustainable Earth applications simultaneously, the more both sectors can benefit from that investment. The necessity for space innovation to provide important benefits for national interests (largely from the application of NASA held patents) had been established since the 1958 National Aeronautics and Space Act (Public Law Number 85-568). The extent to which the larger principle of *space-earth reciprocity* can be applied in practice simultaneously was the subject of this investigation.

C. The Role of Technology Specification in Project Definition

Project delivery at NASA follows a long series of mission requirements from science or mission goals and objectives, through top level requirements, down to systems definition. In order to truly operate for multiple simultaneous stakeholders, Earth-based requirements and definitions and goals must enter in at the earliest stages of project definition. And yet, when writing mission goals and objectives, and level 1 requirements, the specificities of any particular technological solution are secondary, if not entirely derivative of those first level requirements.

Project definition on Earth follows similar methods in practice to a series of ever more specific project requirements. To a large extent in building projects, requirements are largely *performative*, that meaning as long as the final system meets certain performance expectations of the stakeholders, whether that be any particular legal code or guideline, programmatic requirement, or environmental performance metric, the final results was agnostic to the means by which the project was achieved. In practice however, most terrestrial building projects engage a sense of material and construction means based on context and readily available (and affordable) resources. Space projects have far less context or immediate means and more often look towards what must be invented in order to achieve those means.

However, in a context in which a particular technology has already been identified for potentially different goals as a top level requirement independently by both the Earth and Space stakeholders, the definition of the technology, whether that be construction means and methods or material requirements shift towards earlier phases of the design process and becomes part of a more complex and interrelated set of requirements bridging multiple stakeholders.

D. Towards Co-Development Approaches: A Tool for Project Definition and Evaluation

a. Historic Role of Technology Transfer

Many of the technologies that are part of the “sustainable” architecture movement are part of a long history of *knowledge transfer* from space innovation from aeroponics to clean water processing, from the development of LEDs and Solar Energy, to urban agriculture (Wheeler, 1997) and plant-based biotechnology (Wolverton, 1989). Historically, research dollars were used to develop products, systems, and intellectual property internally at NASA which had some relevance for space exploration, and subsequently offered up to the public for further development. Since its founding, national leaders in the US have historically linked advances achieved within NASA as having benefit to the nation (Comstock and Lockney 2007). As the agency moved towards more contracting type roles, where technology is developed outside of the agency, having both earth and space applications makes outside innovation more achievable. Examples of this can be recently seen in the NASA Centennial Challenges program which seeks to “directly engage the public in the process of advanced technology development...to generate revolutionary solutions to problems of interest to NASA and the nation.” As technology development may happen more rapidly in the public sector, with NASA capitalizing on technology developed elsewhere and not in house, we are seeking to move past a model of technology transfer whether “spin out” from aerospace or “spin-in” from the public sector, towards a model of simultaneous co-development of applicable technologies.

b. Application of “Design Thinking” and Whole Systems Approaches

SEArch+ developed an approach to bring together actors across space and earth construction sectors to derive compatible project goals. An interactive and iterative consensus building process was used to attempt to

bridge interdisciplinary ontological frameworks to come to common synergistic goals. The process required an expansion of stakeholder's usual methods to include multiple aspects of a building project as a larger system in multiple contexts. Initial expansion of scope to whole systems thinking was applied to find the interdependencies between multiple potential aspects of design and construction research.

E. Context of the work

a. MMPACT

NASA has committed to developing in-situ resource utilization (ISRU) additive manufacturing (3D-printing) capabilities in concert with other technologies for the delivery of lunar systems. This work was undertaken by SEArch+ in collaboration with NASA's Marshall Space Flight Center (MSFC) in the early stages of project definition for the Moon to Mars Planetary Autonomous Construction Technologies (MMPACT) program which has a mandate to develop, deliver, and demonstrate capabilities to use regolith-based materials for lunar surface infrastructure including landing pads, unpressurized and pressurized radiation shelters, roadways, berms, and blast shields.

Within this context, the technological method and the development of a certain technology became one of the driving goals, and so rather than a design being driven by environment and human factors and guided by available technology in concert, the requirement to develop ISRU AM capabilities as the method of construction was prioritized over other potential solutions for habitation.

b. Specific Instance: Habitat Class III and Additive Manufacturing Methods

Historical habitat design concepts (including the Apollo landers) have traditionally been of the fully-assembled-and-outfitted on earth and launched to the Moon or Mars variety. This type of habitat was later defined by Kennedy in 2002 as a Class I habitat. In this context, a Class II habitat is a prefabricated habitat, which is space or surface deployed with some assembly or setup required. Class III is an in-situ derived habitat in which its structure is manufactured using local resources available on the Moon or Mars. Current long-term plans for lunar habitation include a time-phased deployment of Class I, II and III habitats. The Human Lander System is a current representation of a Class I habitat, while LaRC-developed Lunar Safe Haven concepts (Wong et al, 2022) are representative of Class II and ISRU-based concepts being developed by the MSFC-led MMPACT project are representative of Class III habitats. As such, while there might be multiple avenues to explore overlaps between architectural design for earth and space, this effort focused on the specific project instance of Additive Manufacturing (AM) construction methods and approaches.

II. Conceptual Framework

A. Interdependent Relationships: Design Drives Technology, Technology Drives Design

We start from the perspective of design as an ecosystem of available and emergent technology, human requirements, and material availability and potential. This interconnected and interdependent web of design drivers ultimately influence formal and material solutions represented in a physical design. Rather than accepting a certain level of technology development and working within a predefined system for example, the design drivers of the building which may include environmental loading, human factors, as well as energetic and environmental systems or conveyance concerns may push back on and influence the design and capabilities of the technology. For instance, AM hardware mobility systems include robotic arms, gantry systems, or suggested swarm robotic construction. The choice between and development of any one of these systems is an iterative design process between the technology readiness and timeline of project development, and the requirements of a whole systems concept design.

The Architect, Designer, or Systems Engineer is charged with integration of not only existing but forward thinking construction systems, the materials and methods but, the delivery of an entire integrated environment, for the health, wellbeing, and performance of its occupants and the public, the efficiency of its energy, and the economy of resources, use, and construction feasibility of the owners and builders. Design feedback is required to (a) evaluate a human habitation system on multiple metrics of performance required to deliver a whole building project, and (b) provide insight and push-back on the construction materials and methods necessary to create a whole environment.

When defining the project level requirements and scope the extent to which any particular design driver dominates the priorities of the stakeholders will drive the ultimate habitat solution. When a specific technology or other material or physical system co-development between space and earth stakeholders is a priority, it offers constraints for the formal and material resolution of the habitat system. When there is an opportunity to reflect and design based on human factors, environmental or materials inputs and the use of a specific material, equipment type,

or system is more flexible, additional opportunities present themselves. With a healthy balance between specific technology or material investment and multiple other mission, environmental, and human factors requirements, we have greater potential for innovative solutions.

