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

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The aim of this effort is to develop an integrated set of risk-based financial and technical models to evaluate multiple Off-Earth Mining (OEM) scenarios. This quantitative, scenario- and simulation-based tool will help identify combinations of market variables, technical parameters, and policy levers that will enable the expansion of the global economy into the solar system and return economic benefits. Human ventures in space are entering a new phase in which missions formerly driven by government agencies are now being replaced by those led by commercial enterprises – in launch, satellite deployment, resupply of the International Space Station, and space tourism. In the not-too-distant future, commercial opportunities will also include the mining of asteroids, the Moon, and Mars. This investigation will examine the role of OEM in a growing space economy. (In this 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 will be 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. This investigation will focus on understanding the role and economic prospect for OEM associated with the Human Colonization of Mars (HCM).

Nomenclature

DoDAF	=	Department of Defense Architecture Framework	Y_M	=	Gross Mars Product
DRA	=	Design Reference Architecture	L_M	=	Number of Colonists
HCM	=	Human Colonization of Mars	*AV*	=	All Viewpoint
MCAM	=	Mars Colony Architecture Model	*OV*	=	Operational Viewpoint
MoDAF	=	Ministry of Defense Architecture Framework (UK)	*SV*	=	Systems Viewpoint
OEM	=	Off-Earth Mining	*CV*	=	Capabilities Viewpoint
UPDM	=	Unified Profile for DoDAF and MoDAF	*PV*	=	Project Viewpoint
ISRU	=	*In Situ* Resource Utilization	*CONOPS*	=	Concept of Operations

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I. Introduction

Establishing a viable, permanent colony of Mars, very much the staple of science fiction, is still only an aspiration, but such an entity is possible within the lifetime of persons living today. This paper is a progress report on an effort by NASA to consider afresh how such an entity might come about, under what circumstances, and when.

Human ventures in space are entering a new phase in which missions formerly driven by government agencies are now being replaced by those led by commercial enterprises – in launch, satellite deployment, resupply of the International Space Station, and space tourism. In the not-too-distant future, commercial opportunities will also include the mining of asteroids, the Moon, and Mars. This investigation will examine the role of Off-Earth Mining (OEM) in a growing space economy. (In this 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 will be 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. This investigation will focus on understanding the role and economic prospect for OEM associated with the Human Colonization of Mars (HCM).

A. Research Objectives

The immediate objective of this effort is to develop an integrated set of risk-based financial and technical models to evaluate multiple Off-Earth Mining (OEM) scenarios. This quantitative, scenario- and simulation-based tool will help identify combinations of market variables, technical parameters, and policy levers that will enable the expansion of the global economy into the solar system and return economic benefits.

Beyond that immediate aim, however, is a broader aim to dig deeper and more formally into what form a Mars Colony might take and what operations might be like through the application of a formal architecture definition process. In other words, instead of creating a chimera, a persuasive website, or even a conceptual design for a key element of a colony, we want to establish the idea that to be serious about planning for a Mars Colony, system architecting processes and methods need to be applied. We would add that system architecting has the most value when the problem is ill-structured and the end-point is not clearly known, which is certainly the case here.

The need for an architecture definition process has in fact been recognized by professional groups developing systems engineering standards, and a separate architecture definition process has been incorporated into the latest ISO systems engineering standard, ISO/IEC/IEEE 15288-2015.[1,2] Our secondary objective, then, is to demonstrate by example some first steps in that process.

B. Research Timeframe

For now and the next few decades, NASA's ultimate goal (and perhaps that of others) is to land humans on Mars.[3-6] We can look upon that endeavor as the next "giant leap for mankind." Beyond that, there are other giant leaps, depicted in Figure 1. It is likely that much more in the way of advanced technology development and

