# An Integrated Economics Model for ISRU in Support of a Mars Colony—Initial Results Report

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**Previous work by us focused on creating an ensemble of specialized models intended to explore the commercial potential of mining water on Mars. This ensemble starts with a formal systems architecting framework, based on DoDAF 2.02, 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 "downsteam" analytic models. In particular, we integrated an Extraction Process (i.e., "Mining") Model, an Infrastructure and Integrated Logistics Support (ILS) Model, and an Economics Integration 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 production rate as a function of the systems' technical parameters and the local Mars environment. As with our earlier work, this model focuses on the extraction and processing of Mars water/ice.**

**The Mars Infrastructure and ILS Model simulates the fundamental sustainability relationships associated with establishing and maintaining a Mars Colony of population $L_M$. The model covers both the *in situ* infrastructure needed to support the Mars Colony (e.g., habitation, transportation, ISRU systems, etc.) as well as the interplanetary supply chain necessary to maintain and grow that infrastructure.**

**The Economics Integration Model brings together market information (prices), investment, and operating costs as functions of time for various *in situ* resources, along with measures of market uncertainty, with an objective of determining the profitability of commercial *in situ* mining operations supporting the Mars Colony. To this end, the CDF of Net Present Value is estimated using Monte Carlo techniques.**

**All told, over 50 market and technical parameters can be varied from MCAM in order to address "what-if" questions. Further, by introducing alternative ISRU technologies for water/ice (i.e., different mining equipment and processes), one can develop an Analysis of**

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**Alternatives (AoA). Other significant trades can be performed by, for example, changing the Mars Colony's location or degree of ECLS closure.**

**In addition to the canonical DoDAF Viewpoints, the ensemble of models is extensible, allowing for a variety of other complex Viewpoints/Views to be produced for a given Mars Colony architecture.**

## Nomenclature

| | | | | | |
|---|---|---|---|---|---|
| *DoDAF* | = | Department of Defense Architecture Framework | *OEM* | = | Off-Earth Mining |
| *MCAM* | = | Mars Colony Architecture Model | $L_M$ | = | Number of Colonists |
| *ECLS* | = | Environmental Control and Life Support | *ISRU* | = | *In Situ* Resource Utilization |
| *CONOPS* | = | Concept of Operations | *EDL* | = | Entry, Descent, and Landing |
| *CDF* | = | Cumulative Distribution Function | *NPV* | = | Net Present Value |
| *IRR* | = | Internal Rate of Return | *EVA* | = | Extravehicular Activity |
| *ISS* | = | International Space Station | *ILS* | = | Integrated Logistics Support |
| *MISWE* | = | Mars *In Situ* Water Extractor | *IOC* | = | Initial Operational Capability |

## I. Introduction

Previous work performed by us in 2015 focused on creating an ensemble of specialized models intended to explore the commercial potential of mining water on Mars in support of a Mars Colony.[1],[2] The chain of calculations made by the ensemble of models starts with a formal definition of a Mars Colony that is captured in a DoDAF 2.02 data model with some 'for purpose' extensions, and ends with a Monte Carlo simulation that results in a probability distribution for the mining operation's Net Present Value (NPV). In this paper, we describe each model in the ensemble, how these models were integrated, the end-to-end data flow, and what results were obtained as we varied some the many parameters—both technical and economic—that come into play.

The previous work was initiated in the wider context of sending humans to Mars. Irrespective of the timeframe when that might happen or how it might be accomplished, there is a general recognition that it will be necessary to use *in situ* resources. As humans establish a permanent presence on Mars, ISRU (*In Situ* Resource Utilization) will play a major role by satisfying the demand for oxygen, water, propellant, building materials, and energy. As the size of the human population on Mars expands, so must the scale of ISRU activities. In fact, the reaction to our earlier work was along the lines of how that scale up from a small research station to a full Mars Colony occurs, and at what point would a shift occur from government investment and sponsorship to commercial investment and operation. In other words, while there is a second general realization that it will take government investment in technology and basic infrastructure for a Mars Colony economy to emerge, ultimately it will take partnerships with the private sector to fully develop and sustain that economy once the risks are better understood.

Establishing a Mars Colony would certainly be a tremendous undertaking. Any feasible architecture will contain a variety of infrastructure elements (systems), many of which will contain technologies that have yet to be developed. These systems would have to be successfully put into operation on Mars and sustained over long periods of time. Using current systems engineering terminology, one would describe a Mars Colony as a system-of-systems, but to truly grasp the magnitude of the undertaking, it is worthwhile to put any Mars Colony (and the systems that might comprise its architectural components) in the context of its super-system. A Mars Colony exists within a complex that includes an interplanetary supply chain (and its component systems) and terrestrial enablers. Figure 1, taken from our earlier work, represents a context diagram that sets the stage for what follows. In the figure, the double-headed arrows represent exchanges/interactions that will ultimately have to be considered and perhaps modeled.

The interplanetary supply chain in the figure may include orbits and locations in the solar system (e.g., on the Moon or cislunar space) that serve as sources of propellant and propellant depots.[3],[4] Mars Cyclers may also be part of this supply chain as suggested by Aldrin.[5]

Terrestrial enablers include both physical infrastructure systems and socio-economic "systems" and Earth will certainly be the primary source of colonists through immigration for a considerable amount of time following the initial establishment of the colony. It is interesting to note, however, that all of the terrestrial enablers currently exist in one form or another with the exception of clear legal regimes and treaties needed to foster a resource economy in space, and on Mars, in particular.

