A GENERAL MODEL OF ISRU TECHNOLOGY VALUATION AND TECHNOLOGY PORTFOLIO CONSTRUCTION FOR CREWED MARS MISSIONS.

G. Lordos[1,2], A. Siddiqi[2], M.Hoying[2], J. Milton[2], Y. Lin[2], A. Webb[2], C. Gentgen[2], L. McKinney[2], C. O'Neill[2], W.L. Chan[2], A. Koenig[2], C. Nguyen[2], H Azzouz[2], P. Patel[2], J. Hoffman[2], O. de Weck[2]. [1]Corresponding author: glordos@mit.edu, [2] https://spaceresources.mit.edu, and https://systems.mit.edu, Massachusetts Institute of Technology, 77 Mass.Av, 33-409, Cambridge, MA 02139

Executive Summary: Ideally, investments in *in-situ* resource utilization (ISRU) technologies ought to be motivated by the *total* expected value that ISRU could contribute to crewed planetary surface missions. In practice, however, most approaches to quantify ISRU value have been limited to sectoral cost-benefit analyses of infusing ISRU technology, with most studies focusing on the potential to reduce the cost of space transportation for multiple missions. In response to this, and to other gaps, the NASA ESI Advanced Space Technology Roadmapping Architecture (ASTRA) project at MIT's Engineering Systems Lab [1], now in its third year, is developing a generalized methodology for the valuation of all space technologies. The ASTRA approach includes the construction of efficient technology investment portfolios which can trade off risk against expected "return" from the use of ISRU. ASTRA models accept probability distributions for input assumptions and can be used at the system level [2], system-of-systems (SoS) level, or both. Using two levels of high-fidelity models, at the SoS level (e.g., Mars Human Architecture) and the system level (e.g., produce new water, or recycle water on Mars?), we show how to calculate the relative value of different technologies in terms of their marginal contribution to high-level Figures of Merit (FoM) such as "Mission Cost per Full-Time-Equivalent (FTE) scientist on Mars per year". The approach is illustrated with a case study of a 10-year Mars architecture that relies heavily on ISRU. Early results show promise in quantifying the relative value of large vs. small crewed missions and of open-loop vs. closed-loop life support technologies. This work can provide a quantitative basis to justify the infusion of ISRU technologies in crewed missions to the Moon and Mars and support a variety of program-level activities including: technology roadmapping; prioritization of knowledge gap closure; mission architecting; stress-testing of architectures; and the construction of efficient risk/return portfolios of technologies to prioritize for development.

Motivation: NASA is returning to the Moon with the Artemis project, this time to stay and also to develop technologies for the exploration of Mars. Sustainably staying on the Moon and Mars poses the question of optimal technology selection and infusion to best support diverse mission goals, including the safe return of the crew and mission value, such as science knowledge.

Approach: To select an optimal portfolio of technologies, including ISRU technologies, it is essential to: 1. define goal-driven FoM at the SoS level; 2. develop tradespace exploration models to link the modeled performance and costs of alternative system-level technologies with the SoS level FoM; 3. Vary technology performance at the system level and sample the probability distributions of model assumptions to obtain probability distributions of model outputs as a function of technology performance; 4. Use outputs to construct efficient portfolios of technologies that trade off risk vs. return, where return is typically defined as benefit at cost and risk is typically defined as the variance of the return.

Efficient portfolios. As the output distributions all emerge from the same high-fidelity model, covariances between the returns of diverse technologies allow the construction of efficient technology investment portfolios which naturally pool and hedge technology risks.

Comparison to Current State of the Art: Space technology investment decisions are typically made in two ways: 1. Limited-scope trade studies which aim to optimize an intermediate Key Performance Indicator, such as Equivalent System Mass (ESM) [3]; or 2. Consensus among expert stakeholders. Relying on both of these approaches, NASA-supported working groups, including MEPAG [4], MASG [5], ISECG [6], and the MAT [7], issue and update reports, reference architectures and other publications which implicitly or explicitly ultimately engage in technology selection.

Markowitz Portfolio Theory. Building on the state of the art, the ASTRA approach synthesizes system-level modeling and expert opinion into whole-architecture models to generate distributions of predicted returns from investment in space technologies. In so doing, ASTRA draws from Markowitz Portfolio Theory [8], which underpins nearly all portfolio construction in the trillions-of-dollars financial services industry.

Model Structure: The human Mars architecture model consists of the following elements which support analyses related to the infusion of ISRU technologies into Mars mission architectures, including ISRU technology valuation and technology portfolio construction:

Dashboard. Used to select one of many prescreened, *prima facie* feasible design vectors, such as "two villages of 12 persons with a desired ECLS safety margin of X% and an annual growth target of Y%".

Parameters and intermediate variables. All inputs and intermediate variables are defined, named and cited. Where appropriate, they are defined as probability distributions instead of point estimates.