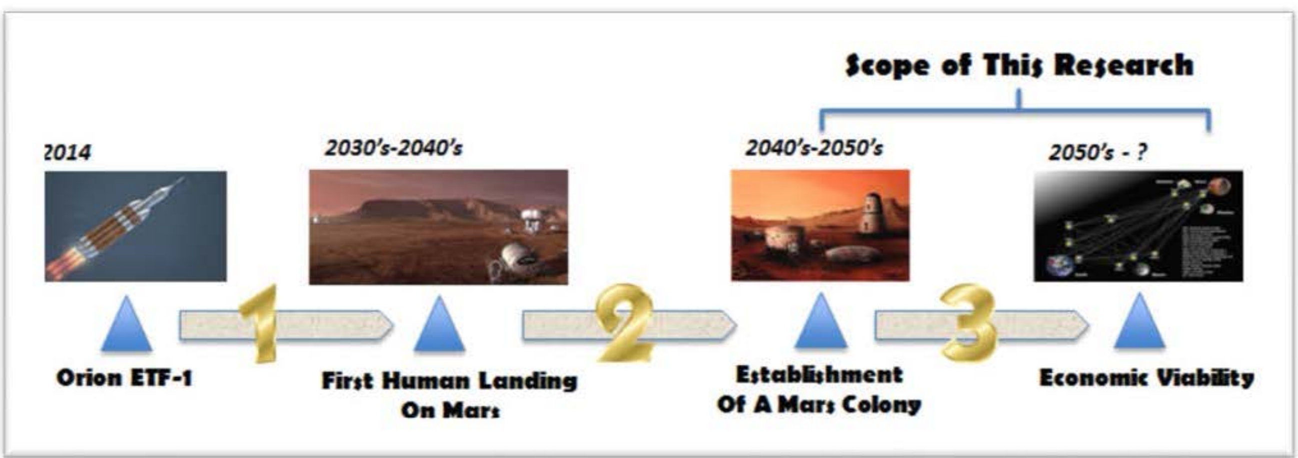


Figure 1: Three Giant Leaps

deployment of infrastructure will be needed before humans achieve Giant Leap #2. Our research effort addresses a timeframe beyond that to an unknown point in time far into the future when a Mars Colony achieves economic viability (Giant Leap #3).

While it is not clear what technology advances will occur in achieving these giant leaps, historical precedences and recent research suggest that technologies enhancing (interplanetary) logistics capabilities and the ability to "live off the land" (*in situ* resource utilization (ISRU)) will be significant in achieving all three leaps.[7-9]

C. Four Models

Our on-going research plans include the development of four models and simulations: the Mars Colony Architecture Model (MCAM); Extraction Process Model; Mars Infrastructure and Integrated Logistical Support (ILS) Model; and the Economics Integration Model. This ensemble of models and simulations can be a testbed for valuing various ISRU, and other interplanetary supply chain and Mars habitat technologies. This paper describes these models and simulations, but only the Mars Colony Architecture Model (MCAM) is presented in detail here.

MCAM is a semantically aware data repository that establishes the artifacts, relationships, and technical parameters for multiple conceptual architectures. It does not establish a single Mars Colony reference architecture, but instead exists as an flexible organizing tool to explore many architecture alternatives. The intended use is to support an "analysis of alternatives" (AoA) capability at the architectural level by feeding multiple downstream models. At the conclusion of such a tradespace exploration, MCAM could be used to capture the preferred architecture. However, managing such a complex AoA process would require a layer of software beyond MCAM; this layer is not part of our current work.[i]

The Extraction Process Model focuses on the technologies and costs associated with *in situ* resource extraction, processing, storage and handling, and delivery. For each mined resource, which may involve multiple cooperating ISRU systems in a given architecture, the Extraction Process Model computes the production rate as a function of the systems' technical parameters (stored in MCAM) and the local Mars environment; in economics terminology, the Extraction Process Model provides the production function for the resource. Different ISRU systems and technologies would naturally have different expressions of this model.

The Mars Infrastructure and Integrated Logistical Support 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 uncertainty, with an objective of determining the profitability of commercial *in situ* mining operations supporting the Mars Colony.

II. Literature Review of OEM and HCM

This section discusses some of the OEM and HCM literature. It is not intended to be comprehensive, but rather to highlight long-standing connections between both areas.

A. Off-Earth Mining

Craig, et al.[10] provide a contemporary literature review of 20 OEM studies.[11-30] Many of the earlier studies covered focused on lunar or asteroid mining for volatiles and minerals, or on proposed OEM systems and operational processes. This is not surprising since NASA's previous human exploration programs—the Space Exploration Initiative (SEI) 1989-1992 and the Constellation Program 2005-2010—were initially focused on a return to the Moon. The more recent studies introduced the use of financial criteria such as Net Present Value (NPV) to evaluate OEM, but found mixed results. Even when study assumptions resulted in a positive NPV, concerns regarding the scale of the required investment, vagaries about the abundance of minable material, and market uncertainty were identified as substantial deterrents to further development.

Perhaps the most complete OEM engineering and economic study reviewed by Craig is the one by Blair, et al.[14] That study describes a modeling approach to evaluate a commercial transportation service using LH_2/LOX propellant produced from water extracted from lunar regolith to provide transfers between Low Earth Orbit (LEO) and Geosynchronous Orbit (GEO). Using the models developed for the study, their report then delves into alternative scenarios by varying such parameters as lunar water concentrations, investment costs, market size, and price.

A similar approach was taken by Charania and DePasquale,[31] except that the commercially produced lunar propellant (and O_2) was sold directly to a customer. Three business case analyses (with variants) were performed:

sale to a government customer on the lunar surface, sale to a government customer in Low Lunar Orbit (LLO), and sale to another commercial customer in GEO. In their approach, uncertainties were explicitly incorporated by means of probability distributions, and then were treated using Monte Carlo techniques.