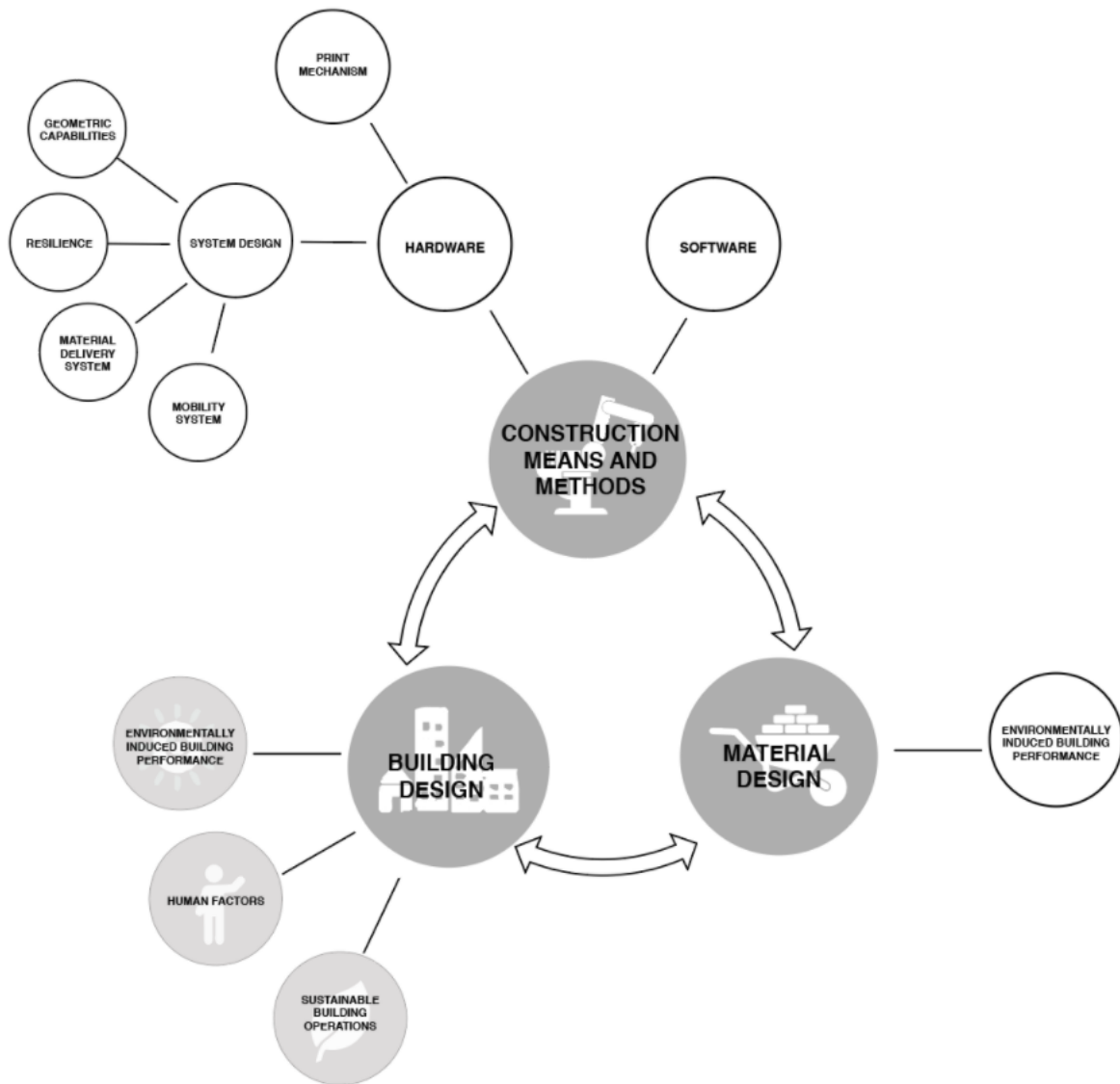


Figure 1. Initial first level representation of interconnected web of potential design drivers in a habitat project, where construction technology and material goals are seen as part of synergistic technology co-development opportunities on par with building design requirements which react to environmental loading, human factors, and energy and environmental systems.

B. Emergent Classifications for Space/Earth Habitat Systems

Within the context of whole building systems design, the SEArch+ team identified an initial potential classification system for *interdependent* categories of built-environment research which might be shared across aerospace and AEC industry. These categories served as the initial ontology for resolving common interests, and were iteratively adapted as the priorities of the individual project instance progressed, but can still be identified as baseline points of departure for a space/earth habitation project.

- a. **Construction Means and Methods** - We take this category to include “the means and methods, sequences, techniques, and procedures of construction, as well as any associated safety precautions and programs, and

all incidental or temporary devices required to construct the project” (Hatem et al 1998). Though typical project development may as we suggested earlier, be agnostic to the means of achieving a particular performance, in a context in which a particular technology development is a top level requirement as identified by both the Earth and Space stakeholder, reasonable attempts were made to break down the particular *performance requirements of the hardware and software of the machinery and devices* that could be overlapping.

- b. **Material Innovation** - In many ways material innovation is an extension of means and methods in that certain environmental, structural, or human factors requirements are specified and achieved by whatever potential material solution. In the context of building innovation, new materials driven by design or environmental necessity, have in turn revolutionized the formal and technical possibilities of building processes. For space, material innovation is also born of necessity and so has great implications for the design of a building or other structure. While in earth and space sectors *low energy, local, potentially circular material processes* are clearly preferred, the local material of choice is quite different.
- c. **Sustainable Operations** - The term “sustainable” is contested. In terms of sustainable development on Earth, more often than not the term sustainable is linked to the idea of designing a structure that *uses materials and energy capable of being renewed*, similar perhaps to the United Nations (UN) definition of sustainable development as that which meets the needs of the present without compromising future needs. In terms of aerospace architecture, it can refer to *the ability for a structure or system to be maintained with as little additional material or energetic input as possible*. For some this concept is entirely related to structural maintainability. For others this implies the suggestion of the formal and material properties of the building and their bearing on the energy and material uses of resources in the operations phase, that is the potential for passive strategies. Being precisely specific with each stakeholders definition led ultimately to multiple interpretations and goals.
- d. **Human Factors** - Human factors is an umbrella term that has quite a number of applications in the NASA context from ergonomics, to environmental health, to human-computer interaction. In terrestrial architectural circles we might come to define this as *functional and scalar relationships of spaces*, where functional can mean both productive as well as physiologically or psychologically beneficial. This might also encompass the whole of what would be considered in the AEC industry as Indoor Environmental Quality and *any other impacts of the material, formal, or spatial properties of a building in terms of human health, comfort, and wellbeing either individually or socially*.

III. Methodology

The process of moving from the first order goal of *designing and demonstrating a human habitat that operates within limited means and resources at scale for both Earth and Space applications* followed an iterative process of ontological alignment and definition from a larger perspective, towards more specific comparative and interdependent requirements to create the scope and definition of the project itself.

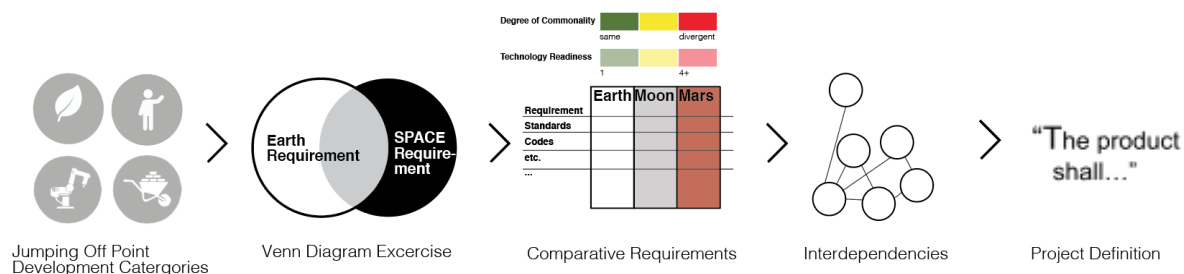


Figure 2. Overview of methodology towards developing project definitions involving multiple planetary stakeholders.

A. Venn Diagram Exercise

As a first order exercise, the four previously mentioned categories of comparative sectors of earth and space habitat construction were presented to both Earth-based and Space-based stakeholders, with suggested and potential areas of interest that represented both concerns of common or similar requirements, as well as areas of significant divergence. As an example, while both Earth and Space stakeholders were interested in autonomous operations and remote command, the operating environment requirements of that equipment are completely different. A visual venn diagram was a simple design tool through to understand relatively quickly where we saw synergistic opportunities. Some divergent conditions were less significant, for example the degree of collapsibility or mass of the equipment, in which case the more restrictive requirement took priority. Through a multi-round process, a refinement of ontological categories and definition of terms emerged and shifted towards common ground.

B. Comparative Requirements Matrix

Selected categories and terms were isolated and a comparative requirement chart was created for planetary habitats which compared Earth requirements, alongside Space requirements for both the Moon and Mars. Requirements were subsequently categorized as per Figure 1: (1) *Construction Means and Methods*: (1a) Hardware and (1b) Software design requirements, (2) *Material Design*, and (3) *Building Design* which included (3a) Human Factors, (3b) Environmentally Induced Building Performance, and (3c) Sustainable Operations. Earth based standards were applied where relevant, ie. ASCE standards or International Building Code. Space standards have been considered where relevant but largely were being defined as the project emerged. A scale was applied to the “potential for overlap,” with 1 being high overlap and 3 low overlap, and a “technology readiness level” also on a scale from 1-3, with 1 being currently available and 3 being years away in development. The direct comparison of not only numeric requirements or standards led to an “overlap” score. Agreement between readiness and overlap in terms of aspects of the design research that were both ready or nearly ready with high degree of overlap pointed to the specific areas for potential simultaneous development. See Appendix for Comparative Requirement matrixes.

