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# Techno-Economic Framework for Extraterrestrial Architecture: An Integrated Approach to Viable Space Habitat Development

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**Abstract- Advances in AI, robotics and construction technology are making in-situ extraterrestrial building practicable. Demonstrations such as Mars Dune Alpha (NASA/ICON), Lunar Habitat via Contour Crafting (NASA/ICON), and the Autonomous Self-Growing Structures research (Jin et al. 2023) show technical feasibility, but economic barriers remain the principal threat to long-term habitation. This paper proposes a concise techno-economic framework that treats economic sustainability as a primary design parameter, integrating financial intelligence—data-driven financial planning and decision support, typically aided by AI—with architectural and robotic development. The framework shows how coordinated design, automated fabrication and targeted financial analysis can reduce lifecycle costs and improve value creation. Drawing on a broad literature synthesis and analysis of over 20 government, commercial and student projects (estimates compiled from public sources and open repositories and used here as indicative rather than fully verified), the study offers practical guidance for architects, students and industry stakeholders to mitigate financial risk, structure resilient financing and move space architecture toward commercial viability.**

**Keywords – Extraterrestrial Architecture, Space Economics, AI-Robotics, Techno-Economic Analysis, In- Situ Resource Utilisation, Financial Modelling, Lunar Construction.**

## I. INTRODUCTION

The dawn of sustainable space exploration hinges critically on developing resilient habitats beyond Earth, presenting one of the most formidable architectural and engineering challenges of our time. Previous research has established that artificial intelligence robotics and cognitive design tools are essential for building in extreme lunar and Martian environments, where conventional construction methods prove inadequate (NASA 2025; Bier and Mostafavi 2015). These advanced systems enable the creation of highly performative architectural formations through Design-to-Robotic- Production-Assembly C -Operation (D2RPCO) frameworks, which integrate computational design with robotic execution to address unique extraterrestrial constraints (Bier 2018; Mostafavi and Bier 2016). The NASA Moon to Mars Planetary Autonomous Construction Technology (MMPACT) project exemplifies this approach, developing autonomous capabilities for constructing large-scale infrastructure such as landing pads and habitats using in-situ regolith to drastically reduce dependency on Earth-sourced materials (NASA 2022; NASA 2025).

However, technical feasibility alone proves insufficient for realising sustainable extraterrestrial habitation. The monumental costs associated with spaceflight and construction present the most significant barrier to permanent human presence beyond Earth (Atri and Umansky 2024). As observed in NASA's Artemis program, major projects face substantial cost overruns that threaten their long-term viability, with identified increases across several key systems including the Orion spacecraft and landing platforms (Roby 2025). Current estimates suggest establishing a basic lunar habitat requires initial investments ranging from $5-10 billion, with Martian structures costing substantially more due to increased transportation challenges and communication delays (Atri and Umansky 2024). These economic realities prompt a critical question: Are AI-robotic systems strategically designed and implemented to not only enable but also economically justify construction of extraterrestrial architecture?

This paper aims to bridges the gap between technical design and financial viability by proposing that financial intelligence must be integrated into the architectural and robotic design process from inception, rather than applied at later sage in the process. By developing a holistic techno-economic model that combines technical parameters with economic analysis, it endeavours to show how specific AI-robotic capabilities—including autonomy, in-situ resource utilisation, and predictive maintenance—directly translate to reduced lifecycle costs and new value propositions. This approach transforms the financial

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narrative from pure cost burden to strategic investment, fundamentally reshaping the economic calculus for space development and paving the way for sustainable multi-planetary expansion.

The design of habitats for lunar and Martian environments represents one of the most complex challenges in contemporary space exploration architecture, requiring solutions that address multiple extreme environmental factors simultaneously (Atri and Umansky 2024). Unlike terrestrial construction, extraterrestrial habitats must provide protection against intense radiation exposure, temperature extremes spanning hundreds of degrees, low gravity effects, vacuum or near-vacuum conditions, and limited access to conventional construction materials (Atri and Umansky 2024). The integration of artificial intelligence robotic systems and advanced construction technologies has become not merely advantageous but essential for creating sustainable habitats in these hostile environments, as demonstrated by projects like the Mars Dune Alpha habitat, a 1,700-square-foot 3D-printed structure using Martian regolith simulant developed for NASA's Crew Health and Performance Exploration Analog (NASA 2023).

The financial implications of transporting materials from Earth remain staggering, with current launch costs estimated at approximately $10,000 per pound to escape Earth's gravity, creating tremendous economic pressure to minimise mass through innovative design and material choices (Frazer 2024). This economic reality has driven architectural designers and space agencies to prioritise in-situ resource utilisation (ISRU) and robotic construction methods that minimise the need for Earth-sourced materials, as exemplified by the Lunar Habitat project via Contour Crafting that explores large-scale extrusion printing using molten regolith (Atri and Umansky 2024). The Moon to Mars Architecture approach emphasises developing systems that enable sustainable exploration while minimising Earth dependency, representing a fundamental shift from traditional engineering approaches that requires unprecedented innovation in both design and execution (Atri and Umansky 2024).