An examination of lunar propellant production may not be entirely misplaced even though NASA's current emphasis is on getting to Mars. Recent research has found that the capability to exploit lunar resources in this way can substantially reduce the initial mass to LEO (IMLEO) needed for a Mars mission.[32,33]

OEM on Mars is treated extensively in Badescu (Ed.)[34] in a series of chapters by subject matter experts. This book investigates the possibilities and limitations of various systems that might be used to supply humans on Mars with energy and other vital resources. The book, which is one of three separate tomes covering the Moon, asteroids, and Mars, is divided in three parts. The first deals with energy sources on Mars, and the second with technical proposals for surveying, drilling, and excavating *in situ* resources, and then using those materials for agricultural and construction purposes. The third part is more speculative and longer term as it deals with Mars colonization strategies. Each chapter contains an extensive bibliography of its own, with citations that also appear in this paper.

At previous AIAA Space Conferences and mining-related conferences, other papers have gone into greater detail in analyzing various OEM processes and systems.[35-39]

B. Human Colonization of Mars

Our searches resulted in a substantial volume of engineering and economic literature on human colonization of the Moon and Mars, though most of it focused on the former, and probably for the same reason mentioned above. Only a sampling of this material is presented in our bibliography. [40-65]

Serious early studies of extraterrestrial outposts began shortly after Sputnik, some of it as classified work. Even before the establishment of NASA, Holbrook[43], for example, lays out a program of study and analysis that included understanding the planetary physical environment, in-space transportation, precursor missions, off-Earth human physiology and psychology, exploration methods and equipment, base design, CONOPS and logistics, and finally, colonization. The last would incorporate farming and food synthesis, mining, construction, and industrial processing. One can only be struck by the persistence of these issues even now.

Some papers presented at previous AIAA Space Conferences qualitatively discuss the evolution from a scientific outpost (8-50 persons, on a rotating basis) to a permanent settlement (150-500 persons) to a large-scale colony of thousands. In an interesting paper, Sheddan,[56] pointing to their isolation and similar vulnerabilities, likened such settlements to mining camps of the American West.

In this research, we have gathered and reviewed an extensive library of material, but we have not seen a complete formal description of a permanent Mars Colony using a recognized architecture framework. That is the subject of Part III.

III. Describing a Mars Colony Using an Architecture Framework

This section describes our approach to a formal description of a Mars Colony that can be used to create alternative colony architectures and architecture evolution plans, and then use those constructs to analyze economic viability.

A. Selecting a Formal Architecture Framework

There are several approaches we could have taken to describe Mars Colony architectures; the primary difference is in the terminology and software tools that would be used in each approach. We selected an approach based primarily on the DoD Architecture Framework (DoDAF) 2.02[66] with some 'for-purpose' extensions that were needed to enable specific analyses. Architecture frameworks in general are useful in so far as they promulgate (and are intended perhaps to enforce) a common terminology (ontology) and a logical structure, thus promoting consistency in the architectural trade studies and analyses that support decisions. That is at least the promise, even if they fall short in practice.[67,68]

We chose DoDAF as our approach for a number of reasons. First, in the *Art of Systems Architecting*, Maier[69] reminds us that the product of system architecting is an architecture description (viewpoints and views, enabled by models), not a system![11] And that there is a continuum of abstraction between the architecture/design boundary defined by the purpose of the effort, decisions to be made, and context of use. At a high level of abstraction, an architecture description might only show critical relationships among the constituent systems within a system-of-systems. As we move a bit closer toward the architecture/design boundary, key features of the individual systems might be spelled out. Still closer, details of the various subsystems might be added. Our intended use requires an architecture description at a fairly high level of abstraction, and we found DoDAF (with the 'for-purpose' extensions) to be a more than adequate standard in that regard.[ii]

Second, several NASA programs and projects have selected other approaches for describing architectures. For example, NASA's Space Communications and Navigation (SCaN) program, JPL's Europa mission, and Advanced Multi-Mission Operations System (AMMOS) chose to use an approach to systems architecting that more closely resembles the ANSI/IEEE 1471:2000 (now updated to ISO/IEC 42010) standard.[70] These efforts were intended to produce a fully reconciled set of requirements and a system design, and ultimately, to implement, verify, and deliver that design. One of these efforts (SCaN) started with DoDAF, but found it advantageous to switch.[iii] That DoDAF has a more operational focus, rather than a requirements and design focus actually makes it more suitable for our intended use.

Third, a number of changes appearing in DoDAF 2.02 improved its suitability for our work. DoDAF 2.02 focuses on architectural data, rather than on developing prescribed views as described in previous versions. We took advantage of this additional flexibility to add new datatables to support new views, while retaining the ability to produce many traditional DoDAF views. Further, whereas prior versions of DoDAF modeled only information flows and data exchanges, Version 2.02 also allows modeling of physical flows of material and people. This is critical to understanding the full breath of an architecture's interfaces.