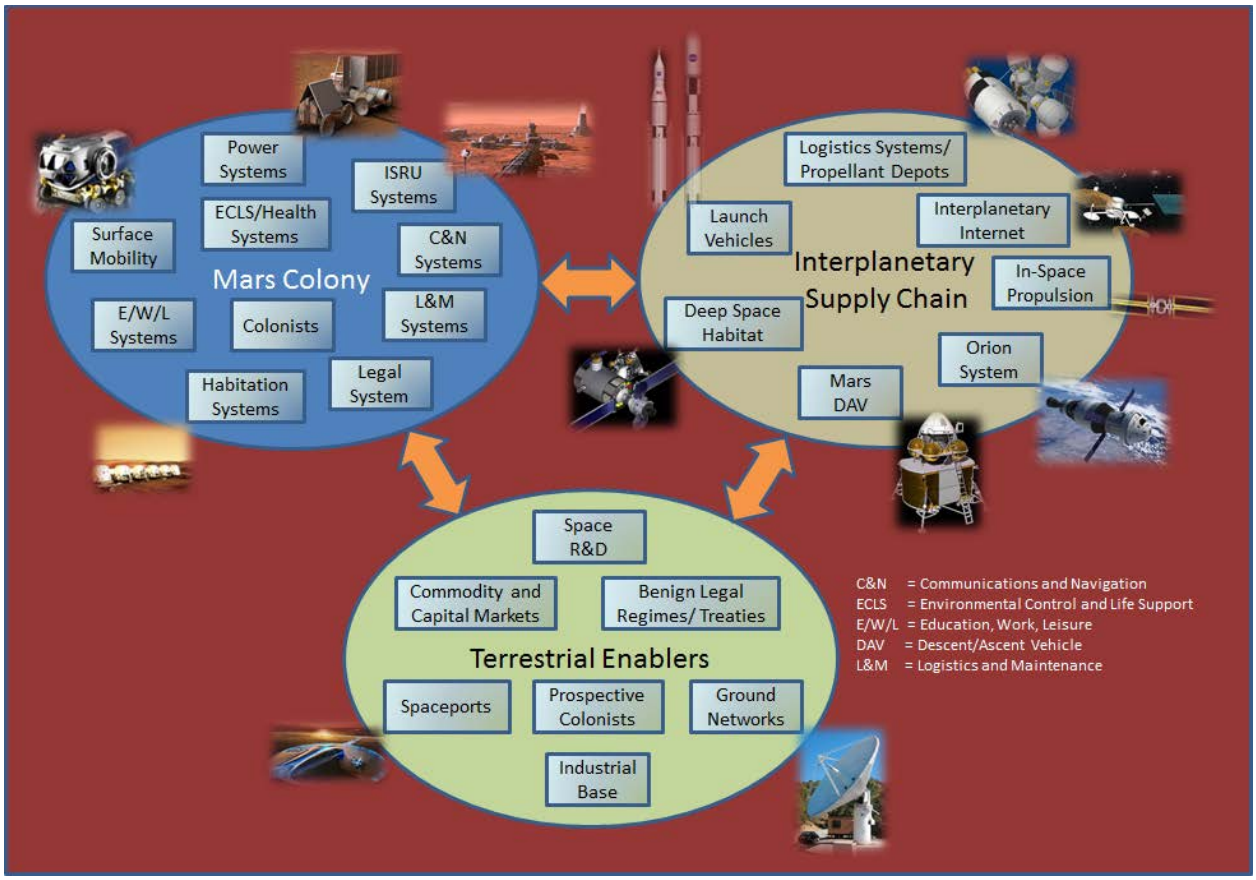


**Figure 1: Mars Colony Context Diagram**

## II. Four Models

Table 1 summarizes the purpose of each of the four models that comprise the ensemble. Each of the four models will be discussed in the sections that follow. It is important to note that each model was developed 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 are automatically passed from one model to another as needed.

**Table 1: Components of the Ensemble of Specialized Models**

| Model Name | Purpose / Outputs | Implemented In |
|---|---|---|
| Mars Colony Architecture Model (MCAM) | Relational data model to describe key architectural constructs (i.e., Operational Nodes, Milestones, Systems, Operational Functions, Performers, Metrics, etc.); provides inputs to the "downstream" models | Excel© |
| Extraction Process Model | For a given Off-Earth Mining (OEM) technology, optimizes the number of ISRU systems needed to fulfill the external demand | Excel with Solver |
| HabNet | Mid-to-high-fidelity time-based simulation; computes external demand for water based on ECLS system closure, number, type, and gender of Mars Colony inhabitants, EVA rates, etc. | MatLab© |
| Economics Integration Model | Generates 20-year average commodity price projections for Monte Carlo iterations; computes yearly investment and operations costs, resulting profits and losses, and Net Present Value (NPV), Internal Rate of Return (IRR) for a 20-year horizon; computes Cumulative Distribution Function (CDF) of the NPV | Excel |

## A. Mars Colony Architecture Model

The Mars Colony Architecture Model (MCAM) is a relational data base. As we emphasized in our initial status paper[1], its purpose is not to establish a single Mars Colony architecture, but rather to serve 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. Which analytic models are introduced into the ensemble is determined completely by what analyses and views are needed to satisfy the concerns of the Mars Colony's multiple stakeholders.

MCAM currently consists of 30 tables. Twenty of these are core tables; core tables hold the quantitative and qualitative data on each architecture's artifacts. The remaining tables serve to define or describe classes, types, and subtypes of the various artifacts. The MCAM Data Dictionary v.1.3 provides definitions for each table. The table below provides a brief summary of the core tables. Tables that contain values for various measures contain the inputs used by the ensemble's analytic models to be described next.

**Table 2: Summary of MCAM Core Tables**

| Table Name | Description of Architectural Content | Classes, Types, and Subtypes |
|---|---|---|
| Operational Nodes | Spatial locations in the solar system; locus of an operational function or activity | Surface locations (terrestrial and planetary); orbits; Lagrange points |
| Systems | Notional objects that fulfill a function; a hardware and/or software build | Based on broad system purposes, e.g., surface mobility, habitation |
| Operational Functions | Activities that transform inputs (resources) into outputs (other resources or end products), or change their state | Based on broad functional areas |
| Milestones | Time-stamped identification of significant changes | Based on capability achieved, e.g., initial operational capability (IOC) |
| Needlines | Needed interactions or exchanges between operational nodes | Based on the resource exchanged |
| Resources | Commodities of value to be tracked, e.g., information, labor, energy, materiel, etc. | |
| Partners | Organizational performers with development and/or operational responsibilities | Space agencies, commercial firms, etc. |
| Measures | Measurable (quantifiable) properties or attributes of interest | |
| Person Types | Individual performers with operational responsibilities that make up the Mars population | Subtypes based on skills from U.S. Bureau of Labor Statistics Standard Occupational Classification (SOC) |
| Standards | Applicable technical, operational or business standards and rules | ISO, ANSI, Community of Practice (CoP), government-unique, etc. |
| Flight Types | Conveyance of systems from one operational node to another | |
| Flights | Time-stamped assignment of flight types | |
| Nodes x Systems | Association of systems with operational nodes | |
| Flight Types x Systems | Assignment of systems to flight types | |
| Milestones x Measures | Time-stamped assignment of measure values to milestones | |
| Milestones x Systems x Measures | Time-stamped assignment of measure values to systems | |
| Milestones x Person Types x Gender Types x Measures | Time-stamped assignment of measure values to person and gender types | |
| Milestones x Resources x Measures | Time-stamped assignment of measure values to resources | |
| Needlines x Resources | Decomposition of needlines into system resource flows | |
| System Resource Flows | Identification of resource flows from one system to another | |

MCAM's table structure was largely based on DoDAF 2.02[6] with some 'for purpose' extensions that were needed for specific analyses in our research. 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 MCAM constructs (operational nodes, systems, operational functions, milestones, etc.) in Table 2 are just a more formal way of describing a Mars

Colony, or for that matter a "Lunar Village," architecture than we have seen elsewhere in the literature, where such constructs are less formally described, if at all. One advantage of a more formal structure for describing architectures lies in the superior consistency that can be achieved across viewpoints, documents, and trade studies, which is one of the goals of model-based approaches to systems engineering.[1] Those familiar with DoDAF, a widely used formal architecture framework, should be able to immediately see the similarities to MCAM constructs.

### B. 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 water extraction technology, 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 demand, based on each system's technical parameters and the local Mars environment. The overall production rate is then computed as a function of the systems' quantities.

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. This rover is based on a one from Honeybee Robotics, called the Mobile *In Situ* Water Extractor (MISWE).[7] The Extraction Process Model performs its constrained optimization using the Excel© "Solver" capability. Figure 2 shows the user interface annotated to facilitate a detailed explanation of each block.