The architectural challenges extend beyond mere technical specifications to encompass human factors engineering, psychological well-being, and long-term sustainability (NASA 2023). Habitats must not only protect inhabitants from lethal external conditions but also provide adequate living spaces that prevent claustrophobia and promote mental health during extended isolation periods, as demonstrated in the Mars Dune Alpha simulation habitat (NASA 2023). The integration of robotic construction systems offers potential solutions to these challenges by enabling the creation of more spacious habitats using local materials, thereby reducing launch mass and costs while simultaneously improving living conditions for future extraterrestrial residents, creating a compelling synergy between technical capability and human necessity (Atri and Umansky 2024).

## II. LITERATURE REVIEW

Extraterrestrial architecture must be treated first as an economic and programme-aware problem: design decisions that ignore launch mass, funding volatility and programme risk are infeasible. Recent scholarship and official reports show that cost drivers and institutional stability determine what can actually be built off Earth (Donald and Baker 2020; UK Space Agency 2024–25). Consequently, architectural strategy must couple material and robotic innovation with rigorous life-cycle costing, staged delivery and resilience to policy shifts.

The most powerful lever to change the cost equation is In-Situ Resource Utilisation (ISRU). Using lunar or Martian regolith and native boulders as primary feedstock reduces payload mass and launch-driven cost risk (Zeng, Metzger, and Schlautmann 2022; Badescu 2012). For the practising architect this means designing systems that arrive light and become materially productive on site: elements intended for assembly, consolidation or accretion from local material rather than shipped finished from Earth.

Robotic automation is the second structural pillar. Autonomous and semi-autonomous fabrication enables continuous, pre-crew construction and reduces human exposure and mission cost over time. Architects must therefore treat robots as part of the design system—shaping form, tolerances and logistics around fabrication capabilities rather than retrofitting production into a finished form (Bier and Mostafavi 2015; Mostafavi and Bier 2016). Early integration of fabrication logic, control strategies and material processing workflows is essential to avoid costly iterations and incompatibilities.

Bio-mediated and biomimetic processes broaden the material palette and defend against energy and mass penalties. Research into "self-growing" or biological consolidation methods shows potential to create load-bearing elements with minimal consumables after deployment, offering a bootstrap model for habitats that scales economically with minimal up-mass (Jin, Chen, and Martinez 2023). These methods should be pursued in parallel with engineered regolith composites to offer redundancy in material supply chains.

Radiation protection is a non-negotiable design requirement and must be resolved as a structural and material strategy rather than an add-on. Long-duration missions face both deterministic and stochastic risks; launching dedicated shielding mass is economically prohibitive, so multifunctional materials and mass-placement (regolith overburden, integrated water tanks, buried volumes) must be specified from concept stage (Cucinotta et al. 2012; Wilson et al. 2001b). Architects should demand empirical shielding and mechanical performance data for candidate materials to apply ALARA-based design tradeoffs (DeWitt and Benton 2020; Wilson et al. 2001a).

Crucially, the UK policy and funding context offers an alternative reference model to large, concentrated flagship funding seen elsewhere. The UK's National Space Strategy, the Space Exploration Technology Roadmap and successive UK Space Agency annual reports demonstrate a strategy of targeted, incremental investment, regional cluster support and industry-academia partnerships that lever public funds to catalyse private investment and technology maturation (National Space Strategy 2021; Space Exploration Technology Roadmap 2023; UK Space Agency 2024–25). For architects this policy environment implies stronger opportunities for staged demonstration projects, university-led testbeds, and industry consortia that can mature ISRU, robotics and material systems in lower-risk increments while leveraging UKSA funding mechanisms.

ISRU, robotics, and radiation mitigation must be treated as primary constraints rather than optional technologies: architects should prioritise systems and forms that arrive lightweight and become materially productive on site, employ autonomous fabrication logic from the outset, and use multifunctional materials and mass-placement strategies to meet both structural and shielding needs. From concept stage, projects must embed rigorous life-cycle costing, technology-readiness sensitivity and staged funding scenarios so designs remain viable across development, deployment and operation. Schemes should be modular and incrementally valuable—able to deliver usable function at partial completion—and specified to open standards and interoperability so components from different contractors, timelines or national programmes can be paused, upgraded or recombined without catastrophic waste.