Nevertheless, DoDAF 2.02 had its limitations so extensions were needed. Chief among these was the lack of an ability to handle dynamic changes in the architecture. Related architecture frameworks such as MoDAF and UPDM recognized this at least for some key milestones (deployment, end-of mission), but we wanted the ability to handle ongoing changes in technology developments, population size, etc. Any modeling or simulation of a Mars Colony must also take into account orbital mechanics and human physiology. Extensions of DoDAF were needed to ensure that this was the case; these are discussed in Part IV of this paper.

B. A Brief Digression: The Concept of Economic Viability

The term 'economic viability' has been used in this paper (Giant Leap #3) and in others, and yet there has been little discussion as to its meaning. Moreover, viability is not the same as self-sustainability, a term that has also been used extensively. The *Mars Now* [46] report defines 'self-sustainability' as having four characteristics:

- Complete independence from Earth resupply
- Population growth
- Evolution of governance system
- Emergence of a Mars culture

We believe that the first characteristic—complete independence from Earth resupply—is not a condition for viability, in fact, just the opposite. A two-way flow of goods and services, we believe, would be essential for the viability of a Mars Colony. One possible definition of viability might involve calculating the real Gross Mars Product (GMP) per capita, Y_M/L_M, over a span of time, and declaring viability when that calculation meets or exceeds a certain value. This metric suggests that viability is achieved when Mars colonists reach a certain standard of living. Alternatively, one could declare viability when a sustained growth rate in real GMP is achieved. Of course, calculating real GMP might be challenging since it involves choosing an initial set of prices at which to value Mars goods and services. Further, we can speculate that the time when viability might be achieved depends on government policies and market uncertainties, e.g., commodity prices, in which case when viability is achieved might best be represented as a probability distribution. Figure 2 shows three hypothetical scenarios in which the probability of achieving viability is an even-money bet in different years depending on how those uncertainties play out.

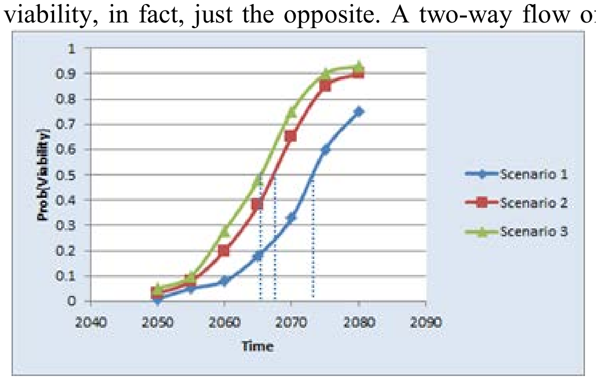


Figure 2: Alternative Scenarios Leading to Economic Viability Viewed as Probability Distribution

Other markers of viability might be when the Mars Colony starts producing goods and services beyond the basic necessities of life, or when subsidies to support the colony are no longer needed, or when Mars colonists move from being jacks-of-many-trades to labor specialization. What is clear is that we lack a clear operational definition of economic viability, so new ideas on this subject will be welcomed.

C. Architecture Definition Process

Figure 3 is a thumbnail sketch of how MCAM fits into a Mars Colony architecture definition process. Starting from the goal of a viable colony, stakeholders are identified, who then express concerns that must be addressed. These concerns lead to the generation of conceptual architectures, whose artifacts, relationships, and parameters are then formalized in MCAM. Exercising various specialized models and simulations linked to MCAM and using the configuration controlled information stored there provides focused analyses that can be turned into a set of views that address those concerns.