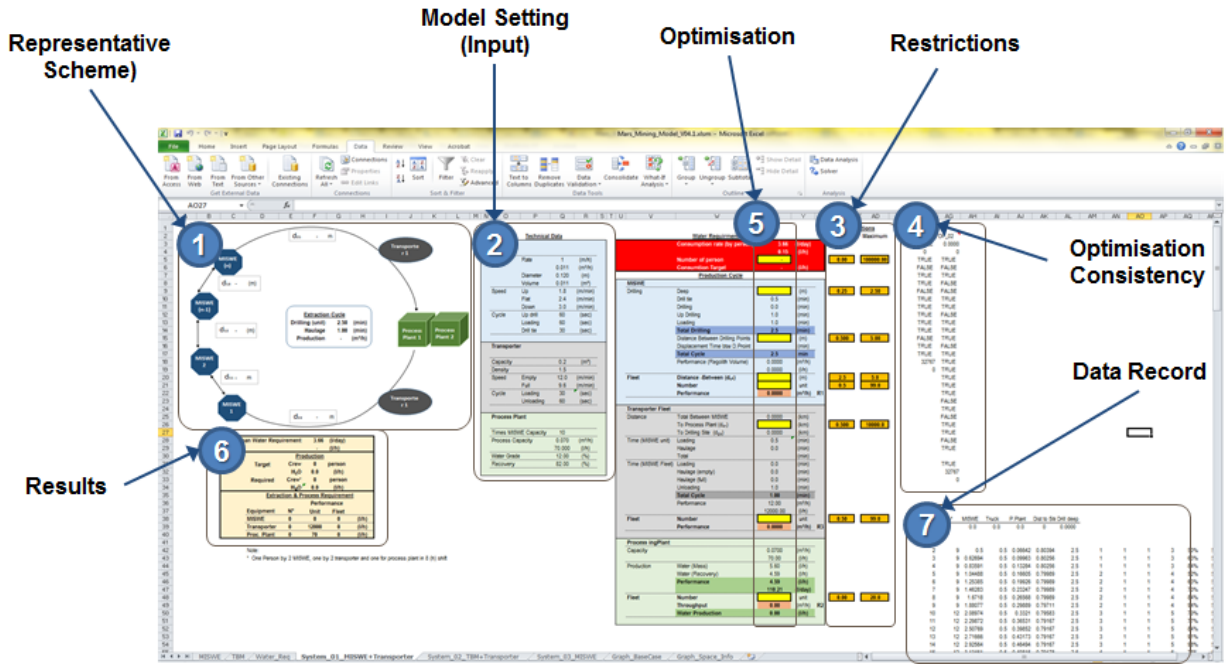


Figure 2: Explanation of Extraction Process Model User Interface

*Block 1—Representative schematic of system operation:* This schematic shows the main equipment involved, the interactions and material flows. The main results for the selected optimization are also displayed. However, the distances shown are not-to-scale, and the number of unit equipment shown is only illustrative, and not the result of the optimization performed by the model, i.e., the graphic is not dynamic.

*Block 2—Model Setting (input):* This block mirrors inputs from MCAM and computes derivative technical parameters of each system as configured as well as several capacity and performance metrics.

[1] This consistency can be enforced because the data and information in a formal structure are machine-readable, which permits automated error-finding checks of logic and terminology.

*Block 3—Restrictions:* To provide a more realistic approach, operating and technical restrictions for a particular configuration are captured in the orange cells. Restrictions are included for variables such as the minimum and maximum distance between the water mining site and the habitation site; for the drilling depth, which may be site-dependent; and for the number of systems. These values are controlled from MCAM.

*Block 4—Optimization Consistency:* This block provides a summary to verify if all of the variables used in the optimization fulfil the restrictions of the model. It also saves the optimized configuration determined by the Excel Solver.

*Block 5—Optimization / Simulation:* The optimization is based on linear programing, thus the model has the capacity to reach a target or maximize the capacity of the system. Yellow cells contain values required to calculate system performance (distance, equipment number, and drilling depth). These cells are filled by the Solver, which are then the optimum values required to reach a target or maximize the system performance.

*Block 6—Results:* For a particular optimization (configuration), this block summarizes the equipment requirements (detailed by main activities), number of operators, and number of people able to be supported.

*Block 7—Data Record:* After each optimization/simulation, the results are stored for further analyses. By using simple macro routine, output values are copied, pasted and stored. This macro routine just records the data and does not influence the optimization process.

### C. HabNet

HabNet is an ECLS system simulation, based on an open-source software package called BioSim[2] that was originally developed by TracLabs in the early 2000s under contract to the NASA Johnson Space Center to support integrated ECLS controls research. BioSim is a mid-fidelity dynamic simulator with execution times on the order of seconds for a 30-day stay on Mars to a few minutes for a 500-day stay on Mars. This relatively fast execution time is enabled by employing a simple Euler time stepping scheme to model system dynamics, and by making the simplifying assumption that all processes are isothermal, such that only mass balance calculations are required. Rapid execution times were necessary for the kind of tradespace exploration we were planning to conduct.

To create HabNet, Do, et al. [8],[9] ported the BioSim software into the MatLab environment, and then tuned the suite of BioSim technologies to behave in the same manner as the set of currently existing ISS life support technologies. (This of course might not reflect future ECLS technologies, but looking at prospective ECLS systems was left as future work in the same manner that future extraction process technologies were also left to be modeled later once we developed and demonstrated our integrated model and methodology.)

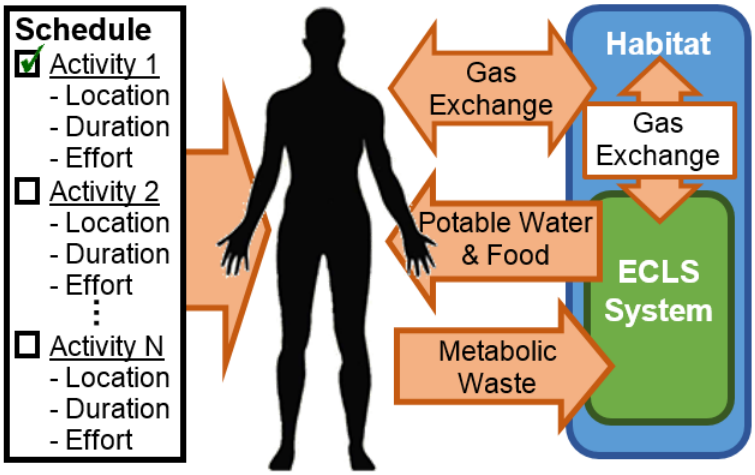


**Figure 3: Data Flow Within the Habitation Module**

HabNet contains several software modules; for this work, the most important was the Habitation Module. The role of the Habitation Module is to calculate the net demand for potable water, given the ECLS technologies within the habitat. Figure 3 depicts the high-level data flow within the Habitation Module. As can be seen in the figure, the first input to the Habitation Module is the assignment of a schedule to each colonist/ crewmember (i.e., the CONOPS). The schedule consists of a set of activities, each with its own location, duration, and effort level. As the simulation propagates forward in time, each colonist/crewmember progresses through their own schedule, expending varying levels of effort, which in turn varies their resource consumption and metabolic exchange rates with the habitat. Here, the model developed by Goudarzi and Ting[10] is used to determine crew resource demands based on their activity level and their basal metabolic rate, which is driven by their gender, age, and body mass. In the case of multi-module habitats, activities can be allocated to individual locations, thus allowing the crew to move throughout the

[2] The source code for BioSim was freely available under the GPL3.0 open source license.

habitat as they work through their activity list. Through the introduction of varying effort levels and activity locations, transient behavior is introduced into the habitation simulation environment.