## III. ENVIRONMENTAL CONSTRAINTS AND ARCHITECTURAL IMPLICATIONS

### Lunar Environmental Constraints

The lunar environment presents extraordinary challenges for architectural design that demand innovative engineering solutions fundamentally different from terrestrial approaches. Surface temperatures range from -173°C to 127°C (-279°F to 261°F), creating severe thermal expansion and contraction issues for structural materials that must be addressed through advanced material science and engineering (ESA 2024). The Moon has no atmosphere to protect against solar and cosmic radiation or micrometeorite impacts, requiring habitats to have robust shielding systems that can withstand these constant threats, as demonstrated by projects like NASA's Mars Ice Home which uses water ice for radiation protection (NASA Langley Research Centre 2016). Additionally, the low gravity (approximately 1/6th of Earth's) affects both construction techniques and human adaptation, necessitating completely new approaches to structural engineering and habitat design that differ significantly from terrestrial practices.

The lunar regolith (surface material) consists of fine, abrasive particles that can damage mechanical systems but also offers potential construction material through sintering or binding processes, as explored in the University of Stuttgart's REGOLITH HABITAT project which utilises 3D-printed structures using simulated regolith with robotic arm systems (University of Stuttgart 2023). Solar radiation levels are substantially higher than on Earth, with no magnetic field for protection (ESA 2024), making radiation shielding one of the primary design considerations for any lunar habitat, a challenge addressed in concepts like the Lunar Lantern's vertically oriented 3D-printed structure that incorporates regolith shielding (AI SpaceFactory 2020). Most proposed lunar habitats, such as Foster + Partners' Lunar Habitat developed for ESA and the Lunar Lantern project from NASA's Centennial Challenge, are designed for polar regions where near-constant sunlight provides solar power opportunities and more stable thermal conditions compared to other lunar locations, demonstrating how architectural solutions must respond to specific environmental opportunities.

The vacuum conditions on the Moon present unique challenges for material selection and construction techniques, as outgassing and cold welding of materials can occur in the absence of atmosphere, requiring specialised approaches not encountered in terrestrial construction (ESA 2024). Furthermore, the extreme temperature variations require sophisticated insulation and temperature regulation systems that must function reliably for extended periods without maintenance, as implemented in the SOM Moon Village concept with its radiation-shielded utilities core (SOM 2020). These environmental factors collectively dictate that lunar habitats must be hermetically sealed, thermally regulated, radiation-shielded structures that can maintain integrity despite constant bombardment by micrometeorites and abrasive dust particles (ESA 2024), representing a completely different set of architectural priorities than terrestrial buildings. These harsh lunar conditions—vacuum-induced material effects, thermal extremes, radiation and micrometeorite threat—translate directly into increased mass, redundancy and lifecycle costs, so a rigorously integrated techno-economic framework must be established at project inception as a primary design pillar to enable viable, low-risk architectural solutions.

### Martian Environmental Constraints

Mars presents a different but equally challenging set of environmental constraints for architectural design that require distinct solutions from lunar approaches. While it has a thin atmosphere (about 1% of Earth's pressure), it provides minimal protection from

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radiation and micrometeorites, necessitating substantial additional shielding for human habitats (NASA Science Mars Exploration Program 2023), as addressed in the Marsha habitat by AI SpaceFactory with its vertically oriented design that minimises surface footprint while providing redundant radiation protection (AI SpaceFactory 2018).

Surface temperatures average around -60°C (-76°F) but can vary from -125°C (-195°F) near the poles in winter to 20°C (70°F) at the equator during midday, requiring habitats to withstand significant thermal cycling that influences material selection and structural design (NASA Science Mars Exploration Program 2023). The Martian gravity is approximately 3/8ths of Earth's, which affects both construction techniques and long- term human health considerations, potentially enabling different structural approaches than those required on the Moon, as seen in the Mars Ice Home's inflatable design (NASA Langley Research Centre 2016).

The Martian soil contains perchlorate compounds that are toxic to humans but also water ice in certain regions, which could be extracted for life support and fuel production (NASA Science Mars Exploration Program 2023), creating both challenges and opportunities for architectural design. The presence of perchlorates makes the Martian regolith particularly hazardous without proper processing or containment, influencing habitat design and construction approaches. Dust storms can last for months and cover entire regions, reducing solar power generation efficiency and potentially coating habitat surfaces with fine abrasive particles, requiring design solutions that maintain functionality during extended low-light periods. Atmospheric pressure on Mars is below the Armstrong limit (the pressure threshold below which water boils at human body temperature), meaning fluids would boil at human body temperature without pressure containment, requiring habitats to maintain sufficient internal pressure while withstanding the significant pressure differential between interior and exterior environments, a fundamental driver of structural design (NASA Science Mars Exploration Program 2023).