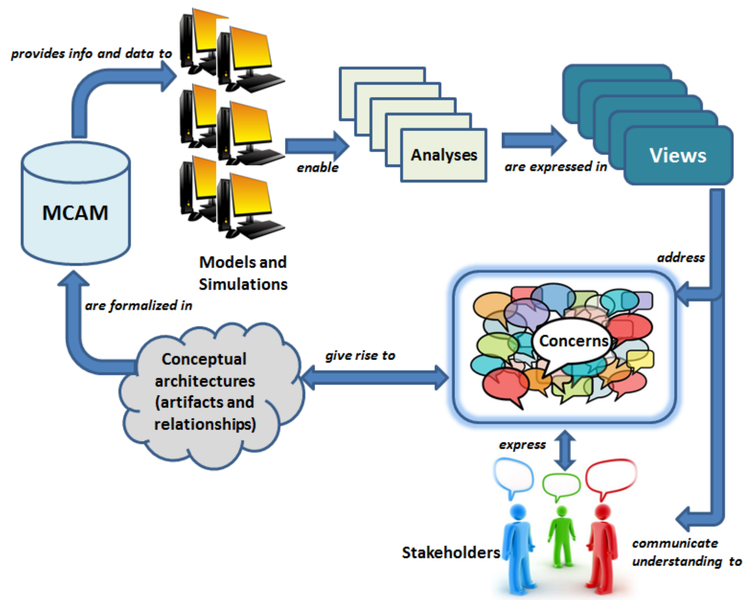


Figure 3: Role of MCAM in Defining the Mars Colony Architecture

For example, Mars colonists would naturally have a concern regarding their ability to survive, as Table 1 shows. It is incumbent upon the Mars Colony system architect to show through detailed analyses how each proposed conceptual architecture would or would not lead to that outcome; this step has apparently been missing in some schemes. Similarly, space entrepreneurs would want to know if there's a profit potential in developing, deploying, and operating a particular OEM system, i.e., whether the business case closes. By running the concept through our ensemble of models and simulations, we can address that concern quantitatively. The results of the analysis can then be represented in a set of traditional business case views, e.g., Net Present Value (NPV), Return-On-Investment (ROI), etc. With the addition of other models and simulations, this AoA capability, we believe, can evolve into one that addresses the broader Mars Colony tradespace at the architectural level.

Table 1: Mars Colony Stakeholders and Concerns

Stakeholders	Concerns
Space Agencies	Public Support; Safety
Private Enterprises	Profitability
Science Communities	Science Opportunities
Space Enthusiasts/Influencers	Frequent Progress
Colonists	Survival; Sustainability

D. Context Diagram

Before embarking on a detailed description of MCAM, 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 4 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 four models and simulations we are developing will, regrettably, cover only some of these exchanges/interactions.

The interplanetary supply chain in the figure may include locations in the solar system (e.g., on the Moon) that serve as sources of propellant and propellant depots.[14] Mars Cyclers may also be part of this supply chain as suggested by Aldrin.[40,71]

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.