C. Interdependencies

In considering the breadth of applicable mission requirements the interdependencies between various requirements became clear and were subsequently subdivided. Mission requirements typically reflect the specifics of a given mission. However, when that mission is part of a series of demonstration and qualification missions to enable a long term capability, it is important to think of requirements as part of an evolutionary process. In many cases, hardware or software can be “scored” to support future integration of functionalities, including the addition of new interdependencies as a function of time. Figure 3 shows an example of this evolutionary process of increased interdependencies for Demonstration Missions (DM-1 and 2) and Qualification Missions (QM-1 & 2).

The scope of the MMPACT project and its interdependencies is broad and spans the capabilities of a number of NASA Centers and commercial entities. These interdependencies include (but are not limited to) those shown in Figure 3. As mission goals and objectives were defined, the relevant interdependencies were identified and conversations were initiated with internal NASA and external entities to ensure that all interdependencies were addressed and funded sufficiently.

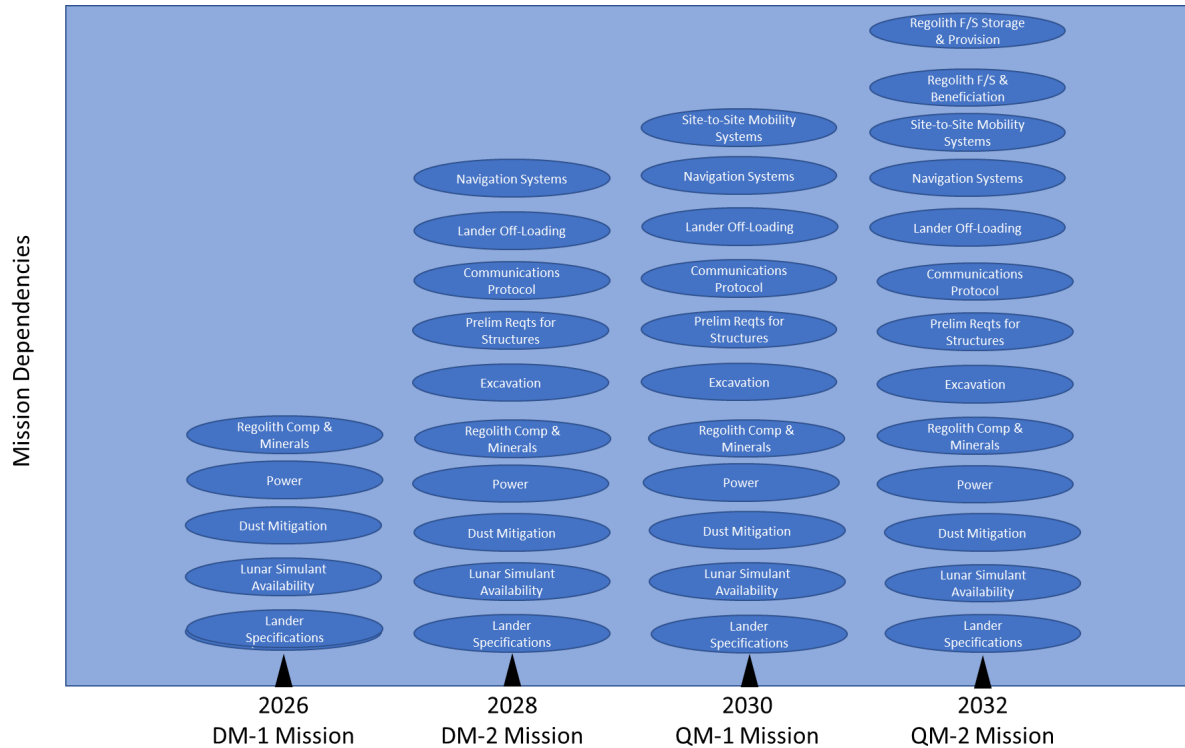


Figure 3. MMPACT project interdependencies as a function of demonstration and qualification missions

D. Definition of Project Scope and Project Selection

The objective of this process was to identify and support the definition of the scope of projects relevant for both Earth and Space design and construction. Sorting common research areas and objectives further by dependencies helped define the scope and sequence of the project, and helped identify necessary collaborations.

As an example, in any construction, the first step is site planning and excavation. This is the case on both Earth and planetary bodies. In the MMPACT case, the excavation on the DM-1 mission will be performed by the same robotic arm used to process the regolith to effect construction. On the DM-2 mission, a mobility system will be placed on the surface to perform the construction process. In addition, as the lead Center for Excavation within NASA, a KSC-developed site prep capability will have been pre-positioned or as part of the DM-2 mission as well, will be deployed. This excavator will be responsible for the required site preparation prior to construction. Understanding the importance of this interdependency, KSC was contacted and funded to begin development of this capability in support of the MMPACT project.

IV. Results

The results of this process represent a first exercise in attempting to define areas of overlapping research interests in building design and construction, revealing both ambition to co-develop synergistic opportunities as well as fundamental challenges in aligning performance requirements. For a full image of venn diagram outcomes and a thorough listing of preliminary comparative performance drivers, see the Appendix.

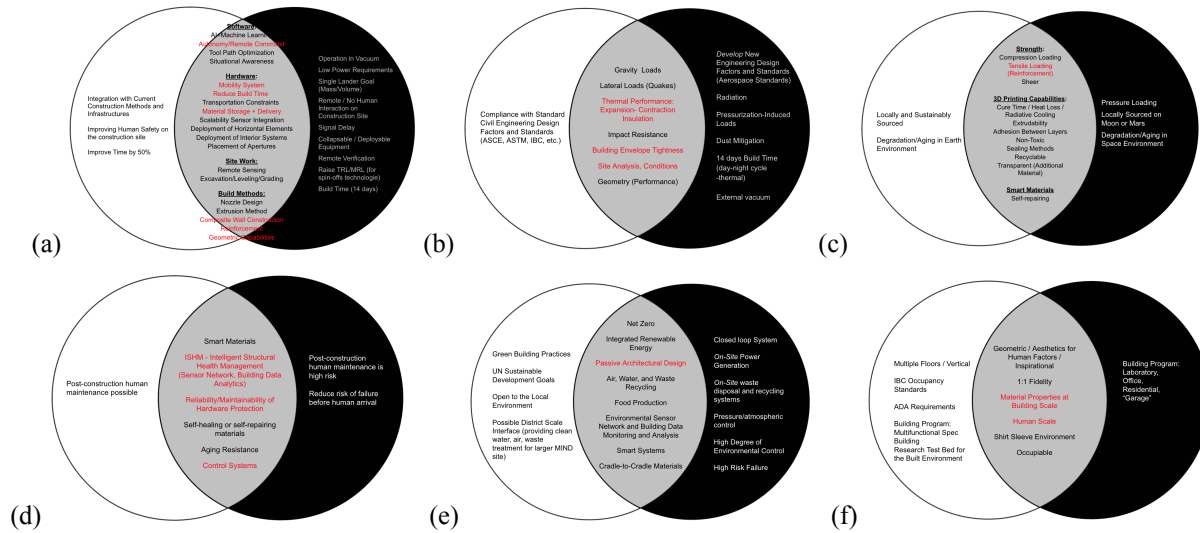


Figure 4. **Overview: Venn Diagrams** (see appendix for detailed view of each area) (a) Construction Means and Methods: Technology Drivers (b) Construction Means and Methods: Environmentally Induced Building Performance (c) Material Design (d) Sustainable Operations: Structural Sustainability (e) Sustainable Operations: Sustainable Resource Management in the Operations Phase (f) Human Factors

A. Construction Means and Methods: Technology Drivers

a. **Definition:** *Operational Requirements and Limitations of the Construction Equipment and Conveyance Factors*

b. Relevant Co-Development Opportunities in AM Habitat Design

Following the top level requirements of the MMPACT project team, additive manufacturing and in particular autonomous construction techniques were identified by both sectors for perhaps different reasons: Earth stakeholders being particularly concerned with speed of construction and safety, while Space stakeholders being concerned largely with autonomous methods.

i. Hardware:

1. **Mobility Systems:** From the Venn Diagram exercise, common interests were extensive however, particular interest was paid to the mobility system which moves the deposition equipment. Venn Diagram results were followed up on with an overall “overlap” and “readiness” level of 1 in the Comparative Requirements charts. With discretion towards pre-existing Earth methods which have been developed in the particular context of earth construction, a gantry system was selected as a starting point for further development. Even though one might imagine smaller robotic equipment or alternate building methods might be favorable in a stand-alone space context, in this case given the weight of investment necessary and the technology readiness level of existing equipment, shifting mission design and scope towards pre-existing Earth based systems was selected. Though this was an initial starting point, further space requirements guided the development of the technology. For example, deployability and scalability for the space context was a necessary adaptation. This was a clear instance in which Earth interests shifted what might have been developed quite differently in the confines of a space-only mission, however resulted in mutually beneficial outcomes.