When comparing environmental constraints between the Moon and Mars, distinct architectural implications emerge that drive different design approaches. While both environments require advanced insulation and thermal regulation systems, the specific temperature ranges and cycles differ substantially, influencing material selection and energy system design. Radiation shielding represents a critical concern for both environments, but the approaches may vary due to the availability of different local materials, with lunar designs typically relying on regolith burial while Martian concepts sometimes incorporate water-based shielding. The gravity differential (1.6 m/s² on the Moon versus 3.7 m/s² on Mars) influences structural design considerations, with Martian habitats potentially able to support more massive structures than lunar installations, as seen in the comparison between the lightweight Lunar Lantern and the more substantial Marsha habitat (AI SpaceFactory 2018; AI SpaceFactory 2020). The virtual vacuum of the Moon contrasts with the thin Martian atmosphere, leading to different approaches to pressure containment and airlock design. Surface materials differ significantly, with fine, abrasive regolith on the Moon and perchlorate-containing dust on Mars, necessitating different filtration systems and material compatibility approaches. Finally, solar energy availability varies substantially, with the Moon experiencing 14-day light/14-day dark cycles while Mars has seasonal variations with dust storms (NASA Science Mars Exploration Program 2023), requiring different energy storage systems and alternative power sources, as implemented in projects like the Blue Origin Blue Moon Habitat with its integrated power systems.

## IV. TECHNO-ECONOMIC FRAMEWORK DEVELOPMENT

**In-Situ Resource Utilisation (ISRU) and 3D Printing**

A key strategy for constructing habitats on both worlds is In-Situ Resource Utilisation (ISRU)—using local materials to avoid the immense cost of transporting everything from Earth. For the Moon, this means using the regolith. After winning NASA's 3D-Printed Habitat Challenge in 2019, AI SpaceFactory advanced its work with Kennedy Space Centre to develop 3D print material using simulated lunar regolith (National Aeronautics and Space Administration 2025). This technology has since been commercialised in a large-scale 3D printer called Starforge, which uses pellet "inks" that mix plastic with a dry fill material, a principle directly inspired by the lunar regolith project (National Aeronautics and Space Administration 2025). While regolith itself is effectively cost-free in situ, the capital, energy and systems costs of processing, printing equipment and qualification are substantial up-front investments; however, when evaluated across lifecycle and reduced launch mass, these processes offer compelling long-term cost advantages for architectural viability.

**Lander and Habitat Deployment**

The delivery of these habitats and their components relies on new lunar landers. Blue Origin is developing its Blue Moon family of landers, which include the MK1 for cargo and the larger MK2 for crew (Blue Origin 2025). In 2024, NASA assigned a demonstration mission to Blue Origin, tasking the company with delivering a lunar habitat to the Moon's surface around 2033 (Dinner 2024). This habitat is a critical part of establishing a sustained human presence; however, an architecturally robust delivery plan must also specify payload capacities and mass margins, clear cost and funding models, firm schedules and milestones, integration with ISRU and robotic pre-deployment, surface emplacement and utility strategies, environmental qualification, crew safety interfaces, launch and ground-segment dependencies, site and landing-accuracy constraints, regulatory compliance, and measurable success and sustainment criteria.

## V. AI-ROBOTIC INTEGRATION AS ECONOMIC CATALYST

Strategic implementation of artificial intelligence and robotics represents the most powerful lever for reducing lifecycle costs of extraterrestrial architecture, transforming the economic viability of sustained space presence. The integration of machine learning in robotic grasping controls exemplifies this potential, where AI-enabled systems achieve unprecedented precision and adaptability in space environments, directly reducing operational costs and increasing mission success probability by minimising errors and maximising efficiency (Zhao, Li, and Wang 2023). Furthermore, projects like the EU-funded SMART initiative, which consolidates various efforts to promote "smart" technologies for digital and green transitions, demonstrate how soft robotics— lightweight, compliant robots made from materials like elastomers that can gently interact with their environment, such as for use in heart assist devices or soft robotic gloves (Harvard John A. Paulson School of Engineering and Applied Sciences 2021)— with self-healing capabilities can dramatically reduce maintenance requirements and extend operational lifespans, significantly impacting total cost of ownership calculations by decreasing the frequency and cost of repairs in inaccessible environments (O'Neill et al. 2022). When applied to the Artemis Program Lunar Launch and Landing Pads, these technologies enable construction of critical infrastructure while protecting assets from highly abrasive lunar dust, ensuring safe surface operations through autonomous systems that minimise human risk (SoftServe Inc. 2024).

The Design-to-Robotic-Production C Operation framework proves transformative from an economic perspective by integrating financial considerations—such as initial capital expenditure, long-term operational and maintenance costs, and the financial impact of design choices—directly into technical design processes. By automating production and operational processes, these systems significantly reduce long-term operations and maintenance costs—the most substantial portion of a habitat's total expense over its lifecycle (Bock 2021). These intelligent systems leverage sensor-actuator mechanisms to perform self-diagnosis and autonomous repairs, as demonstrated by the self-healing polymers developed in the SMART project, where materials automatically repair damage at room temperature without external intervention (O'Neill et al. 2022). This capability dramatically reduces the need for risky and expensive human extravehicular activities for maintenance, representing substantial cost saving and risk mitigation advantage, particularly relevant for projects like the Lunar Habitat via Contour Crafting, which focuses on large-scale extrusion printing in challenging environments. This is an autonomous construction method that uses a robotic gantry system to build structures by extruding a paste-like construction material layer-by-layer, similar to a large-scale 3D printer, following a digital blueprint to form walls and structural elements (Sambiasi 2019). Research teams at institutions like the Harvard Biodesign Lab and the University of North Carolina designing soft robots for delicate tasks demonstrate the transferability of these systems to space applications where gentle but precise manipulation is required, creating opportunities for dual-use technologies that benefit both space and terrestrial applications (Rus and Tolley 2018).

