PREDICTIVE MODELING FOR PHASED INFRASTRUCTURE BUILDUP ON THE LUNAR SURFACE.

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Introduction: The shifting focus of space as a competitive domain requires us to rethink it as a geopolitical geography, mirroring terrestrial contested zones such as the South China Sea [1]. As state and commercial actors begin to perceive space resources as strategic, these resources will become "securitized", and those parties that have the ability to compete will compete. The Moon has always been a key part of ISRU strategy, not only for its own resources, but as a staging point for other missions to Mars and beyond. The Moon to Mars Architecture is a multi-decadal campaign with a goal of ensuring access to the lunar south pole and expanding capability for non-polar expeditions. These "when" and "where" critical questions impose the need for an overarching strategy of phased placement and staging of equipment and infrastructure on the lunar surface, potentially in a competitive geopolitical climate. This project aims to develop and use geological and geospatial metrics to inform an optimization problem set that initiates strategy development for phased lunar operations in both an uncontested and contested environment.

Methods: The study employs a deterministic optimization approach through an Integer Programming (IP) problem formulation to develop a strategy for the phased emplacement of lunar mining infrastructure. The IP model is designed to maximize the net value of extracted lunar resources over a multi-turn time horizon, subject to budgetary, technological, and resource constraints. A region of interest on the lunar surface is discretized into a map of hexagonal tiles (Fig. 1) to reduce the overall complexity of the model and increase the feasibility and accessibility of future human-in-the-loop simulations.

Sets: Time periods (T) represent the distinct phases of infrastructure development and resource extraction. Hex tiles (H) on a lunar surface grid represent potential operations sites. Resources (R) include various extractable lunar materials. An example metric shown in Fig. 1 is the Ice Favorability Index (IFI, in blue) to indicate locations of potential water ice resources on the surface [3]. Vehicles (V) and Infrastructure (I) represent the technological elements available for deployment.

Parameters: Model parameters include initial resource quantities ($q_{r,h,1}$) and monetary values (val_r) per unit, costs associated with purchasing (c_v, $c_{i,purchase}$) and deploying ($c_{i,deploy}$) vehicles and infrastructure, along with research costs (rc_v, rc_i), capacities of vehicles (u_v) and infrastructure (u_i) at various technology levels, and initial budget (b_1) available for investments in infrastructure and technology.

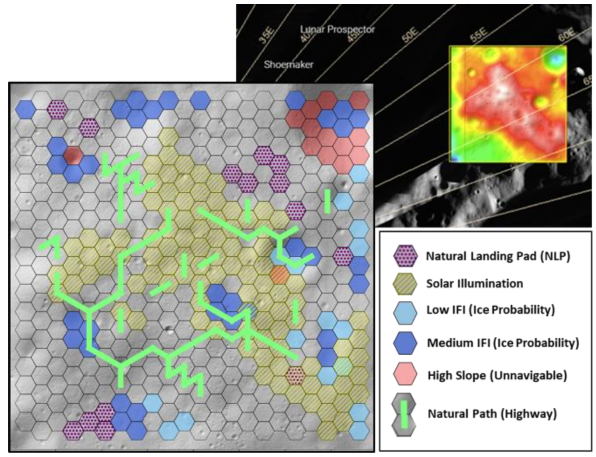

Fig. 1. 20x20 km Artemis ROI near Shoemaker Crater, discretized to 407 hex tiles, 1km center to center.

Decision Variables: Binary and integer decision variables capture vehicle purchases ($X_{v,t}$), infrastructure purchases ($F_{i,t}$) and deployments ($Y_{i,h,t}$), technology research ($W_{v,t}$, $W_{i,t}$), and resource extraction quantities ($Z_{r,h,t}$).

Objective Function: The objective function maximizes the total net value of resources extracted, considering expenditures on technology, infrastructure, and operations.

$$\begin{aligned} Maximize \sum_{t\in T}\Bigg(\sum_{r\in R}\sum_{h\in H} val_r Z_{r,h,t} \\ -\Bigg(\sum_{v\in V} c_v X_{v,t} + \sum_{i\in I} c_{i,purchase} F_{i,t} \\ + \sum_{i\in I}\sum_{h\in H} c_{i,deploy} Y_{i,h,t} + \sum_{v\in V} rc_v W_{v,t} \\ + \sum_{v\in V} rc_i W_{i,t}\Bigg)\Bigg) \end{aligned}$$

Constraints: The model incorporates constraints on budget expenditures, technological research prerequisites, infrastructure deployment based on research outcomes, dynamic resource availability, and extraction limits based on deployed capacities.