2. *Multi-material/Composite Wall Printing Capabilities* was also of common interest for development on both sides, including the potential printing of integrated reinforcement, however the initial material choice was divergent (see results on material innovation)
 3. *Geometric Capabilities*. Both Earth and Space sectors were potentially interested in expanding the height and width capacity of the chosen printing method, however Earth side stakeholders were not as interested in the ability for the horizontal printing of floors, domes, or roof systems, typically using alternative means to incorporate these elements, shifting the focus of the work towards initial demonstrations which would not to incorporate horizontal surfaces.
 4. *Whole Building Systems Integration*. A fundamental difference in the application of additive construction on Earth as opposed to the moon is that on the moon, a habitat must be sealed and must withstand a pressure differential due to internal close-to-atmospheric pressure inside the habitat and what is essentially a hard vacuum external to the habitat. While both sectors were interested in the autonomous integration of other building components, the integration of prefabricated horizontal elements was more critical from the perspective of Earth development, while the ability to integrate and seal windows and doors autonomously was more important from the perspective of the space habitat. Still, the need for systems to have real time sensing and feedback and level of situational awareness was a common concern.
- ii. **Software:**
1. *Remote Mission Control*. The distance of both the Moon and Mars from Earth results in a latency in all communication to and from Earth. Although on a different scale, such latencies also exist between long-distance locations on Earth itself. This poses potential issues on the Moon during operations that are remotely controlled from Earth. Many large-scale construction operations on Earth are now controlled remotely (Takai et al 2020). In addition, an MMPACT partner has demonstrated remote control of additive construction activities from significantly remote locations as well. This precedent will prove useful as we contemplate Earth-controlled lunar additive construction
 2. *Digital Twin*. The ability for real-time sensing during construction and the simultaneous creation of a “digital twin” was identified as a critical tool for monitoring and maintaining high risk space habitats, and is an emerging tool to control the operations and maintenance phase of a building (Lu et al, 2020).

B. Construction Means and Methods: Environmentally Induced Building Performance

- a. **Definition:** *Functional requirements of the structure and equipment in response to the surrounding environment including structural and thermal performance relative to creating a stable and habitable interior environment*
- b. **Relevant Co-Development Opportunities in AM Habitat Design**
 - i. *Hardware Operations Requirements* in terms of working in vacuum conditions and under extreme temperature loading represented divergent interests and placed additional requirements on the Earth development side to meet these requirements.
 - ii. *Hardware Resilience* especially towards environmental concerns such as projectile shielding, dust mitigation, etc was less critical to Earth side stakeholders and not considered in early stages of codevelopment. It remains unclear how these considerations may retroactively alter hardware development in future applications.

C. Material Innovation

- a. **Definition:** *Required material properties in terms of structural, thermal, and environmental loading, and lifecycle considerations including: sourcing, complexity and energy of manufacturing, production and reuse*

- b. **Relevant Co-Development Opportunities in AM Habitat Design**

On Earth, Ordinary Portland Cement (OPC) is commonly used as a binder for concrete. However, the production of OPC requires high-temperature calcining and an equivalently high power and carbon footprint to manufacture. Despite the strong demand of concrete processes in Earth construction, even in light of questions of sustainable practice, the cost of delivering raw materials and binders from Earth to the lunar surface is exorbitant, so the use of in-situ-based materials is required (Fiske et al 2018). The requirements of materials that are also sealed (non-porous) and able to structurally withstand the potential force of interior pressure, puts a number of burdens on the material system that are not necessary in Earth construction.

While there is ambition for a synergistic cementitious process, perhaps due to the strictness of material requirements for lunar or martian construction, this area of building research diverged for the time being with those in the space sector focusing on the structural and material properties of sintered lunar regolith, a process and material which is not likely to be used in Earth construction.

In future applications, should there be a move towards more synergistic construction materials, geopolymer concrete has gained interest as an environmentally friendly alternative to OPC concrete as it has a lower carbon dioxide footprint (Gartner 2004). Geopolymer concrete makes use of an aluminosilicate source that is mixed with an alkaline solution. Geopolymer cements can also theoretically be manufactured from lunar in-situ resources and mixed with lunar regolith as a potential construction material (Takai et al 2020) on the Moon.

D. Sustainable Operations: Structural Sustainability

- a. **Definition:** *The ability of a habitat or structure to self-repair, autonomously monitor, and or maintain itself over time*

- b. **Relevant Development Opportunities in AM Habitat Design**

Remote, high-risk, and potentially temporarily unoccupied settlement solutions for the moon and mars place an emphasis on the long term monitoring and hopefully autonomous maintenance of structures. Since about 2017, MSFC's In-Space Manufacturing (ISM) group has focused on the development of a multi-materials 3D printer for maintenance and sustainability operations on long-duration space missions. As part of this effort, a Digital Design Database (DDD) was developed as a precursor to what would hopefully become the input to an on-board Manufacturing Execution System (MES). The combination of the DDD and MES would then form the framework for a mature "Digital Twin" concept, initially to be demonstrated on ISS and then to be fully deployed on Gateway and for surface operations. This concept should be fully adaptable to large-scale construction activities on Earth as well, acting as preventative measures for long term structural maintenance.

E. Sustainable Operations: Sustainable Resource Management in the Operations Phase

- a. **Definition:** *Formal and material elements that reduce energy and resource use over the lifetime of the building*

- b. **Relevant Development Opportunities in AM Habitat Design**

The subject of the role of building and building systems design in sustainable resource management is rich and the subject of future research. In the narrow case of Additive Manufacturing habitats and initial construction demonstrations, there was overlap in the investigation of the application of potentially passive techniques for daylighting or air movement in the building, and how that might largely influence the form of habitat structures and therefore the capabilities of the printer, as well as in

the makeup of the composite wall and its abilities to contribute to mitigating heating and cooling loads in the building.

F. Human Factors:

- a. **Definition:** *Building design elements (scale, form, organization, and material) which influences personal and social human health and well-being, including functional programming, indoor environmental quality and comfort, ergonomics and human scale requirements, aesthetic and psychological factors*

- b. **Relevant Development Opportunities in AM Habitat Design**

While the impacts of design in this area are broad, will well established standards of practice for Earth habitats, as well as research and standards in the space design industry, in the case of Additive Manufacturing design, the most critical common areas of development were simply in the ability to scale up to larger, potentially multi-level habitat designs

V. Discussion

A. Design Thinking Approach

While there is a deep ambition in both Earth and Space sectors to collaborate on emerging technologies, both camps come to the table with deeply entrenched historic and disciplinary conceptualizations. Diagram and other Visualization Tools may be a potentially successful method to break down pre-existent images and methods and help towards developing an initial common language across multiple design disciplines. This initial reduction and/or re-shifting is critical towards creating common frameworks from which to define successful projects.

B. Bridging the Ontological Gap

To that end of creating common frameworks, this work clearly highlights the necessity to further develop a common ontology between aerospace and terrestrial architectural practice. More systematic efforts towards ontological clarity will help to make future efforts more seamless. First order ontologies for Space Architecture have been defined by the AIAA Space Architecture Technical Committee, but further common language in more depth in specific areas of habitat design, possibly in the four original categories here mentioned, or using the data and information collected in this instance as an example across earth and space stakeholders would help to aid future similar project definitions. Further work is necessary to come to a more comprehensive ontology of relevant goals across Earth stakeholders using standards, metrics, and frameworks which can be commonly agreed to, as well as aligning definitions of terms and classification systems, in all areas of building design and development beyond those related to Additive Manufacturing.

C. The Role of Design Standards / Pre-defined Requirements

Building project standards, whether in material and structural requirements or human occupancy requirements have had centuries of development through trial and error on Earth. Standards relating to the physical human body are more developed for space, while other structural standards are in development. The way that metrics or standards are framed and the terminology and variables used has direct implications for chosen formal and technological solutions. Standards provide baseline requirements that are mission, design, and technology agnostic. The application of design standards in the extreme environment of space asks us to be ever more fundamental in our definitions of what constitutes human health and well-being.