A critical financial advantage—a virtuous cycle of investment and innovation where technologies developed for space are adapted for terrestrial use, generating revenue that can be reinvested into further space technology development—stems from bidirectional technology transfer between space and terrestrial applications, creating economic synergies that improve the overall return on investment profile (Bresnik, Maurer, and Metcalf 2020). Robotic construction technologies developed for space environments find immediate commercial applications in hazardous terrestrial settings including underwater construction, nuclear facility maintenance, and disaster response, creating parallel revenue streams that help justify initial research and development investment (Zheng et al. 2021). For instance, computer vision systems for autonomous planetary rovers have been commercialised for agricultural monitoring and mining operations, while soft robotics for delicate assembly tasks in space have applications in precision manufacturing and surgery. This establishes a financial feedback loop wherein terrestrial applications generate revenue to fund space technology development, while space-derived innovations enhance terrestrial capabilities, creating a virtuous cycle of innovation and investment that benefits both domains simultaneously, as seen in the Texas ACM Autonomous Self-Growing Structures project where bio-mediated construction approaches have potential terrestrial applications in sustainable building (Mondragon 2022).

According to comprehensive market analysis by Mordor Intelligence, the global robotic arms market is projected to expand from $36.93 billion in 2024 to $76.2 billion by 2029, representing a compound annual growth rate of 15.6%, indicating strong economic tailwinds for space robotics development (Mordor Intelligence 2024). The space sector represents a fast-growing niche within this market, characterised by high barriers to entry due to technical complexity and certification requirements, premium pricing power for firms with proven reliability, a distinct trend toward modularity allowing customisation while amortising development costs across multiple missions, and increasing emphasis on human-robot collaboration to enhance overall mission efficiency and safety (European Space Agency 2023). This robust growth trajectory reflects increasing confidence in robotic systems' capabilities to perform economically critical functions in space environments, with specialised space robotics companies commanding valuation premiums due to their specialised expertise and limited competition, creating attractive investment opportunities in this emerging sector (Kutschera and Lindman 2024).

Artificial intelligence is revolutionising financial planning for space projects through advanced analytical capabilities that improve decision-making and risk management. AI-powered financial modelling systems like the one developed by the European Space Agency's "Discovery" program, which uses machine learning to simulate mission costs under thousands of different scenarios, can process vast datasets to identify optimal investment structures, predict cost overruns, and simulate funding scenarios under extreme uncertainty, providing valuable insights for projects like the Moon Project Cost Modelling which creates sophisticated mathematical models for forecasting lunar construction expenses (European Space Agency 2023). For example, in traditional construction, machine learning models like HistGradient Boosting are used for accurate cost prediction, and similar AI systems can be applied to space projects (ScienceDirect 2025). Machine learning algorithms are being deployed to assess the creditworthiness of space ventures by evaluating technological viability using non-traditional data sources, analysing factors such as technical team expertise, patent portfolios, and simulation results that traditional financial models overlook, creating more accurate risk assessment frameworks (Kutschera and Lindman 2024). Furthermore, AI is transforming risk assessment and management in space architecture projects through advanced algorithms that can identify potential failure modes, quantify their financial implications, and recommend mitigation strategies—capabilities that are invaluable for insurance underwriting of space missions. These AI-driven financial technologies are reducing the cost of capital for space architecture projects by improving risk assessment accuracy, with demonstrated applications including machine learning for cost prediction with improved budget estimation accuracy, natural language processing for regulatory compliance monitoring across jurisdictions, predictive analytics for early identification of potential cost overruns, and optimisation algorithms for efficient resource allocation despite complex system interdependencies, though implementation challenges remain around limited historical data for training models and difficulties in quantifying unknown-unknowns in unprecedented space ventures (Bresnik, Maurer, and Metcalf 2020).

## VI. ANALYSIS OF EXTRATERRESTRIAL ARCHITECTURAL PROJECTS

The systematic examination of notable extraterrestrial architectural projects reveals significant patterns in technical approaches and economic considerations across different implementation frameworks. It is important to note that the cost estimates provided in this section are compiled from public sources, project proposals, and open repositories. They are intended for comparative analysis and to illustrate the economic paradigm of extraterrestrial construction, rather than representing fully verified final costs.

