AN INTEGRATED ECONOMICS MODEL FOR ISRU IN SUPPORT OF A MARS COLONY—INITIAL RESULTS.

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Introduction: Previous work by us focused on creating an ensemble of specialized models intended to explore the commercial potential of mining water on Mars.[1] [2] This ensemble starts with a formal systems architecting framework to describe any Mars Colony and capture its artifacts' parameters and technical attributes. This database, the Mars Colony Architecture Model (MCAM), is then linked to a variety of "downstream" analytic models. In particular, we integrated an Extraction Process (i.e., "Mining") Model, a Habitation Model ("HabNet"), and an Economics Integration Model.

All told, over 50 market and technical parameters can be varied from within MCAM in order to address "what-if" questions. Further, by introducing alternative ISRU technologies for mining water/ice (i.e., different equipment and processes), one can develop an Analysis of Alternatives (AoA). Other significant trades can be performed by, for example, changing the Mars Colony's location or degree of Environmental Control and Life Support System (ECLSS) closure.

Mars Colony Architecture Model: MCAM is a relational database based on the Department of Defense Architecture Framework (DoDAF) 2.02 with 'for purpose' extensions.[3] Chief among these were extensions to handle dynamic changes in Mars surface assets and population (L_M), to make explicit a set of time-ordered deployment missions (i.e., an "assembly sequence"), and to take into account orbital mechanics and human physiology. The model serves as a flexible organizing tool to explore many architecture alternatives. The intended use is to support an "analysis of alternatives" (AoA) capability by linking to and feeding multiple "downstream" models with architectural-level artifacts (e.g., operational nodes and systems), relationships, and technical parameters.

Extraction Process Model: The Extraction Process Model focuses on the technologies associated with *in situ* resource extraction, processing, storage and handling, and delivery. For each mined resource, which may involve multiple cooperating *In Situ* Resource Utilization (ISRU) systems in a given architecture, the Extraction Process Model computes the optimal number of systems needed to support a particular level of (net) water demand, based on each system's technical parameters and the local Mars environment.

The water mining technology we modeled, commonly called "shovel and truck" is one familiar to the mining industry. The shovel here is actually an autonomous rover capable of being landed on Mars and drilling into Mars regolith of hydrated minerals. One of the variables of interest in the model is the distance between the Mars Colony habitation site and the water mining site. The Mining Model performs an optimization of the extraction, transportation, and processing cycle times to compute the number of systems needed.

HabNet: HabNet is a MatLab simulation based on software called BioSim. BioSim is a mid-to-high fidelity dynamic simulation, developed by TracLabs under a NASA contract, for the purpose of research on integrated ECLSS controls.[4] HabNet's purpose in this research is to quantify the demand for water in support of a Mars Colony population of size L_M.

One of the variables of interest in HabNet is the degree of ECLSS closure. A greater degree of closure results in less demand for water from external (mining) sources, but may increase the demand for spares and other supplies.

Economics Integration Model: The Economics Integration Model brings together market information (prices), investment, and operating costs as functions of time for various ISRU systems, along with measures of market uncertainty, with an objective of determining the profitability of commercial *in situ* mining operations supporting the Mars Colony. With results computed from the Mining Model and HabNet, the Economics Integration Model calculates yearly revenues and costs, and the Net Present Value (NPV) over a 20-year scenario.

In the calculation of revenues, we introduce price volatility with drift to represent a common aspect of commodity markets, the tendency for prices to exhibit random variability over time. NPV must therefore be treated as a random variable, whose probability distribution can best be determined through Monte Carlo simulation. For each experiment (consisting of a particular set of parameter values), we run the Economics Integration Model in a Monte Carlo mode to estimate the Cumulative Distribution Function (CDF) of NPV.

End-to-End Data Flow: Figure 1 shows a simplified block diagram of the ensemble of models. The ensemble is integrated using a commercial product, ModelCenter©, which executes the models in the order needed. It is important to note that each constituent model was developed and validated by that discipline's subject matter experts, and would normally be run in a standalone mode to address a particular issue within that discipline. In that case, required inputs would normally be entered by the user, but by linking them together as we have, inputs and outputs are automatically passed from one model to another as needed.