Pre-defined ECLS technologies modeled within the Habitation Module act to manage this transient behavior by controlling resource consumption and production to the levels appropriate for maintaining crew health. The user allocates these ECLS technologies to different modules within the habitat, which in turn, handle varying metabolic waste loads as each colonist/crewmember moves through a given habitat module. The modeled efficiencies of these technologies are a key part of how HabNet calculates the net demand for potable water. The table below shows what water recovery, storage, and management-related functions are represented in HabNet.

**Table 3: Potable Water Technologies Represented in HabNet**

| Function | Technology | Based On |
|---|---|---|
| Water Processing | Multi-filtration, Catalytic Oxidation, Ion Exchange | ISS Water Processor Assembly (WPA) |
| Urine Processing | Vapor Compression Distillation | ISS Urine Processor Assembly (UPA) |
| Water Storage | Tanks | ISS Contingency Water Containers (CWC) |

## D. Economics Integration Model

The Economics Integration Model addresses the business case by estimating the revenues and costs over time, specifically over a 20-year scenario, and then calculates the resulting Net Present Value (NPV). Though this approach has its critics, NPV is the time-honored evaluation technique in business case analyses.

The Economics Integration Model has a feature worthy of further discussion. 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. This volatility comes from the somewhat unpredictable market forces of supply and demand. The volatility parameter (with or without drift) for a commodity is usually estimated statistically for a given time period by actual observations of its price fluctuations. The estimate also depends on the time scale over which the price changes are measured, for example, daily, weekly, or annually. Naturally, we do not have market observations by which to estimate the price volatility of water on Mars, so we simply elected to vary volatility parametrically across a set of values to assess its effect.[3]

### *1. Net Present Value and Internal Rate of Return*

The NPV is calculated as the discounted sum of revenues minus costs over a given time horizon. The discount rate, $r$, and the time horizon, $T$, are key parameters in the calculation. Generally, the discount rate is set at the prevailing market rate of interest for that class of investment, so when the $\mathrm{NPV}(r,T) > 0$, it is said that the business case closes. A closely related evaluation metric is the Internal Rate of Return (IRR), which is defined as the discount rate, $r^*$, such that the $\mathrm{NPV}(r^*, T) = 0$. Given a set of inputs, the Economics Integration Model calculates both NPV and IRR using the built-in functions provided by Excel.

In the model, yearly revenues accrue from the commercial sale of *in situ* water to the Mars colonists, computed using the average weekly price over that period. Costs include any investment costs for new hardware, including deployment (launch from Earth and Mars EDL) plus fixed and variable costs of ongoing operations. Investment costs are the result of an initial buildup of capability to extract water from Martian sources, then process, deliver, and store it at the Mars Colony site. Investment costs also arise from the need to replace worn-out equipment at regular intervals determined by the equipment's design life. Equipment deployment cost is represented as a linear function of equipment mass.

In the model, management costs remain fixed, but are escalated by the cumulative inflation factor to obtain then-year dollars. Variable operations costs depend on the number of each system times a cost per unit; this amount is also escalated by the cumulative inflation factor to obtain then-year dollars. Depreciation and amortization for systems and facilities alike depend on the cumulative investment in then-year dollars and the number of years in the investment scenario. Because replacement units are purchased and deployed during the scenario, some depreciation and amortization occurs beyond the scenario's time horizon.

### *2. Commodity Price Volatility*

We represented the discrete stochastic process of price volatility with drift using Eq. (1), where $p(t)$ is the price of Mars water in week $t$, $\delta$ is the weekly drift, and $\sigma$ is the weekly volatility parameter. The Excel function RAND()

[3] We have made an implicit assumption that once a large Mars Colony emerges, the market for Mars water will behave as markets on Earth—that is, the laws of supply and demand will still apply.

generates a random number from a uniform distribution on the interval (0, 1). Eq. (1) approximates a stochastic process known as geometric Brownian motion via a binomial lattice with small discrete time intervals, $\Delta t$. [11]

$$p(t+\Delta t) = \begin{cases} p(t)\exp(\sigma) & \text{if RAND()}>1\text{-}\frac{1}{2}\left(1+\frac{\delta}{\sigma}\right) \\ p(t)\exp(-\sigma) & \text{if RAND()}\leq 1\text{-}\frac{1}{2}\left(1+\frac{\delta}{\sigma}\right) \end{cases} \tag{1}$$

The effects of price volatility and drift can be quite dramatic. Vastly different price "histories" over the scenario time horizon can result from a fixed set of values for $\delta$ and $\sigma$. Figure 4 shows three examples (labelled Blue, Red, and Green) of price propagation over time for Mars water using Eq. (1) with the same price volatility and drift parameters. To generate these three "histories," the volatility was set fairly high, equivalent to about 18% per year, while the drift parameter was set fairly low, equivalent to about 2.6% per year. Over 20 years without volatility, the price of water would grow exponentially to about 68% above its original price, but with the volatility taken into account, prices can have periods of large sustained increases and periods of sharp decline, typical of extractive commodity prices on Earth. With the same price volatility and drift parameters, an entirely different "history" occurs on each random trial, which would then result in a different NPV. NPV must therefore be treated as a random variable, whose probability distribution can best be determined through Monte Carlo simulation.

*3. 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, setting the number of trials at 500. (This low number of trials allows us to obtain results in just a few seconds.) Most technical parameters are treated deterministically, but are varied across a range of reasonable values in our experiments. The set of NPV results for each experiment are binned into 100 intervals, from which a cumulative distribution function (CDF) (technically, a histogram) for NPV emerges. The model graphs the CDF and computes the probability that the NPV is greater than zero, $\boldsymbol{Pr}\{\text{NPV}(r,T)>0\}$. The model also calculates the estimated NPV Expected Value and Standard Deviation. Appendix Figure A-1 shows a 10-year portion of the Profit and Loss Statement and the NPV calculation for a single trial along with the CDF for the NPV resulting from the full set of Monte Carlo trials.