### NASA and Space Agency Projects

NASA and space agency projects like the Mars Ice Home, a collaborative design by NASA Langley Research Center, SEArch+, and Clouds Architecture Office, represent innovative approaches to radiation protection through an inflatable habitat surrounded by water ice, with development costs of approximately $130 million significantly less than alternative designs due to extensive use of in-situ resources. The Lunar Lantern, a NASA Centennial Challenge winner, exemplifies vertically oriented 3D-printed habitat using lunar regolith with radiation shielding, costing an estimated $45 million compared to ~$200,000 for similar terrestrial structures due to technology development and space adaptation requirements. ESA's Luna Village modular concept for lunar settlement uses interconnected inflatable and 3D-printed modules with an estimated cost of $1.2 billion for initial operational capability, demonstrating how scalability and incremental development can distribute costs over longer time horizons. Marsha by AI SpaceFactory presents a vertical Mars habitat 3D-printed using basalt fibre from Martian rock that won NASA's 3D-Printed Habitat Challenge, with terrestrial comparisons showing similar structures cost approximately $500,000 while Mars implementation is estimated at $60 million due to automation requirements, highlighting the premium for extraterrestrial implementation. SOM's Moon Village collaborative project with ESA features interconnected modules with radiation-shielded utilities core at an estimated cost of $2.3 billion, reflecting the comprehensive nature of designs that include living quarters, laboratories, and agricultural areas.

### Academic and Student-Led Projects

Academic and student-led projects contribute innovative concepts that expand the solution space for extraterrestrial architecture, often exploring higher-risk approaches that may yield substantial long-term benefits. MIT's Mars Urban Design utilises lava tubes for natural radiation protection with estimated deployment costs of $350 million compared to $5-8 million for similar terrestrial underground structures, with the differential primarily due to transportation and specialised equipment requirements. Columbia University's Lunar Habitat modular design with regolith-shielded inflatable components has development costs estimated at $120 million versus $800,000 for comparable terrestrial inflatable structures, with the increase attributable to radiation hardening and redundant systems. University of Stuttgart's REGOLITH HABITAT 3D-printed structure using simulated regolith with robotic arm system has cost assessments estimating $85 million development costs, with terrestrial equivalents approximately

$300,000, demonstrating the premium associated with space-rated systems. Carnegie Mellon's Moon Arch prefabricated arch design covered with regolith has cost projections estimating $70 million implementation versus $1.2 million for similar Earth-based architectural forms, with the differential reflecting transportation costs and specialised assembly equipment. Tokyo University's Mars Dome double- shelled dome with water-filled layer for radiation protection has cost estimates of $180 million compared to $4 million for similar terrestrial geodesic domes, with the increase due to water processing systems and radiation-resistant materials.

**Private Sector Initiatives**

Private sector initiatives bring commercial perspectives and efficiency-driven approaches to extraterrestrial architecture, often focusing on scalability and business model innovation. Bigelow Aerospace's B330 inflatable habitat module adaptable for lunar or Martian use had cost estimates of $125 million per unit compared to $12 million for terrestrial inflatable structures of similar size, reflecting additional requirements for space habitation including radiation shielding and life support systems. Blue Origin's Blue Moon Habitat integrated lunar landing system and habitat concept has estimated development costs of $1.5 billion, reflecting the company's vision for lunar settlement through commercial approaches leveraging reusable launch systems. SpaceX's Mars Habitat Prototype using Starship vehicles as structural components has cost projections of $800 million per habitat cluster, demonstrating innovative reuse of transportation hardware as habitable structures to reduce development costs. Lockheed Martin's Mars Base Camp orbital habitat concept with surface landers has an estimated cost of $3.2 billion for the complete system, incorporating heritage technology from NASA's Orion program to potentially reduce development risks. Foster + Partners' Lunar Habitat 3D-printed using regolith has cost analysis estimating $250 million implementation versus $1.5 million for terrestrial equivalents, bringing professional architectural expertise to space habitat design through collaboration with ESA.

**Advanced Conceptual Projects**

Advanced conceptual projects push the boundaries of architectural possibility for extraterrestrial environments, exploring transformative approaches that could fundamentally change economic assumptions. The Zopherus Mobile Printer autonomous robotic system that collects and processes local materials won NASA's challenge with estimated costs of $95 million per unit, demonstrating how mobile systems could construct multiple habitats across extended areas. SEArch+'s Mars Habitats radiation-resistant designs with optimised light distribution cost $140-180 million per habitat, emphasising human-centred approaches that prioritise occupant well-being through connection to the external environment. XArc's Lunar Oasis commercial habitat concept with greenhouse module is estimated at $320 million for the complete system, incorporating commercial approaches that support both research and potential tourism activities. SICSA's Mars Habitat 3D-printed structure with separate crew and laboratory areas costs approximately $110 million, emphasising operational efficiency through separation of noisy laboratory areas from quiet crew quarters. The Bioshield Habitat biological protection system using fungi-based radiation shielding has development costs of $65 million, representing how radically innovative approaches might transform space habitat design through interdisciplinary research that could dramatically reduce shielding mass requirements.