D. Applying Multiple Metrics of Success

In order to successfully address both Earth-bound and extraplanetary requirements, metrics of success for both sectors must be identified. In terms of Earth construction, outside of any particular stakeholder, we might look towards more established frameworks such as the UN Sustainable Development Goals (SDGs) to provide metrics and guidelines which might steer technology development towards Earth applications. Following a similar process to the above Venn Diagram methodology we might in the abstract begin to link specific NASA Strategic Technology Integration Goals with what might be considered relevant to the SDG framework. This would naturally shift



UN Sustainable Development Goals



How can we continue to support the sustainable development of human societies and simultaneously inspire a love of science through space exploration?

NASA Strategic Technology Integration Framework



Figure 9. Above: Reframing potential space habitat development goals through the lens of the UN Sustainable Development Goals. Below: Framework to further identify more in-depth/specific cross-linkages between Earth-Space Development and NASA Strategic Technology Integration Framework (based on visualization strategies developed at Yale CEA) .

VI. Conclusions

This paper represents a single instance of attempting to arrive at common development interests between Earth and Space building construction and design, and proposes a potential workflow towards establishing synergistic requirements for Earth and Space buildings. Future work should expand the scope of architectural and building design practices to construction practices beyond Additive Manufacturing to encompass Habitat Class levels I-III and should include further depth in architectural design principles beyond construction methods which was the focus of this instance.

Despite the substantial motivation and value of linking construction methods and building design in terms of both sustainable practice, technological advancement for site safety and speed, and potential to design for better health outcomes, the practice of establishing project scopes that work simultaneously towards synergistic goals is complex. Ultimately, the resultant scope of work in this instance represented productive compromise. While the initial material construction choice of lunar regolith sintering processes were not necessarily appropriate for Earth construction processes, there is still future ambition to incorporate knowledge from cementitious processes on Earth. A gantry style mobility system which was developed largely with specification of Earth construction in mind was further developed to incorporate factors necessary to adapt to the environmental constraints of the lunar or martian environment. Initial solutions which might have emerged from a starting point in the history of development in each sector, did find the opportunity to move closer towards the requirements of the other.

Perhaps the extent to which designers and builders can *simultaneously* work towards technology that advances space habitation while benefiting earth building design and construction practice involves largely or primarily an alignment of actors which can, if not develop a truly synergistic instance outcome, build a network of expertise and individuals and common framework with which to tackle multiple instances and applications of similar technologies.

Retroactively we might investigate design and construction processes which continue to be developed in isolation in the space and earth sectors, to evaluate if the combined effort was indeed more successful in terms of investment spent. But we might ask if investment would be the only metric of success. Perhaps success lies in mutual exchange of ideas, and in the spirit of common ambitions for healthy and sustainable habitats for humans on any planet.

Acknowledgments

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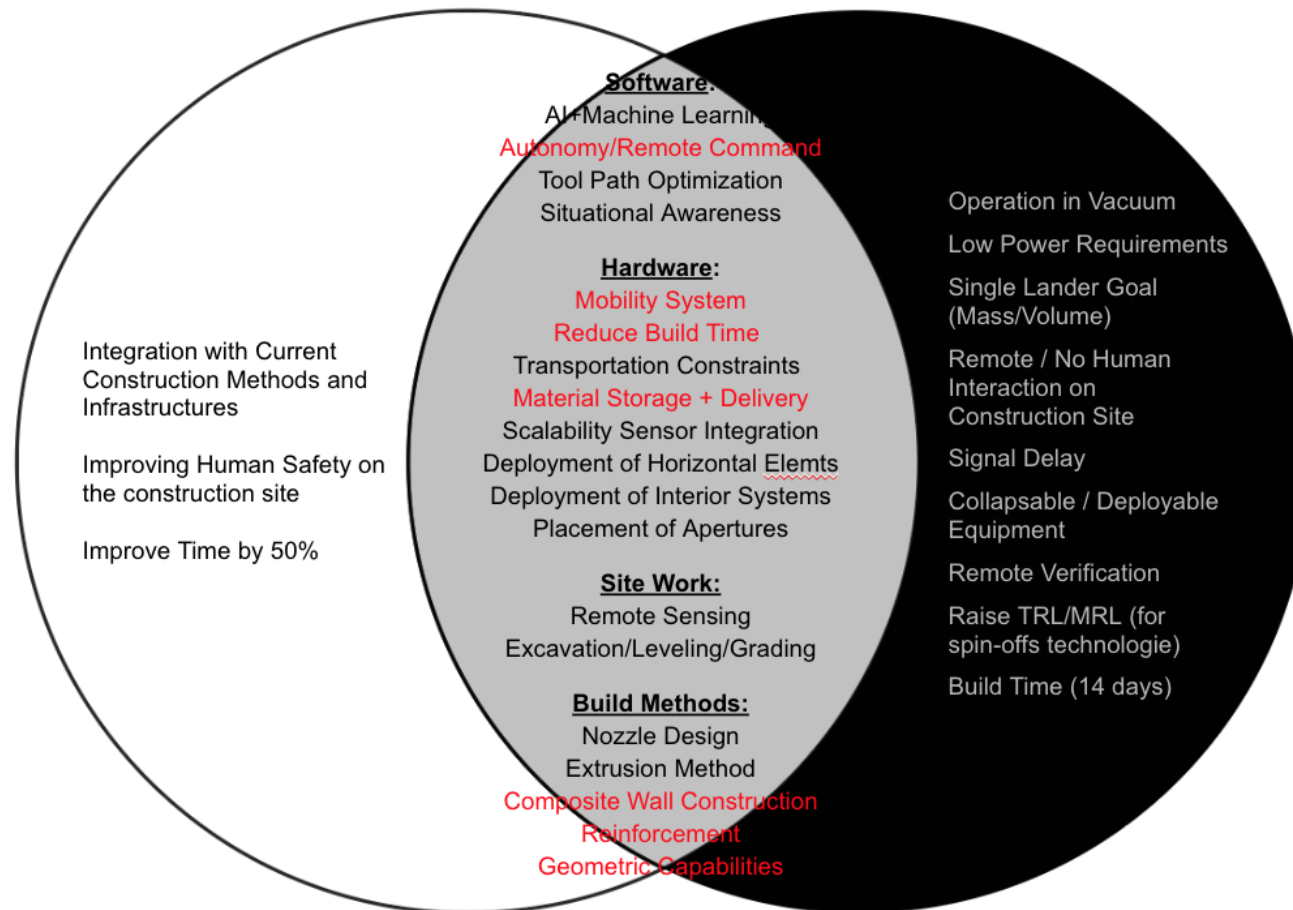
Appendix