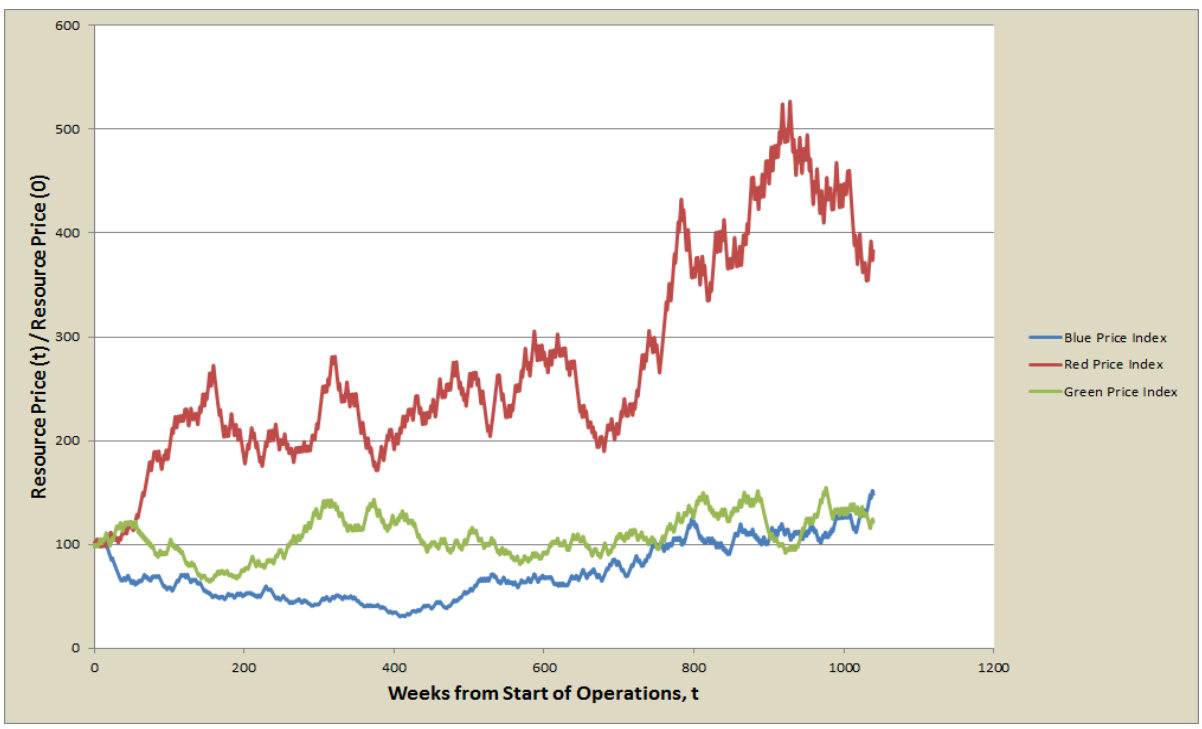


**Figure 4: Three "Histories" for Mars Water Price Index with a Weekly Price Drift=0.05% and Volatility=2.5%**

## E. End-to-End Data Flow

Figure 5 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.

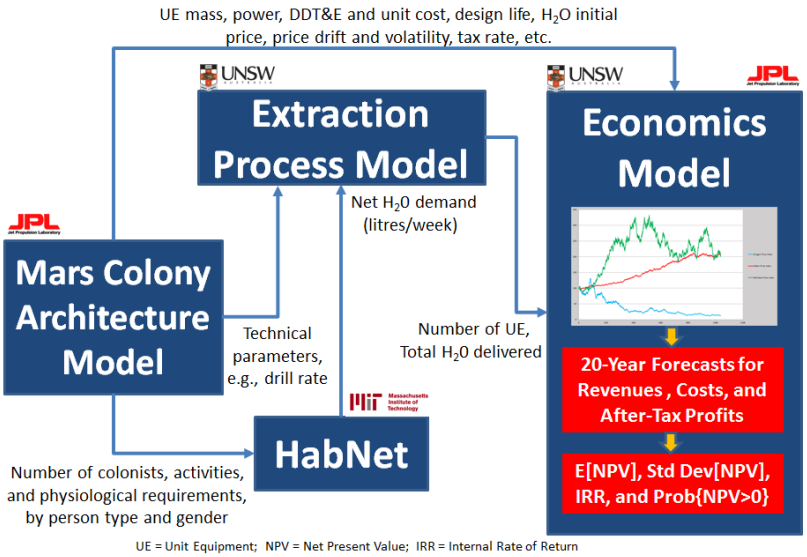


**Figure 5: End-to-End Data Flow-——-MCAM to Economics Integration Model**

The ModelCenter user interface at the top level resembles the block diagram of Figure 5, but can be expanded to reveal all the active links between parameters across the models in the ensemble. (Figure A-2 shows the top-level screen of the ensemble, and Figure A-3 shows (a portion of) the expanded view.)

Our current version of the ensemble in ModelCenter enables the user to manipulate over 50 technical and economic parameters. Runtime for most of the experiments we conducted was approximately one minute; runtime naturally would be larger if we had chosen to execute more Monte Carlo iterations, or if we exercised HabNet for a longer period than just a short stay on Mars of 30 days.

# III. Results

## A. Parameters

As mentioned above, most technical parameters and economic attributes in our experiments were treated deterministically, but varied across a range of reasonable values. Some examples of these parameters with a range of values for each are shown in Table 4. With the large number of technical and economic attributes that could be varied in exploring the tradespace, the "curse of dimensionality" was enormous. For example, experimenting with just ten parameters each stepping through four values would require $>10^6$ runs. To explore the tradespace then, we had to substantially bound the number of parameters and the number of values to be run for each parameter.

**Table 4: Parameter Space and Ranges**

| Model Name | Input Name | Value Range |
|---|---|---|
| Extraction Process Model | Minimum distance between drill points (m) | 0.5-50 |
| | Drill rate (m/hour) | 0.5-2.0 |
| | Transporter capacity ($m^3$) | 0.1-2.0 |
| | Minimum distance to processing plant (km) | 0.5-15 |
| | Processing plant capacity relative to extractor capacity | 5-25 |
| | Processing plant system efficiency (%) | 65-95 |
| | Regolith water content (%) | 1-20 |
| HabNet | Number of colonists, $L_M$ | 4-100 |
| | Number of simulated days | 30-1000 |
| | Number of 2-person EVAs per week | 1-24 |
| | Degree of ECLS system closure (%) | 50-99 |
| Economics Integration Model | Price volatility (%/week) | 0.5-2.5 |
| | Initial price of water ($K/liter) | 10-100 |
| | Unit equipment price (Mars *In Situ* Water Extractor) ($M) | 200-750 |

| | | |
|---|---|---|
| | Unit equipment mass (Mars *In Situ* Water Extractor) (kg) | 185-900 |
| | Launch and EDL cost per unit mass ($M/kg) | 0.25-1.0 |
| | Discount rate (%) | 5-20 |
| | Tax rate (%) | 0-30 |

For this paper, we ran about 100 cases, only varying a few parameters from Table 4 throughout. The values used are shown in Table 5. Our general strategy was based on the following tenets: (1) the number of colonists was set throughout at 16. This represents an established research station population or a small settlement. This was believed to be well within the range of HabNet scalability; (2) technical parameters for OEM equipment (e.g., MISWE mass,[4] drill rate, etc.) were kept at their nominal published values so that credibility would not be stretched; (3) the HabNet ECLS system closure was kept at ISS levels, again so as to be conservative. This resulted in a net demand for water of about 72 liters/week of potable water in all cases; and lastly, (4) we focused on economics parameters (e.g., MISWE cost, water price volatility) to show their importance in commercial profitability. All of these restrictions taken together had a significant effect on our results, which we discuss below. In future experiments, we can explore different parts of the tradespace by removing these restrictions.

**Table 5: Parameter Space and Values Used**

| Model Name | Input Name | Value or Values Used |
|---|---|---|
| Extraction Process Model | Minimum distance between drill points (m) | 2.5 |
| | Drill rate (m/hour) | 1.0 |
| | Transporter capacity ($m^3$) | 0.1 |
| | Minimum distance to processing plant (km) | 1.5, 5 |
| | Processing plant capacity relative to extractor capacity | 10 |
| | Processing plant system efficiency (%) | 82 |
| | Regolith water content (%) | 5, 12 |
| HabNet | Number of colonists, $L_M$ | 16 |
| | Number of simulated days | 30 |
| | Number of 2-person EVAs per week | 4 |
| | Degree of ECLS system closure (%) | ISS value; depends on assembly |
| Economics Integration Model | Price volatility (%/week) | 0.5, 2.5 |
| | Initial price of water ($K/liter) | 20, 40, 60 |
| | Unit equipment price (Mars *In Situ* Water Extractor) ($M) | 200, 350 |
| | Unit equipment mass (Mars *In Situ* Water Extractor) (kg) | 250 |
| | Launch and EDL cost per unit mass ($M/kg) | 0.25, 0.5, 1.0 |
| | Discount rate (%) | 20 |
| | Tax rate (%) | 30 |

## B. Basic Results

We recognized two ways to run the ensemble of models: (1) just meet the demand for potable water, or (2) keep the processing plant(s) running at full capacity while meeting the demand for potable water. The latter CONOPS typically increases the number of MISWEs and Transporters needed, but for this paper, it seemed to make more sense to model this CONOPS since any additional water could be stored for future colonists or used as safety stocks or radiation protection.[5] In this CONOPS, the relative size of the water processing plant then drives the number of MISWEs and Transporters.