This comparison reveals that extraterrestrial architecture operates under a fundamentally different economic paradigm, where the cost of adaptation for space— including radiation shielding, life support, and transportation—dwarfs terrestrial construction expenses. Architects can learn that the most viable solutions heavily prioritise the use of in-situ resources, modularity for scalability, and the innovative reuse of delivery systems as structural components, demonstrating that extreme constraints can drive highly efficient, integrated, and resource-conscious design thinking. It is also important to highlight the significant research gap concerning verifiable cost data for these projects, which underscores the nascent state of this field and the critical need for more transparent, peer-reviewed economic analyses to advance from conceptual design to practical implementation.

## VII. INTEGRATED TECHNO-ECONOMIC ANALYSIS

The ambition to acquire and utilise space resources predates the history of human spaceflight, with early visions documented by Clarke (1951), Jenks (1956), Holmes (1962), Carr (1963), and McDougal, Lipson, and Ellis (1963). For humanity to sustainably expand beyond low Earth orbit, mastering the use of local resources through in situ resource utilisation (ISRU) is essential. However, significant knowledge gaps remain regarding resource locations, availability, and accessibility before human site selection, mining, or ISRU can begin. Donald and Baker (2020) emphasise that without accurate prospecting data, selecting the first human landing site should not occur arbitrarily or purely for scientific discovery. Given the enormous costs of human spaceflight, the initial site must be optimised for resource acquisition, particularly when the ultimate goal is establishing permanent, sustainable infrastructure (Taylor and Martel, 2003; Carpenter, Heneghan, and Martinez, 2016). Deploying multiple human missions to disparate locations without reusing infrastructure wastes resources and increases program risks, including potential cancellation between budget cycles or administrations. Historical parallels can be drawn from early colonial attempts in the Americas, such as the failed settlements of La Navidad (lasting less than a year) and La Isabela (surviving only four years) following Columbus's 1492 voyage (Flint, 2019;

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Morison, 1940; Deagan, 1988). While terrestrial colonisation benefited from gravity, radiation protection, breathable air, water, food, and building materials, the transition to space must overcome these same hurdles in the most extreme environment humans have ever inhabited (Donald and Baker, 2020).

The cost differential between terrestrial and extraterrestrial construction projects is substantial, primarily due to transportation expenses, extreme environmental adaptations, and the need for autonomous systems, creating economic challenges that require innovative solutions. Based on analyses, extraterrestrial construction costs are approximately 200-500 times higher than comparable terrestrial projects, with the multiplier varying based on complexity and technology readiness, creating significant barriers to entry that must be addressed through technological innovation. As highlighted by Lesley Henton of Texas ACM University Division of Marketing and Communications, "it costs anywhere from $500,000-1 million to haul one kilogram of anything into space," underscoring the dramatic economic challenges of space construction. NASA's Artemis mission is working toward a future where humans are an interplanetary species—with lunar bases planned by 2030 and a round trip to Mars in 2039—requiring buildings in which to live and work despite these prohibitive transportation costs (Henton, 2023).

Transportation impact represents a significant factor, with launch costs accounting for 35-60% of total project expenses for extraterrestrial habitats, creating tremendous economic pressure to minimise mass through innovative design and material choices, as demonstrated in the MMPACT project's focus on using in-situ regolith. Projects utilising in-situ resources demonstrate 30-45% lower costs compared to those relying on Earth-sourced materials, providing compelling economic justification for developing ISRU technologies despite their technical challenges, as seen in the Lunar Habitat via Contour Crafting which explores large-scale extrusion printing using molten regolith (Zeng, Metzger, and Schlautmann, 2022).

The development of autonomous robotic systems adds 25-40% to initial project costs but reduces long-term operational expenses by minimising human intervention and maintenance requirements, creating favourable lifecycle cost profiles despite higher upfront investment (Foster, Mueller, and Mohon, 2021). The economic case for extraterrestrial construction relies on significant reduction of transportation mass through ISRU and prefabrication, fundamentally changing the cost structure of space habitation. According to delta-v calculations (change in velocity required for missions), every kilogram of material sourced locally instead of transported from Earth saves approximately $20,000 in launch costs alone, creating powerful economic incentives for developing local material utilisation technologies (Foster, Mueller, and Mohon, 2021). This economic reality drives architectural innovation toward designs that maximise local materials and minimise Earth dependency, though this approach remains dependent on utilising expensive cutting-edge technology and robots that themselves require substantial development investment, creating a complex economic balancing act between different cost categories.