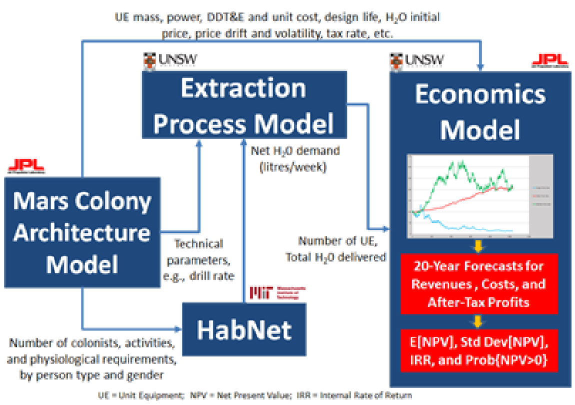

Figure 1: End-to-End Data Flow

Results: In our experiments, most technical parameters are treated deterministically, but are varied across a range of reasonable values. Some examples are shown in Table 1. A large number of experiments could be run using the ensemble; for example, with just 10 parameters each stepping through 4 values would require $>10^6$ runs. To explore the tradespace, we initially selected mid-range technical parameters, but economics inputs we thought would favor the likelihood of a positive NPV.

Table 1: Sample of Inputs Varied with Ranges

Model Name	Inputs Varied	Range
Extraction Process Model	Distance between drill points (m)	5-100
	Drill rate (m/hour)	0.5-2.0
	Transporter capacity (m^3)	0.5-4.0
	Minimum distance to processing plant (m)	1500-50,000
	Processing plant rate relative to extractor rate	5-20
	Water content (%)	5-15
HabNet	Number of 2-person EVAs per week	1-4
	Degree of ECLS system closure (%)	85-99
Economics Integration Model	Price volatility (%/week)	0.5-2.5
	Initial price of processed water ($/liter)	100-4000
	Unit equipment price (Mars *In Situ* Water Extractor) ($M)	200-800
	Launch and EDL cost per unit mass ($K/kg)	200-1000

In Figure 2, we show the results of a single such run. The number of colonists was set to 16 to see how much an initial investment would be needed to support a minimal colony population. These colonists conduct a two-person EVA on four days out of each week. The initial price of processed water in this run was set to (a very high value of) $4000/liter, and the weekly price volatility was also set very high at 2.5%. Launch/EDL costs were set at $500K/kg, a mid-range value. Unit equipment prices were set at the low end of the range shown. Even so, this run had an "in-the-money" probability, ***Pr***{NPV>0}, of only about 0.14 (14%).

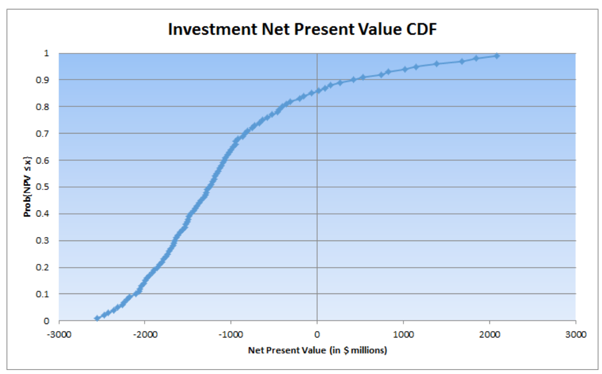

Figure 2: Sample Results (Expressed as the CDF of NPV) Under "Favorable" Economic Parameter Settings

References:

[1] Shishko, R., et al. (2015) AIAA-2015-4564.[2] Saydam, S., et al. (2015) 3rd *International Future Mining Conference Proceedings*, 305-311. [3] DoDAF Architecture Framework 2.02 website http://cio-nii.defense.gov/sites/dodaf20/index.html. [4] Do, S., et al. (2016) *Acta Astronautica, 120,* 192-228.