Given the inputs above, the Extraction Process Model calculated the requirement for seven MISWE, four Transporters, and one Processing Plant in all cases. (In actuality, the Solver computes fractional quantities, which are rounded up to next integer by the model. Water production is computed based on these integer quantities.) The resulting water production, which is highly dependent on the regolith water content and plant efficiency, was then passed to the Economics Integration Model. In some excursion cases, we also saw that changes in OEM equipment

[4] OEM equipment mass and cost was assumed to include a kit of critical spares parts concurrently delivered to the Martian surface.

[5] Propellant production was not considered since colonists were not expected to return to Earth. In other architectures and CONOPS, water for propellant production could be included as an additional demand.

technical parameters (e.g., drill rate, MISWE speed, etc.) could be traded, while maintaining the same water production. For example, the same number of MISWEs and Transporters resulted when the minimum distance from the water mining site to the processing plant was raised from 1.5 km to 3.5 km, and to compensate, the capacity of the Transporters was raised from 0.1 $m^3$ to 0.2 $m^3$. We can surmise that as the scale of the Mars Colony grows, we would see which OEM equipment technical parameters have the greatest influence on the economic results.

The Economics Integration Model results are shown in Table 6 for the 24 cases we ran in the part of the tradespace where the initial price of water ranged from $40K per liter to $60K per liter. One can immediately see the difficulty of overcoming the large capital investment costs needed for OEM on Mars. Several other observations, however, can be made. First, while this range of initial water prices may seem high (or not high enough from the point of view of commercial offerors), it should be viewed against the cost of delivering potable water from Earth (or from elsewhere in the solar system). The initial water price range is a fraction of the $250K to $1M per kg of landed mass used in the 24 cases shown.

Second, in these cases the strong influence of the regolith water content can be seen, and the direction is as anticipated. This suggests the critical role for water availability estimates in selecting the site for a Mars Colony. Third, the cost of deploying OEM equipment to Mars also has a strong and systematic effect on the probability of a positive NPV. Lowering that cost will be important in building a Mars Colony. Lastly, *ceteris paribus*, the price volatility had some effect on the expected NPV and a modest-to-significant effect on the probability of a positive NPV, improving both when the expected NPV was negative, but decreasing the probability of a positive NPV when the expected NPV was positive.

**Table 6: Selected Results for Expected NPV, NPV Standard Deviation, and "In-the-Money" Probability**

| Case No. | Water Price Volatility (%/week) | Initial Water Price ($K/l) | Launch/ EDL Cost ($M/kg) | Regolith Water Content (%) | E[NPV] ($M) | StdDev[NPV] ($M) | Pr{NPV>0} |
|---|---|---|---|---|---|---|---|
| 8-1 | 0.5 | 40 | 0.25 | 5 | -3776.866 | 121.471 | 0.0% |
| 8-2 | 0.5 | 40 | 0.25 | 12 | -1608.577 | 300.547 | 0.0% |
| 8-3 | 2.5 | 40 | 0.25 | 5 | -3593.515 | 733.493 | 0.0% |
| 8-4 | 2.5 | 40 | 0.25 | 12 | -1177.624 | 1735.885 | 20.8% |
| 8-5 | 0.5 | 40 | 0.5 | 5 | -4666.737 | 121.365 | 0.0% |
| 8-6 | 0.5 | 40 | 0.5 | 12 | -2501.618 | 303.065 | 0.0% |
| 8-7 | 2.5 | 40 | 0.5 | 5 | -4563.965 | 655.173 | 0.0% |
| 8-8 | 2.5 | 40 | 0.5 | 12 | -1958.921 | 1911.846 | 14.0% |
| 8-9 | 0.5 | 40 | 1.0 | 5 | -6436.069 | 126.047 | 0.0% |
| 8-10 | 0.5 | 40 | 1.0 | 12 | -4274.139 | 288.764 | 0.0% |
| 8-11 | 2.5 | 40 | 1.0 | 5 | -6205.828 | 769.168 | 0.0% |
| 8-12 | 2.5 | 40 | 1.0 | 12 | -3726.303 | 1763.082 | 3.8% |
| 8-13 | 0.5 | 60 | 0.25 | 5 | -2991.669 | 186.796 | 0.0% |
| 8-14 | 0.5 | 60 | 0.25 | 12 | 259.673 | 420.967 | 70.8% |
| 8-15 | 2.5 | 60 | 0.25 | 5 | -2800.636 | 1062.798 | 2.6% |
| 8-16 | 2.5 | 60 | 0.25 | 12 | 1058.540 | 2973.926 | 58.2% |
| 8-17 | 0.5 | 60 | 0.5 | 5 | -3869.749 | 192.485 | 0.0% |
| 8-18 | 0.5 | 60 | 0.5 | 12 | -629.142 | 427.180 | 7.0% |
| 8-19 | 2.5 | 60 | 0.5 | 5 | -3565.097 | 1150.127 | 1.4% |
| 8-20 | 2.5 | 60 | 0.5 | 12 | 44.759 | 2756.261 | 41.8% |
| 8-21 | 0.5 | 60 | 1.0 | 5 | -5642.397 | 175.417 | 0.0% |
| 8-22 | 0.5 | 60 | 1.0 | 12 | -2412.560 | 436.303 | 0.0% |
| 8-23 | 2.5 | 60 | 1.0 | 5 | -5365.606 | 1131.772 | 0.2% |
| 8-24 | 2.5 | 60 | 1.0 | 12 | -1617.472 | 2742.953 | 19.6% |

### C. Visualization

Figure 6 uses the data in Table 6 to create an interpolated surface for the $\boldsymbol{Pr}\{\mathrm{NPV}(r,T)>0\}$. Changing the technical attributes of the Mars Colony (for example, OEM equipment characteristics, ECLS closure, or natural environment) or the key economic parameters (for example, the discount rate, $r$, or the tax rate on Martian profits) will naturally alter this landscape. We recognize that with the large number of technical parameters and economic

attributes that can be changed, it is difficult to grasp what design choices and technology investments have the highest payoff. Still, we have established a methodological start toward that goal.