Table of Contents:	(A) Venn Diagrams
	(B) Comparative Requirements Matrix

(A) Venn Diagrams

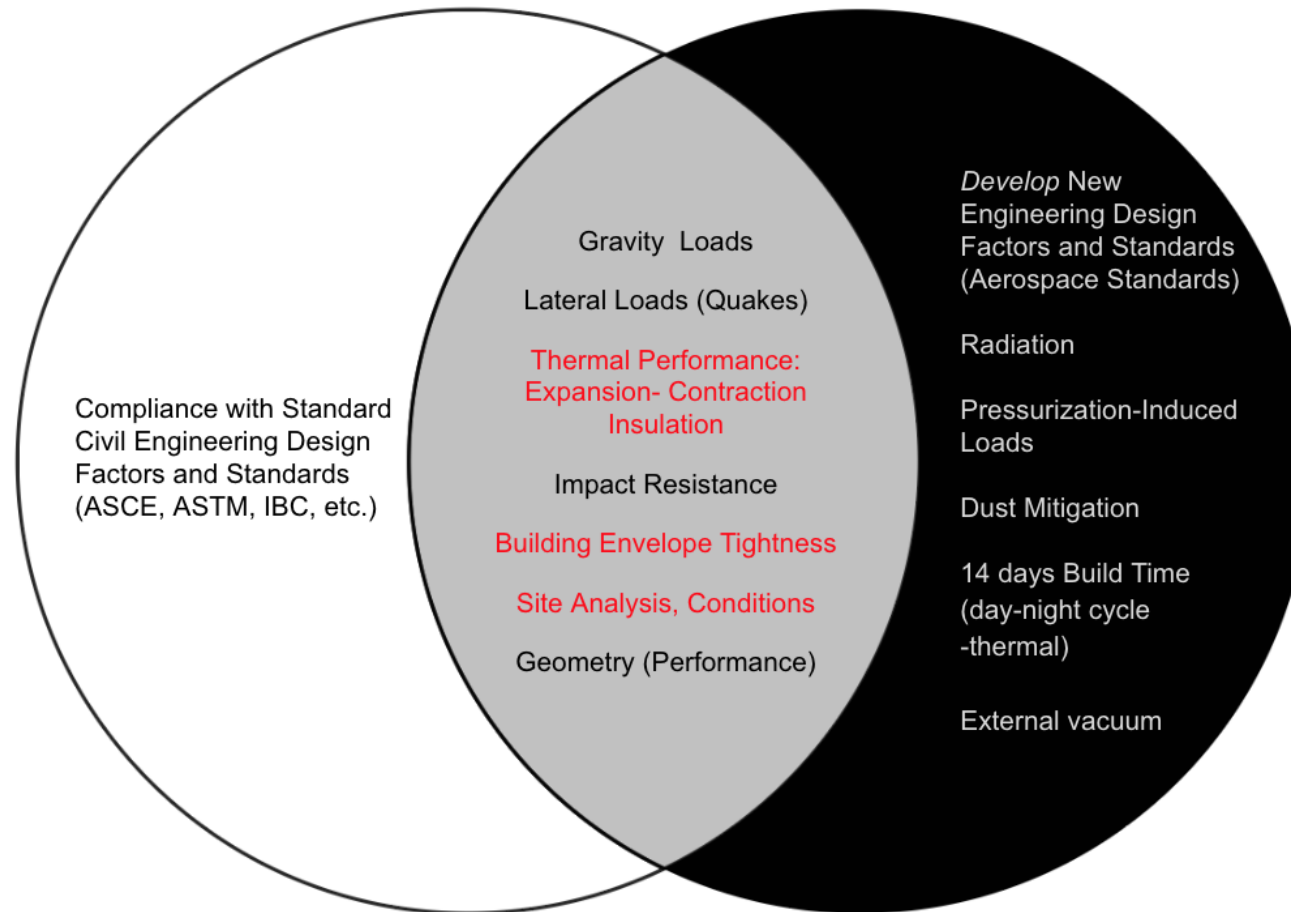


Construction Technology Construction Means and Methods



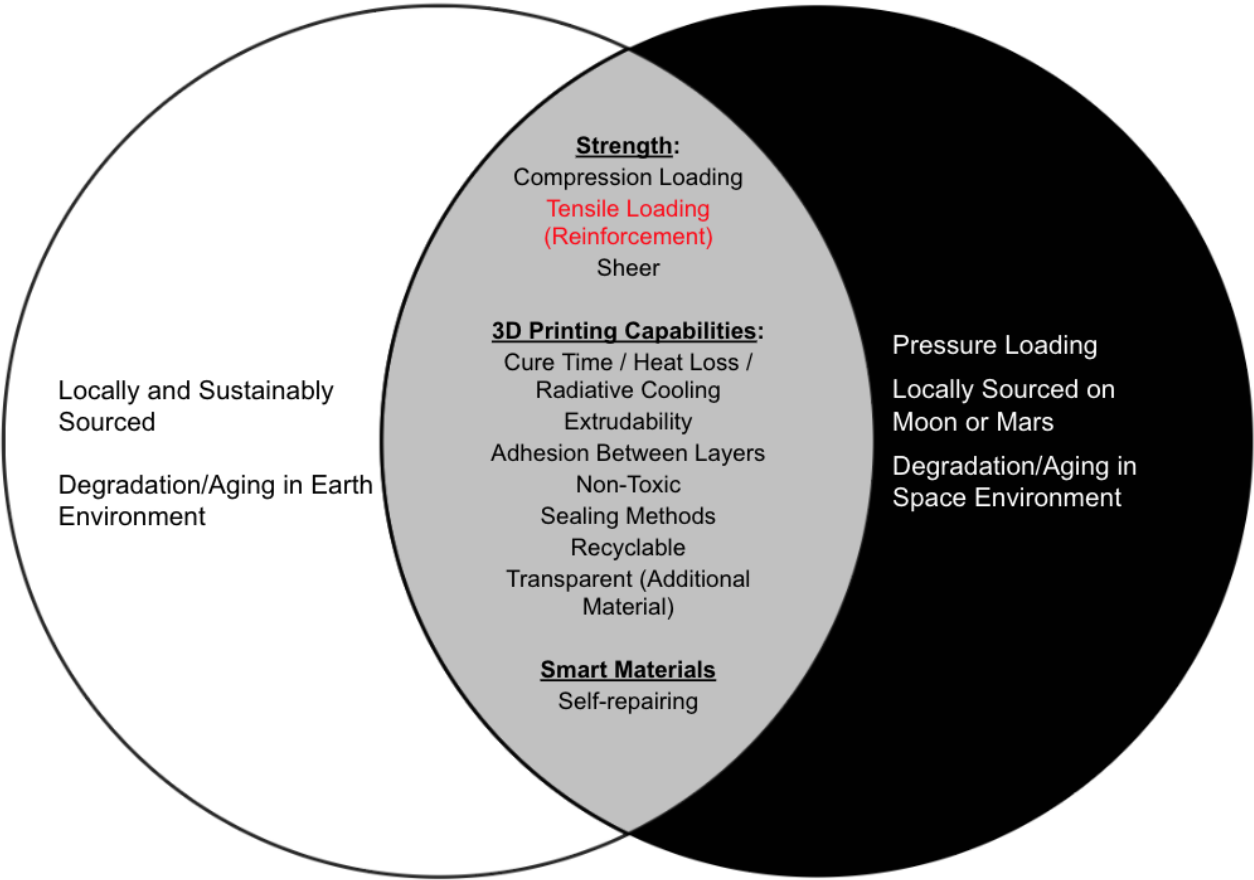


Construction Technology Environmentally Induced Building Performance



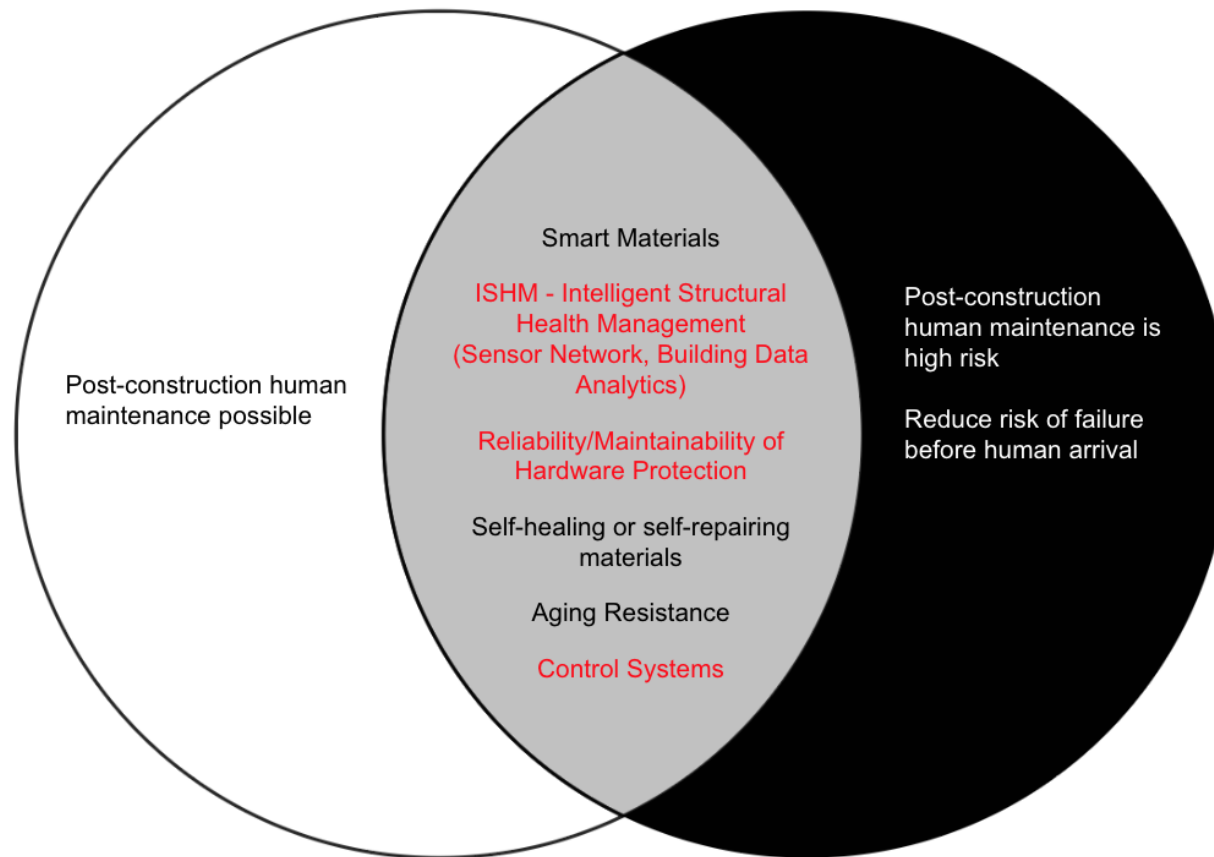


Material Innovation



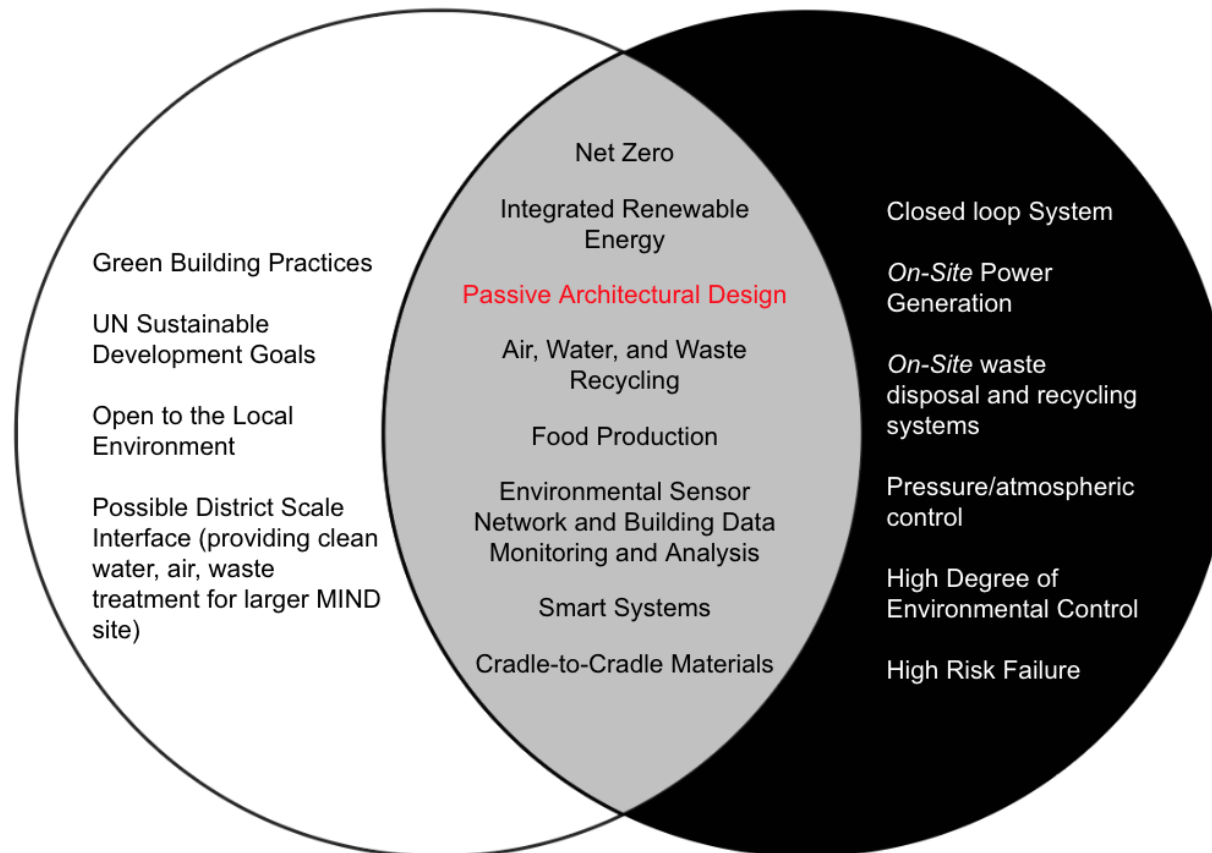


Sustainable Operations (ISHM-Intelligent Structural Health Management)



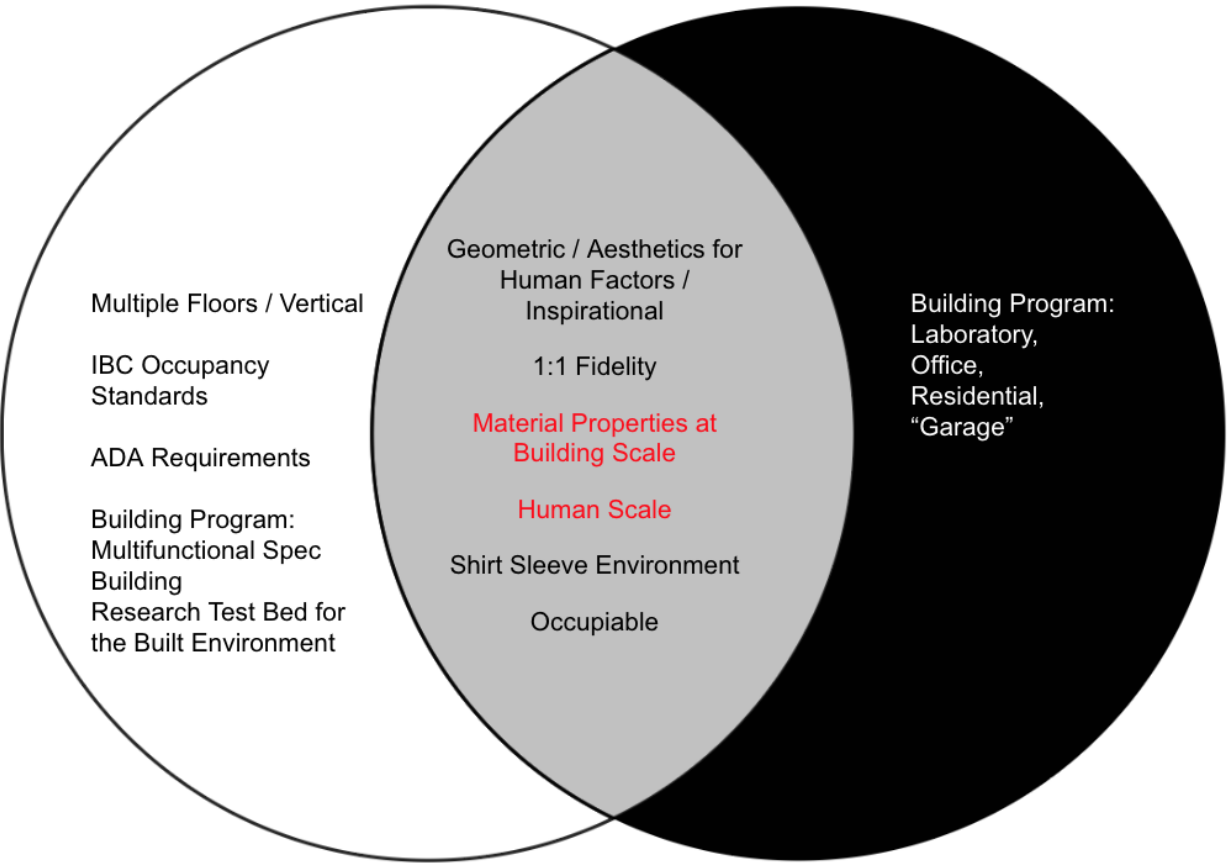


Sustainable Operations Environmental Building Systems (MEP / ECLSS)





Human Factors



(B) Comparative Requirements Matrix

Comparative Design Requirements: Additive Building Design for Earth and Space						
OVERL AP	READI NESS	Category	Sub-Category	EARTH	MOON	MARS
		CONSTRUCTION MEANS AND METHODS				
		Hardware Design				