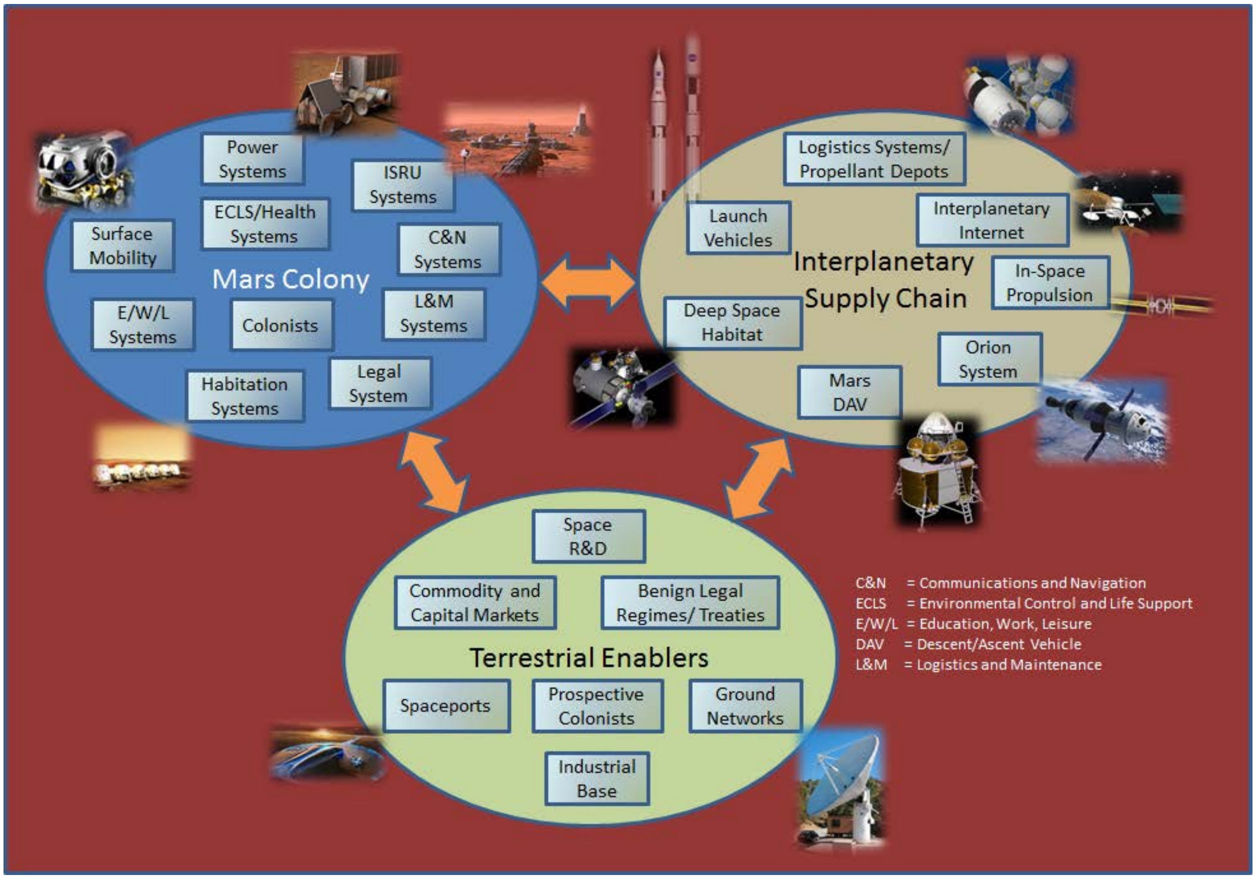


Figure 4: Mars Colony Context Diagram

IV. Key Constructs in the Mars Colony Architecture Model

The Mars Colony Architecture Model (MCAM) is a relational data model. It is useful to first understand what key architectural constructs (i.e., building-block artifacts) MCAM uses. These key constructs are Operational Nodes, Milestones, Systems, Operational Activities/Functions, Measures, and Resources. Other constructs that we found useful in formally describing the architecture are Resource Flows, Performer Classes, and Flight Types. These constructs form the basis for semantic precision in describing alternative architectures so that they may be subject to a variety of quantitative analyses. The datatables in MCAM that define these constructs form MCAM's Integrated Dictionary, known as an AV-2 in DoDAF.

A. Operational Nodes

Operational Nodes in MCAM are spatial locations in the solar system. Operational Nodes are used to represent the locus of an Operational Activity (or Function). Nodes are vital to describing a Mars Colony architecture because they are often associated with (or provide a home for) other fundamental constructs such as systems, facilities, resource sinks and sources, or combinations of those things.

Operational Nodes in MCAM have three basic subtypes: surface nodes, orbital nodes, and Lagrangian nodes:

- Surface nodes are fairly straightforward. They exist on the surface of a central body such as the Earth, the Moon, or Mars, and they are further characterized by their latitude and longitude on that central body. Examples of surface nodes include the Kennedy Space Center (28.6°N, 80.6°W) or the Apollo 11 landing site at Mare Tranquilitatis (0.7°N, 23.5°E).
- Orbital nodes are also characterized by their central body (e.g., Earth, Moon, Mars, or Sun), as well as other characteristics describing the orbit itself: apoapsis, periapsis, and inclination. Therefore, the ISS

orbit could be an orbital node located around Earth at a circular altitude of 400 km and an inclination of 51.6 degrees. Recently, because of its long-term stability, a lunar distant retrograde orbit (L-DRO) has been suggested as a useful orbital node in Mars exploration missions.

- Lagrangian nodes are located at any of the Lagrange points in the solar system. They are characterized by the two bodies and the index number of the Lagrange point. One commonly considered Lagrange point is the Earth-Moon L1 point, which lies between the Earth and the Moon (at 85% the distance towards the Moon as seen from Earth) at the point where the two bodies' gravitational pulls are balanced.

The existence of an Operational Node within an architecture does not necessarily indicate that a system, facility, or organization exists at that location. A node is simply a way to refer to locations in space where something operationally important happens, for example, an in-space rendezvous of two vehicles. The nomenclature developed around nodes allows us to build up a potential interplanetary transportation network, and thusly to formalize descriptions of interplanetary supply chain and logistics architectures. However to complicate matters, the spatial and energy relationships among nodes in space are governed by the laws of orbital mechanics, and hence may change over time. This is especially conspicuous for planetary transfers.

Rudimentary descriptions of an architecture found, for example, in a Design Reference Architecture (DRA) may identify Operational Nodes by generic names, but without identifying specific locations. As the architecture matures, these generally become very specific as alternatives are considered. Consider the Mars DRA 5.0 [72-74] in Figure 5. The four Operational Nodes (Launch Site, High Mars Orbit, Mars Surface, and Earth Recovery Site nodes) are not imbued with specific locations, but eventually these must be given explicit locations in order to perform any serious mission analysis. Ultimately during execution, critical operational activities, functions, or events (such as an in-space rendezvous or landing on a planetary body) occur at a specific time at a specified Operational Node, leading to the next fundamental concept—Milestones.

B. Milestones

A Milestone represents the occurrence of a change in any attribute defining an architecture. In MCAM, Milestones are defined (spatially and temporally) by identifying the Operational Node and a specific date/time at which the change occurs. Milestones allow a dynamic description of an architecture, such as one may want to describe an assembly sequence, and not just "As-Is" or "To-Be" architecture snapshots. Besides defining an assembly sequence or build-up, Milestones are typically used to mark the introduction of new technologies, or to signal a change in a key parameter at a particular Operational Node or for a particular System at an Operational Node.