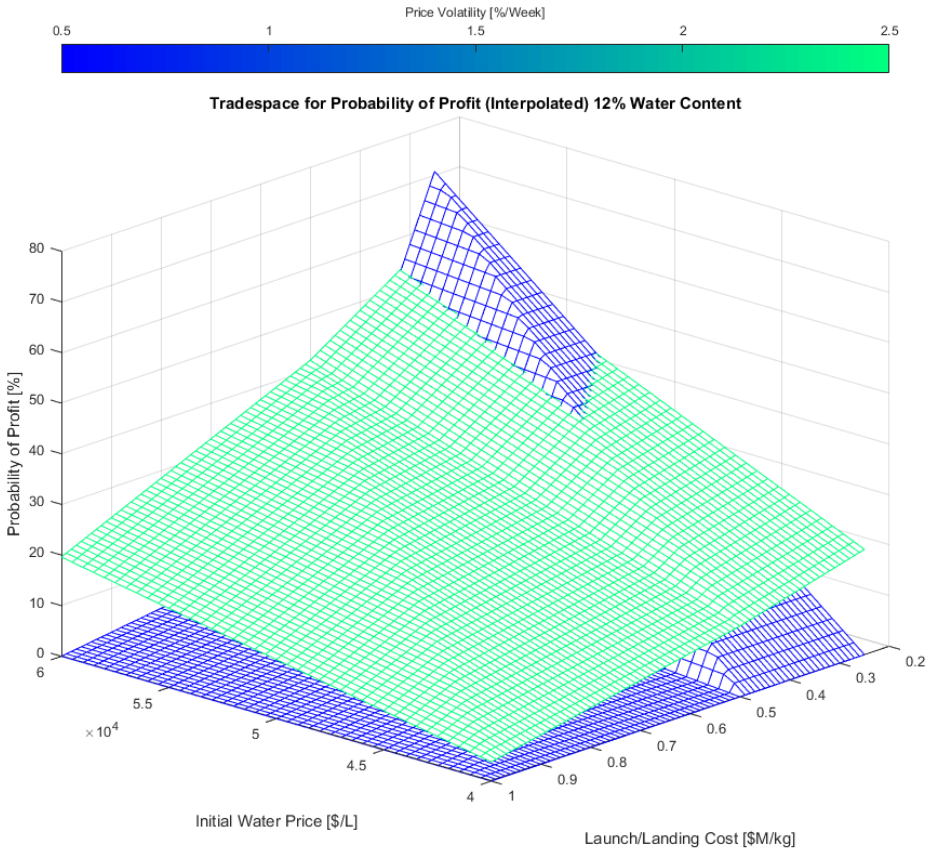


**Figure 6: Pr{NPV>0} Surface as Function of Initial Water Price and Launch/EDL Cost**

## IV. Conclusions and Future Directions

This paper reports on the initial results from our long-term investigation examining the role of Off-Earth Mining (OEM) in a growing space economy. (Throughout our investigation, the term 'mining' is taken to embrace minerals, ice/water, and other *in situ* resources.) OEM can be the engine that drives the space economy, so it would be useful to understand what OEM market conditions and technology requirements are needed for that economy to prosper. These specific elements are studied in the wider context of creating an economy that could ultimately support a sustainable Mars Colony. Such a colony will need *in situ* resources not only for its own survival, but to prosper and grow, it must create viable business ventures, essentially by fulfilling the demand for *in situ* resources from and on Mars.

We chose to focus on the extraction, delivery, and processing of water because recent research [12] suggests that the long-term sustainability of a permanent human presence on Mars is strongly dependent on the cost of producing water from *in situ* sources. This, in turn, is strongly dependent on the quantity and form in which water is locally available (e.g., as water ice or as hydrated minerals), as well as on the performance and reliability of available ISRU technologies. Our modeling efforts, in this context, may help inform the selection of a surface location for the initial human exploration of Mars as well as for a permanent settlement/colony. [13]

Our initial results follow the expected (theoretical) economic predictions and presumptions—the higher the water price, the higher the expected NPV and chances for profitability. Similarly, a lower cost of deploying OEM equipment has the same effect. Price volatility increases the standard deviation of NPV, and hence may provide opportunities for larger profits.

While the initial results suggest that the ensemble of models we have created is capable of producing credible analyses, it is clear that improvements and extensions are possible. For example, planned upgrades to the Extraction Process Model will more accurately represent maintenance activities, spares requirements, and OEM system

availability constraints. Eventually, alternative mining technologies need to be modeled to the same degree of fidelity. HabNet v.2 promises improvements in the way the Habitation Module scales up to accommodate a growing Mars population and includes propellant production. The Economics Integration Model can be improved by a more detailed model of cash flow, and by improved cost estimates. Some evidence exists that commodity prices exhibit volatility with some form of reversion to the mean. We have not included that feature in our current work, but could in future versions of the Economics Integration Model. A more realistic ensemble of models would also have to include aspects of the interplanetary supply chain, as depicted in Figure 1, the Mars Colony Context Diagram. Such a model would need to capture the constraints on deliveries to the Mars surface of infrastructure, spares, consumables, and colonists. Naturally, each of these improved or new models needs to be re-validated before it can be integrated into the ensemble.

Integrating heterogeneous models (i.e., models for different disciplines, with different levels of fidelity, and/or software languages) is not easy. Even with ModelCenter, linkages must be built so that the meaning of an input parameter or output variable in one downstream model is the same as in another. Further, the appropriate interactions and feasibility constraints must be maintained. For example, if the mass of a system goes up, how does that affect all of the deployments (assembly sequence) in the scenario? How are "optimal solutions" and key "tipping points" changed when the tradespace is enlarged to include further considerations? What is clear is that exploring the system-of-systems architectural tradespace of a Mars Colony (or a "Lunar Village") is going to be a complex endeavor. Hopefully, certain patterns will emerge in analyses that give us confidence in our architectural decisions.

## Acknowledgments

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## Disclaimer

The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

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# Appendix

**PROFIT AND LOSS STATEMENT (in millions)**

**PROJECT:** MISWE

**SCENARIO:**

| | 2055 | 2056 | 2057 | 2058 | 2059 | 2060 | 2061 | 2062 | 2063 | 2064 |
|---|---|---|---|---|---|---|---|---|---|---|
| Sales Revenue | $ - | $ - | $ - | $ 770.83 | $ 772.39 | $ 863.89 | $ 868.22 | $ 725.89 | $ 687.46 | $ 558.47 |
| Less: Cost of Goods Sold | $ 1,111.70 | $ 1,775.70 | $ 170.76 | $ 250.87 | $ 232.64 | $ 239.62 | $ 246.81 | $ 254.21 | $ 261.84 | $ 269.70 |
| Less: Direct Overheads | | | | | | | | | | |
| ***Gross Margin*** | $ (1,111.70) | $ (1,775.70) | $ (170.76) | $ 519.96 | $ 539.75 | $ 624.27 | $ 621.41 | $ 471.68 | $ 425.62 | $ 288.77 |
| Less: Indirect Overheads | | | | | | | | | | |
| Less: Depreciation and Amortization | $ 49.75 | $ 52.25 | $ 54.75 | $ 54.75 | $ 54.75 | $ 54.75 | $ 54.75 | $ 54.75 | $ 54.75 | $ 54.75 |
| Plus: Interest Income | | | | | | | | | | |
| ***Net Profit Before Tax*** | $ (1,161.45) | $ (1,827.95) | $ (225.51) | $ 465.21 | $ 485.00 | $ 569.52 | $ 566.66 | $ 416.93 | $ 370.87 | $ 234.02 |
| Less: Income Tax Expense | $ (348.44) | $ (548.39) | $ (67.65) | $ 139.56 | $ 145.50 | $ 170.85 | $ 170.00 | $ 125.08 | $ 111.26 | $ 70.21 |
| ***Net Profit After Tax*** | $ (813.02) | $ (1,279.57) | $ (157.86) | $ 325.65 | $ 339.50 | $ 398.66 | $ 396.66 | $ 291.85 | $ 259.61 | $ 163.82 |