Crew Time Model. A high-fidelity crew time model to estimate crew time absorbed by each of 515 unique Mars surface operations tasks, after Stuster et al [9].

Architecture Decomposition. A four-level decomposition of the entire architecture to facilitate granular calculations of manufacturability and crew-time requirements for each element of the architecture. This also facilitates the roll-up of results and ultimately the calculation of the value of a technology in terms of its impact on system-level FoM.

Industrial Ecology Model. Simulates capabilities available to the crew so that they can transform available inputs to needed intermediate or final outputs. Capabilities are selected from a range of modeled ISRU and in-situ manufacturing technologies. The industrial ecology model outputs are all subsystems defined in the Architecture Decomposition, and the inputs include the capabilities available in the ecology, energy, crew time, Earth resupply of ready-made spare parts or complex sub-assemblies, and Mars natural resources.

Other Sectoral sub-models. These include an energy model, farming model, simulated failures model, resource stockpile model, permanent habitat sizing model, radiation budget model, and more. Intermediate inputs and outputs serve as interfaces between sub-models.

Output tables. These include, for each design vector, a Master Equipment List, Cost Budget, Crew Time Utilization analyses, In-situ Resource Supply demands, Earth resupply demands, and Total Radiation Dose.

Case Study Overview – Pale Red Dot: The NASA / NIA RASC-AL 2023 challenge [10] requires a 7-year surface stay with minimal resupply of only 5 tons every two years. In the Pale Red Dot architecture [11,12], precursor missions close knowledge gaps, de-risk technologies and support site selection: the site has high potential for science returns, ease of access to water and other resources, and is compatible with technologies for the construction of permanent habitats. Next, landing pads, energy, ISRU, agricultural, industrial, and habitation infrastructure are deployed robotically and validated remotely before crew departure. One or two villages, for a total of 4 to 36 crew, serve as intermediate habitats upon arrival. Over the years, the crew operate the farms, industrial and construction systems aiming to not only maintain but steadily grow the carrying capacity of their habitat. A key design goal is to strive to maximize unallocated crew time to enable secondary expression-related professions and to allow free time which can be used for self-rescue in the event of contingencies.

Results: With a given set of technologies, varying mission size reveals whether the resulting architecture is feasible, and how the FoM vary. We observed that the most relevant metric, cost per FTE scientist on Mars, can be two orders of magnitude higher for small missions vs. large missions: $19.3 billion per FTE scientist on Mars per year for a 6-person mission, vs $235 million per FTE scientist/yr for 36 crew. Alternatively, for a given mission size, varying the technology selection design vector leads to changes in the output variables of cost and of time available for science. We have studied two supply chains in-depth, a CO_2 removal system and a water recovery system. For a 2-site, 36 crew mission, the CO_2 system exhibited average manufacturability from Mars in-situ resources of 94% and a crew time lien of 12.5 crew-hours per year per crew on Mars. However, the water recovery system analysis yielded a manufacturability metric of just 56%, which poses a high lien on the Earth resupply budget. This indicates that water production technologies could be traded as an alternative to water recovery technologies. Ultimately, we showed that the more diverse the industrial technologies available, the higher the manufacturability of systems from in-situ resources, the larger the crew that can be supported, and the lower the cost per FTE scientist on Mars. Visuals will be shared with the presentation.

Discussion and Conclusion: Mission size and the selection of technologies were found to strongly influence both mission safety and mission value. Work is ongoing to complete more supply chain studies and to calculate value metrics for alternative ISRU technologies in terms of FTE scientists on Mars. Ultimately, the result is a new capability for the relative valuation of any ISRU and non-ISRU technologies vs. a common unit of measure selected by the planner, here "Mission cost per FTE scientist on Mars, per year of operations".

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References: [1] NASA STMD (2021) ASTRA project web page [2] Lordos, G., de Weck, O. (2022) *Technology Roadmapping of an ISRU System for NASA Using a Medium-Fidelity System Dynamics Simulation*, ASCEND 2022 [3] Levri, J.A. et al, *Theory and Application of Equivalent System Mass Metric,* SAE 2000-01-2395 [4] Jakosky, B.M. et al (2020) *Report by NASA MASWG*, [5] Drake B.G. et al, (2009) *Mars DRA 5.0*, [6] *ISECG Global Exploration Roadmap*, [7] Rucker, M.A. et al, (2022) *NASA's Strategic Analysis Cycle 2021 Human Mars Architecture*, [8] Markowitz, H. (1952) *Portfolio Selection*, Cowles Commission Paper, New Series, No. 60 [9] Stuster, J. W. et al (2018) *Human Exploration of Mars: Preliminary Lists of Crew Tasks*, NASA NTRS [10] *RASC-AL 2023 web page* [11] Hoying M. et al, (2023) *Pale Red Dot*, MIT RASC-AL submission [12] Lordos, G. et al (2023) *Tradespace Exploration of Large, Multi-Site Mars Human Exploration Architectures*, subm. ASCEND