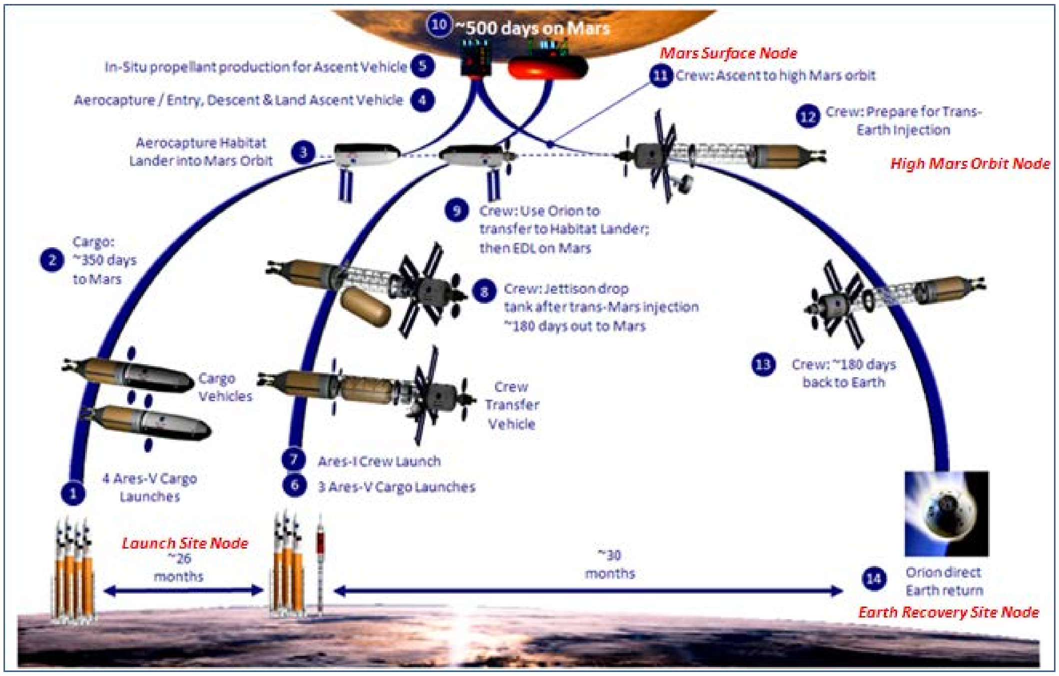


Figure 5: Mars Design Reference Architecture 5.0

As an example, consider again the Mars DRA 5.0 in Figure 5. Milestones were created for each launch, rendezvous, and landing event with actual dates dictated by launch site processing constraints, and of course orbital mechanics. Similarly, in previous work for the Constellation Program, we constructed individual Milestones for the build-up of a lunar outpost. In both cases, the number of Milestones needed was very manageable. For the Mars Colony, the number of Milestones may be larger, but still manageable. For a given architecture, the actual number will generally depend on the time horizon one wants to represent in the MCAM, and specifically on how many deployment (colony build-up), operations, population, and technology events need to be recognized.

C. Systems

A System represents a physical object within an architecture that fulfills a function. In MCAM, a System can be something that is already developed such as the Falcon 9, or something merely conceptual such as a Deep Space Habitat. From Figure 5, we can identify some of the Systems in Mars DRA 5.0—Orion, Ares V and Ares I, an *in situ* propellant production plant, a habitat lander, etc. While these are intended to operate in space, terrestrial facilities such as a Mission Control Center are also considered Systems. Each System belongs to a System Type that shows what broad functionality is served. In an architecture, Systems interact and interface with other Systems. The characteristics of these interactions and interfaces need to be captured within the architecture description. (See Section F, Resource Flows and Needlines.) The number of Systems defined in MCAM's Integrated Dictionary (i.e., the Systems Table of the AV-2) is unconstrained, meaning that new ones can be added whenever needed to describe a new architecture.

D. Operational Activities/Functions

Operational Activities/Functions transform inputs (resources) into outputs (other resources or end products) or change their state. In economics terms, an operational activity/function has a production function (the technical relationship between the inputs and output, $y = f(x_1, x_2, \ldots, x_n)$) and a cost function ($C = C(y;\ w_1, w_2, \ldots, w_n)$) derivable from the production function and input (i.e., factor) prices, w_i. Typical Operational Activities/Functions for space missions include mission planning and design, real-time mission execution, facility maintenance, and training. OEM Operational Activities/Functions include mining, transporting, and processing. Operational Activities/Functions are performed by an organization, system, a team of individuals, or one person, but this is not a defining attribute. That allocation is defined in a specific architecture. (See Section G, Performer Classes and Types.) The number of Operational Activities/Functions defined in MCAM's Integrated Dictionary (i.e., the Operational Activities/Functions Table of the AV-2) is unconstrained.