The cost analysis reveals that the most significant factors influencing extraterrestrial construction economics are transportation mass, degree of autonomy, and technology readiness level, providing clear guidance for research and development prioritisation. Projects incorporating higher levels of in-situ resource utilisation demonstrate better economic viability despite higher development costs, particularly as scale increases, suggesting a pathway toward economic sustainability through technological maturation (Zeng, Metzger, and Schlautmann, 2022). Similarly, habitats designed for expandability using local materials show favourable long-term economics compared to fixed designs that require additional Earth-based components for expansion, highlighting the importance of flexible architectural approaches. These economic considerations fundamentally shape architectural approaches to extraterrestrial habitats, favouring designs that creatively integrate local materials and robotic construction methods, as seen in projects ranging from the Mars Dune Alpha to the Autonomous Self-Growing Structures that explore fundamentally different approaches to construction (Foster, Mueller, and Mohon, 2021).

For architects and architecture students considering design and cost implications, radiation protection presents both a critical challenge and opportunity for innovation.
Designs for long-term missions to the Moon, Mars, and beyond must account for prolonged crew exposure to biologically-hazardous space radiation, requiring shielding strategies that are integrated from the outset rather than added later, as was done with polyethylene shielding on the International Space Station (Shavers et al., 2004). The space radiation environment produces both deterministic effects (acute radiation sickness, cataracts) from short-term exposure to solar particle events and stochastic effects (cancer) from long-term exposure to galactic cosmic rays, with the latter being particularly concerning for missions lasting three months or more (Cucinotta, Chappell, and Kim, 2012; Cucinotta, 2014; Cucinotta and Cacao, 2017). The prohibitive cost of launching dedicated shielding materials makes multifunctional materials—which serve both structural and radiation protection purposes—an economically essential design strategy (Wilson et al., 2001b; NRC, 2008). This approach enables mass optimisation through material replacement, relocation, or repurposing to better protect space crews while reducing overall mission costs. DeWitt and Benton (2020) emphasise that engineers and designers require empirically-obtained performance data on space radiation shielding efficacy to match mechanical characteristics with the As Low As Reasonably Achievable (ALARA) principle, creating an urgent need for quantification methods that evaluate

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candidate materials for future spacecraft and planetary habitats (Wilson et al., 2001a).

When examining specific technology implementations, the following six Moon-to-Mars Planetary Autonomous Construction Technology (MMPACT) projects demonstrate how targeted technological development addresses critical economic challenges in extraterrestrial construction. The foundational MMPACT project (NASA, 2021) focuses on developing autonomous capabilities for constructing large-scale infrastructure using in-situ regolith, with the fundamental economic driver being In-Situ Resource Utilisation (ISRU) to offset exorbitant launch costs that can reach hundreds of thousands of dollars per kilogram. The Mars Dune Alpha habitat (NASA and ICON, 2021) represents a critical, ground-based investment in risk mitigation, with expenditure analytically categorised as necessary upfront cost to de-risk and refine operational protocols for actual Mars missions where errors would be far more costly. The Artemis Program Lunar Launch and Landing Pads (NASA, 2022) address essential infrastructure needs, though within a program facing significant identified cost overruns that highlight the financial challenges of lunar return efforts (GAO, 2023).

The Autonomous Self-Growing Structures project (Texas ACM University, Dr. Congrui Grace Jin, 2020s) explores a bio-mediated construction approach using synthetic lichen systems, offering potentially revolutionary cost efficiency by eliminating needs for external nutrient supplies and reducing long-term operational costs to near-zero after initial setup (Jin, Chen, and Martinez, 2023). The Lunar Habitat via Contour Crafting (NASA and ICON, 2023) demonstrates substantial cost-saving potential through using local regolith to avoid heavy launch costs associated with traditional building materials. The Moon Project Cost Modelling (Various space agencies and research institutions, 2020s) develops sophisticated mathematical models for forecasting lunar construction costs, highlighting the severe risks inherent in lunar projects and advocating for advanced statistical forecasting techniques to improve financial viability.

## VIII. CONCLUSION

Architectural practice for the Moon and Mars must be economically literate and programme-aware. ISRU and autonomous fabrication are not optional technologies but the primary levers for feasible, low-mass design; funding strategy and institutional resilience determine what can actually be built. Embedding economic realism, staged delivery and policy alignment into the design process produces resilient, buildable solutions that convert bold forms into operational habitats.

The review of current projects shows that tightly integrated design—where form, fabrication and finance are co-developed—delivers the greatest gains. Autonomous robotic systems, predictive maintenance and in-situ resource use reduce upmass and operational risk, producing lifecycle savings commonly estimated in the tens of percent versus Earth-dependent approaches. As launch costs fall and autonomy matures, these savings grow, enabling more ambitious programmes and more durable architectures.

Real progress depends on sustained collaboration between agencies, industry and academia: agencies supply long-term vision and testbeds, universities provide research and prototypes, and companies scale engineering and supply chains. The best teams will fuse architecture, robotics, AI and finance so economic sustainability is a design requirement from day one. That integration—autonomy + ISRU + financial intelligence— turns extraterrestrial architecture from a speculative cost burden into a strategic, scalable investment.

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