**NET PRESENT VALUE TABLE (in millions)**

| | 2055 | 2056 | 2057 | 2058 | 2059 | 2060 | 2061 | 2062 | 2063 | 2064 |
|---|---|---|---|---|---|---|---|---|---|---|
| Net Profit After Tax | $ (813.02) | $ (1,279.57) | $ (157.86) | $ 325.65 | $ 339.50 | $ 398.66 | $ 396.66 | $ 291.85 | $ 259.61 | $ 163.82 |
| Plus: Depreciation and Amortization | $ 49.75 | $ 52.25 | $ 54.75 | $ 54.75 | $ 54.75 | $ 54.75 | $ 54.75 | $ 54.75 | $ 54.75 | $ 54.75 |
| Cash Flows | $ (763.27) | $ (1,227.32) | $ (103.11) | $ 380.40 | $ 394.25 | $ 453.41 | $ 451.41 | $ 346.60 | $ 314.36 | $ 218.57 |
| Less: Capital Expenditures | $ 1,045.00 | $ 125.00 | $ 100.00 | $ 25.00 | $ - | $ - | $ - | $ - | $ - | $ - |
| Free Cash Flows | $ (1,808.27) | $ (1,352.32) | $ (203.11) | $ 355.40 | $ 394.25 | $ 453.41 | $ 451.41 | $ 346.60 | $ 314.36 | $ 218.57 |

| | |
|---|---|
| ***Net Present Value (This Run)*** | $ (1,965.94) |
| ***Project IRR (This Run)*** | 0.03% |

| | |
|---|---|
| ***Expected[Net Present Value]*** | $ (1,039.67) |
| ***Prob{NPV>0}*** | 0.144 |

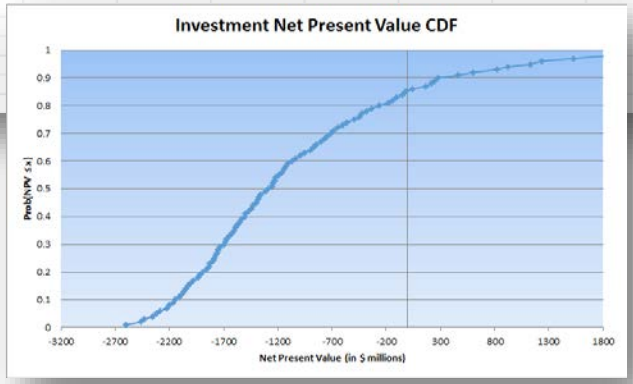


**Figure A-1: NPV Calculation for a Single Trial and CDF for 500 Trials**

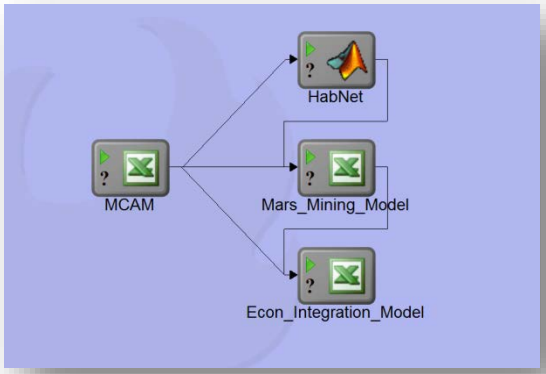


**Figure A-2: Ensemble of Models in ModelCenter© (Top Level)**

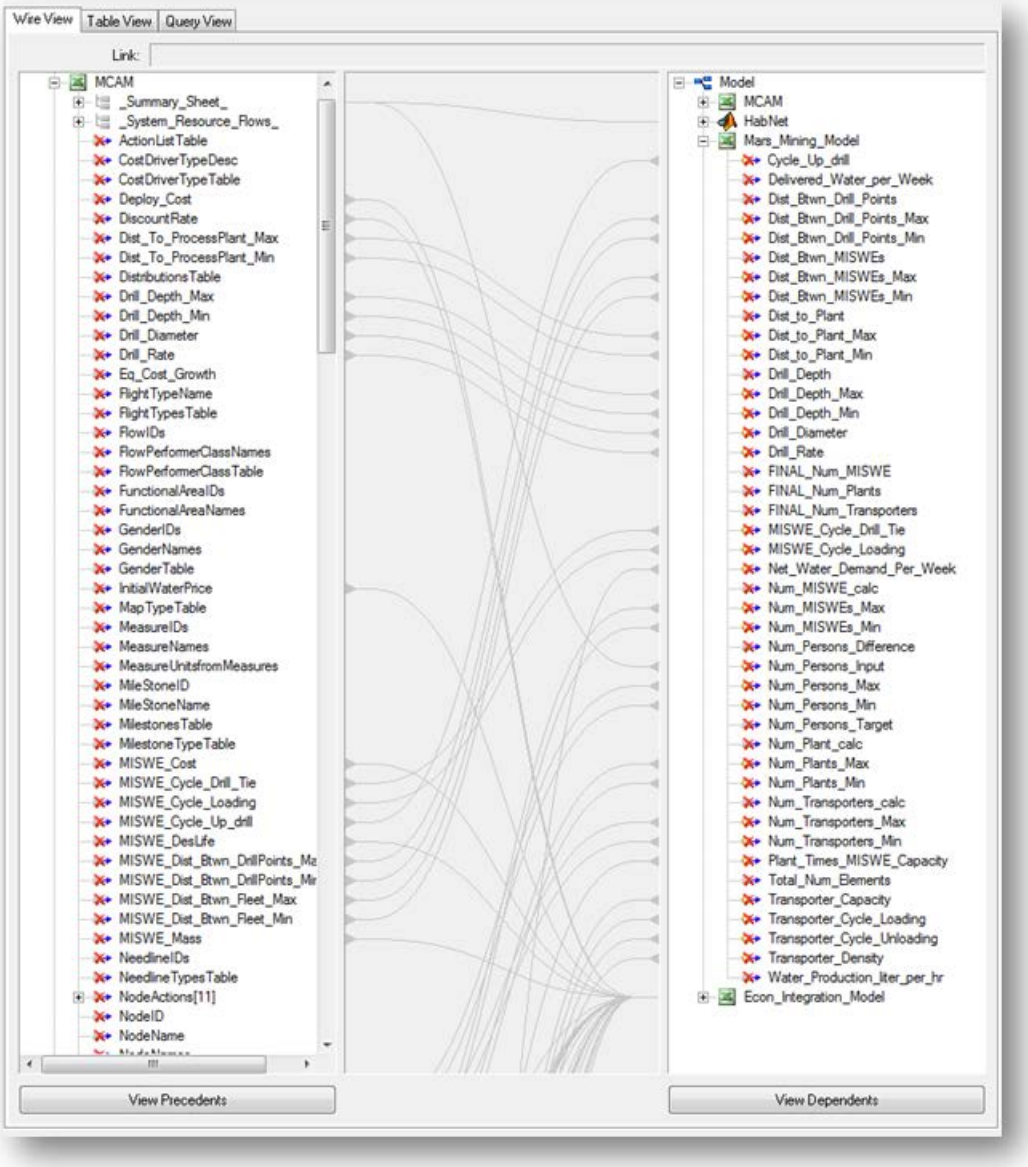


**Figure A-3: Ensemble of Models in ModelCenter© (Expanded View)**