2	1	Hardware-System Design	Transportability (volume)	Standard Road Legal Trailer (8.5' high, 8'5 wide, 53' long)	SLS / CLPS Payload	SLS / CLPS Payload
2	1		Transportability (weight)	Highway Standard: 40k lbs	SLS / CLPS Payload	SLS / CLPS Payload
2	2		Scalability	yes	no	no
2	?		Collapsible / Deployable	yes	yes	yes
?	3		Power Requirements	60 kVA	?	?
?	3		Integrated Renewable Power Source	no	no	no
1	1	Hardware-Mobility System		Gantry Printer	?	?
2	?	Hardware-Geometric Capabilities	Horizontal Elements (Floors, Roof)	no	yes	yes
2	1		Height Print Capacity	3.6 m (12 ft) (per floor)	?	?
2	1		Width Print Capacity	12 m (40ft)	?	?
1	3		Design Freedom/Flexibility	no	yes	yes
1	1	Hardware-Printing Mechanism	Material Specific Nozzle Design	yes	?	?
3	1		Material Specific Nozzle Design (In Vacuum)	no	yes	yes
1	1		Multi-Nozzle / Multi-Material / Composite Wall Construction	yes	yes	yes
1	1		Layer-by-Layer Deposition	yes	yes	yes
2	?		3D (Mid-Air) Extrusion Capabilities	no	?	?