Using CPLEX, the deterministic model can be solved, iterating over the set T to simulate the strategic deployment of lunar mining infrastructure, finding an optimal set of decisions that maximizes the objective function within the given constraints.

Discussion: The proposed IP model offers an initial systematic framework for planning the phased emplacement of lunar mining infrastructure. By integrating decision variables related to technology research, infrastructure deployment, and resource extraction, the model facilitates a strategic approach to lunar ISRU. This method allows us to optimize resource allocation and scheduling to maximize the return on investment while considering the constraints imposed by technology, budget, and resource availability. The model's ability to incorporate technological progression and resource depletion over time provides valuable insights into the long-term planning of lunar mining operations. The deterministic optimization approach ensures that each phase of infrastructure deployment is aligned with the overarching goal of sustainable and efficient resource extraction. This planning tool could significantly impact decision-making processes for space agencies and private entities interested in lunar exploration and resource acquisition.

Stochastic Models for Uncertainty. The deterministic framework provides a foundational approach for strategic planning in lunar mining operations. However, lunar operations are fraught with uncertainties. Future research will explore stochastic models to better account for these elements. This includes probabilistically quantifying resource deposits, which would reflect the real-world uncertainty in estimating resource quantities. Stochastic elements like the probability of catastrophic events or equipment failures will be integrated to offer more resilient planning options. In a competitive, contested multiplayer scenario, changing game states can significantly impact strategic decisions. Stochastic modeling can simulate such dynamic environments, incorporating strategies under uncertainty and the actions of competing entities.

Terrain and Environmental Considerations. Advanced terrain assessments and regolith impact hazard metrics [4] will be integrated into future models to enhance site selection and infrastructure placement strategies. Pathfinding algorithms tailored for austere lunar terrain will be integrated to identify routes of high trafficability for resource transport operations. Fig 1. shows how metrics like the SHIELD equations [2], slope values, solar illumination, and pathfinding over DEM datasets can be integrated into the hex map.

Essential Infrastructure and Sustainability. Incorporating essential infrastructure elements such as power stations, habitats, and landing pads is crucial for supporting sustained human presence and operations on the Moon. Future iterations of the model will include these components, assessing their optimal placement and integration into the mining infrastructure.

Forecast Horizons. Forecast horizons [6] can be integrated into the model to anticipate future demand, resource availability, and technological advancements over a specified period. This approach would allow for adaptive planning, where decisions are continually updated based on new information, ensuring that infrastructure placement and resource extraction strategies remain optimal as conditions evolve.

Integer Programming Games. [5] introduces a computational framework for analyzing competitive scenarios through integer programming games (IPGs). Applying this approach to a multiplayer lunar mining scenario enables us to model interactions between multiple entities (e.g., commercial companies, international space agencies) competing for lunar resources. This model extension could simulate strategic decision-making in response to competitors' actions, allocation of resources and infrastructure under competitive pressure, and negotiation and cooperation strategies for resource sharing and infrastructure development.

Human-in-the-Loop Simulations. To bridge the gap between theoretical models and practical application, designing and conducting human-in-the-loop (HITL or "wargaming") simulations will be essential [7]. These simulations will allow real-time human interaction with the model in simulated lunar mining scenarios, providing invaluable insights into human decision-making, adaptability, and innovation in unpredictable environments. Metrics from these simulations will be compared to those generated by the optimization model. This comparison will identify areas for refinement, enhancing the model's predictive accuracy and applicability.

Conclusion: The goals of this project will significantly enhance the strategic planning framework for lunar mining, making it more robust, realistic, and applicable to real-world scenarios. By accounting for uncertainties, integrating comprehensive terrain and environmental assessments, and considering the infrastructure necessary for sustained operations, the model will offer a holistic approach to ISRU planning. Human-in-the-loop simulations will further bridge the theoretical and practical aspects, ensuring that the model remains relevant and adaptable to the evolving landscape of lunar exploration and mining.

References: [1] Goswami & Garretson (2020). [2] Menges & Cannon (2022), *53rd LPSC*, 1559. [3] Cannon & Britt (2020), *Icarus*, 347. [4] Menges & Cannon (2023), *SRR XXIII*, Poster 17. [5] Carvalho et al., (2023), *INFORMS*. [6] Daskin et al., (1992), *Ann. of OR*, 40, 125-151. [7] Curry et al., (2022), *Matrix Games.*