3	3		Sintering	no	highly likely	highley likely
2	1	Hardware-Material Delivery System (Feedstock Storage and Delivery Systems)	Autonomous Concrete Mixing	yes	?	?
2	1		Autonomous Concrete Pumping	yes	?	?
2	?		Dry Harvesting Regolith	no	yes	yes
2	?		Dry Regolith Conveyance	no	yes	yes
1	?	Hardware-Control Systems	Real-time or Batch Rheology Control	yes	?	?
3	2	Hardware-Environmental Influences / Environmental Performance	Operating Temperature	0C to 45C	-173C to 127C	-163C to 20C
3	3		Operation in Vacuum	no	yes	yes
3	3	Hardware-Resilience	Radiation (Gamma Ray) Protection	no	yes	yes
1	?		Moisture/Water Management	yes	yes	yes
2	2		Dust Mitigation	medium	high	high
2	?		EMP Protection	no	yes	yes
2	2		Projectile Shielding	no	yes	yes
3	?		Quake Protection			
1	1		Repairability / Maintenance	100% Field Repairable	100% Field Repairable	100% Field Repairable
?	?		Cleaning of System Post-Deposition	manual	automatic	automatic
1	?	Hardware-Whole Building Integration	Autonomous Placement & Sealing of Wall Apertures (Windows, Doors, Inlets/Outlets)	no	yes	yes
1	?		Autonomous Placement/Deployment of Interior Systems	no	yes	yes
1	?		Autonomous Placement of Horizontal Elements (Walls/Floors)	yes	yes	yes
1	?		Autonomous Placement of Reinforcement	yes		
2	?		Autonomous Placement of Building Integrated Sensor Networks	no	yes	yes
1	?		Building Envelope Tightness	?	100% Sealed	100% Sealed
1	1	Build Time		(-50% standard construction)	14 days	

2	?	Site Work	Site Survey/Remote Sensing/Conditions Monitoring	no	yes	yes
2	?		Site Work (Leveling, Grading)	no	yes	yes
2	3		Foundation Printing (Off Foundation Construction)	no	yes	yes
1	1	Software	Baseline Autonomy (Minimize On-Site Human Operators)	2	0	0
1	1		Communications / Monitoring Systems	Global	Interplanetary	Interplanetary
1	1		Remote Mission Control	yes	yes	yes
1	3		Design Platform	yes	yes	yes
1	?		Operating System	Modern, Touch-Screen Based		
1	2		Useability / Ease of Operation	High/Basic Training	Medium/Intermediate Training	Medium/Intermediate Training
1	1		Situational Awareness	yes	yes	yes
1	?		Tool Path Optimization	yes	yes	yes
		MATERIAL DESIGN				
		Construction Material Development / Material Performance Requirements				
		Materials Approach		Water-Based Proprietary Cementitious Material	Sintering of Regolith	
2	1	Construction / Print Medium	Concrete (Gravity Loads)	1g - 9.8 m/s/s		
2			Lunar Regolith (Gravity Loads)	1.6 m/s/s		
2			Insulation (Thermal Loads)	International Residential Code		
1			Polymers (Load?)	No		
2			(Basalt Fiber) Reinforcement (Tensile Loads)	Under Development		
2			Other In-Situ Materials (ie, Water?)	No		
1	2	Binder Development			minimal / no up-mass	minimal / no up-mass
1	2	Mechanical Properties	Aggregate Size	1/4"		
	2		Constituent Variability Allowance - Robustness	"± 50%		
1	2	Ideal Properties	Tensile			

1	2		Compressive	6500 psi		
1	2		Shear			
1	2	Thermal Properties	Expansion-Contraction			
1	2		Insulation Properties (U Value)	Thermal Mass + R15		
1	2	Print Properties	Layer Adhesion / Bonding Agents for Cold Joints	No (unless seismic)		
1	2		Cure Time / Heat Loss / Radiative Cooling			
1	2		Buildability			
1	2		Extrudability			
1	2		Formability			
1	2		Open Time			
1	2	Resilience / Smart Materials	Self-healing Construction Materials	No		
3	2	Aging/Weathering Conditions	Radiation			
2	2		Hot/Cold Cycling			
2	2		Water	yes	no	no
2	2		Oxidation			
3	2		Vacuum	no	yes	yes
1	2	Building-Integration	Composite Wall System / Multiple Layering / Interaction with Other Materials / Corrosion	Yes		
2	2		ISHM (Intelligent Structural Health Management) / Sensor Network	No		
2	2	Source		Regional	Locally/Sustainably	
1	2	Human Factors	Non-Toxic	Non-Toxic upon curing		
		BUILDING DESIGN				
		Architectural Design: Human Factors				
1	1	Scale	Human Scale - Interior Height			
1	1		Human Scale - Interior Area			
?	?		Human Scale - Multiple Floors			

1	1	Interior Environment	Shirtsleeve Environment	23C	23C	23C
2	1		Lighting	25-1000 lux	25-1000 lux	25-1000 lux
1	1	Circulation / Planning	Ingress/Egress (Apertures in Exterior Envelope)	IBC Standards		
			Isolation Requirements	IBC Standards		
1	1	Occupancy	Laboratory	IBC Standards		
1	1		Residential	IBC Standards		
1	1		Workshop	IBC Standards		
2	2	Non-enclosed program	Landing Pads			
2	2		Runways			
2	2		Roads			
2	2		Walls/Barriers			
		Architectural Design: Environmentally Induced Building Performance Requirements				
3	1	Gravity		9.8m/s/s	1.62 m/s/s	3.71 m/s/s
2	1	Gravity Loads	Dead Loads (Roof, Walls, Floors, Structure)	(kN/m ²) (ASCE Standards)		
2	1		Live Loads (People, Equipment)	(kN/m ²) (ASCE Standards)		
3			Live Loads (Snow, Weather)	(kN/m ²) (ASCE Standards)		
2		Lateral Loads	Quakes	(kN/m ²) (ASCE Standards)	Moonquakes (Force?)	Marsquakes (Force?)
3			Wind	(kN/m ²) (ASCE Standards)	-	-
1 ?		Thermal Performance	Expansion/Contraction	DT 50C (-5C to 30C)	DT 300C (-173C to 127C)	DT 200C (-163C to 20C)
1 ?			Insulation Properties	U value = 0.3 W/m ² k		
1 ?			Sunlight/Heat Exposure			
2 ?		Impact Resistance			Micrometeoroid (Force?)	Micrometeoroid (Force?)
3 ?		Pressurization Induced Loads / Vacuum	Outward Hoop Stress			
3 ?			Hold-down Loads			

3	?	Radiation Protection			CsV	CsV
2	?	Dust Mitigation		(medium)	(very high)	(very high)
1	?	Moisture / Water Management				
3	?	Special Certifications		ASCE, IBC Standards	Launch TRL 7-8	Launch TRL 7-8
		Architectural Design: Sustainable Operations / Environmental Building Systems				
1	1	Passive (Low-Energy) Architectural Design (Material and Geometric)				
	1	Building Sensor Network	Input/Output Monitoring			
	1		Smart Home			
	1		Integrated System Health Monitoring			
	1		Microbial Detection / Monitoring			
	1		Control Systems			
	1	Building Integrated (On-Site) Systems	On-Site Renewable Energy			
	1		Air Recycling/Remediation			
	1		Water Recycling/Remediation			
	1		Waste Recycling			
	1		Food Production			