E. Measures

In MCAM, Measures encompass any measurable property or attribute of an architecture or any of its components. This includes physical measure (e.g., mass, size, and power), economic measures (e.g., cost and profitability), and performance measures (e.g., I_{sp}, efficiency, and reliability), but may also include measures of an architecture like the number of participating countries. The quantitative magnitude of an individual Measure is called the measure's value. Each Measure must be defined so that consuming models and simulations understand the units associated with a value. Hence, each Measure has a well-defined Unit Type, e.g., meters for distance. The number of Measures defined in MCAM's Integrated Dictionary (i.e., the Measures Table of the AV-2) is unconstrained, as is the number of Unit Types.

F. Resources, Resource Flows, and Needlines

1. Resources

In MCAM, Resources encompass any forms of information, labor, energy, or matériel that we want to track in an architecture. Typically, we would want to track Resources that are consumed or produced, or are moved from one Operational Node to another. In some cases, we would want to be specific (e.g., propellant or water) about the Resources that are tracked, but for other Resources, an aggregate mass (e.g., for spares) is sufficient. The number of Resources defined in MCAM's Integrated Dictionary (i.e., the Resources Table of the AV-2) is unconstrained.

2. Resource Flows

Resource Flows in MCAM represent actual interactions/exchanges of Resources between Systems or Operations Nodes. Resource Flows have performers, different kinds of interfaces, and physical rates. Resource Flow modeling can be performed at varying levels of detail and fidelity depending on the areas of concern, the Operational Activity/Function being analyzed, and the architectural solutions being sought. In this modeling, it is particularly important to distinguish between a Resource quantity and its rate of change since a Resource quantity is a stock, but a Resource Flow is its time derivative. The Units Type Table should contain both kinds of units.

3. Needlines

A Needline indicates a demand for an interaction (or exchange) of some sort between two Operational Nodes. In MCAM as in DoDAF, a Needline is an upper-level aggregation consisting of one or more Resource Flows. Other terminologies expressing levels of aggregation are used depending on the community of interest; for example, the SysML modeling standard uses the term "lifeline."

G. Other Constructs

1. Performer Classes and Types

In MCAM, Performers Classes are Systems, Organizations, or Persons. For each of these three classes, we can assign a specific Performer Type. When the Performer Class is a System, MCAM uses the Systems Table to identify the performer. In particular, this tells us which system is responsible for the interface in, for example, a Resource Flow. When the Performer Class is an Organization, MCAM uses the Partners Table to identify which organization is responsible for a process or activity. Organizations listed in this table can be a space agency (or another government body or international body) or a commercial enterprise. The Partners Table is used to assign development responsibility and " ownership" to Systems, and to assign operational responsibility to Operational Nodes or Flight Types. This is particularly useful since the HCM, we assume, will be an international endeavor, and an architecture description should have the capability to assign such roles and missions. Lastly, when the Performer Class is a Person, MCAM uses the Person Type Table to identify who has the responsibility.

The Person Type Table was appropriated (unchanged) from the U.S. Bureau of Labor Statistics (BLS) Standard Occupational Classifications (SOC).[75] In DoDAF, the equivalent notion is Personnel Types, which allows representation of training, usually defined by Military Occupational Specialty (MOS), and education levels. Since we expect that a Mars Colony might eventually contain many of Earth's occupations, there was no logic in inventing something new, so we chose to use the BLS SOC. For now, however, MCAM uses only the 23 major SOC groups.[iv]

While MCAM uses a skills-based approach to Person Types, that was not sufficient for modeling a Mars Colony. We needed to introduce the notion of a binary Person Gender Type. The obvious reason is that in the long run a viable Mars Colony must, future reproductive technologies aside, have a roughly equal number of each type, and we want our architecture description to be capable of tracking each population. A less obvious, yet important reason is that in modeling food consumption (for example, caloric requirements) and other metabolic processes, men and women differ even when performing the same activities.

2. Flight Types and Flights

Flight Types are defined by which Operational Node is the departure node, which Operational Node is the destination node, what launch or in-space propulsion vehicle is used, and what space vehicle/carrier is being transported. Both the launch/propulsive vehicle and space vehicle/carrier are considered systems and should already be defined in the Systems Table. (The departure and destination nodes should already be defined in the Operational Nodes Table.) Other metadata characteristics may be used to distinguish Flight Types, such as number of persons (when transporting humans), mission duration (when independent of the departure date) and responsible partner, but the nodes and systems used are paramount. As part of MCAM's AV-2, the Flight Types Table may contain as many Flight Types as needed to accurately capture an architecture's operations concept.

Once the needed Flight Types have been defined, the Flights Table represents a flight schedule that defines a scenario or campaign. The flight schedule is a list of all flights by type along with the anticipated departure date for each. The Flights Table may contain as many flights as needed to accurately capture a scenario or campaign.

H. MCAM Terminology Compared to Other Related Architecture Frameworks

To possibly avoid confusion, it is useful to compare terminologies in DoDAF, MoDAF, UPDM, and MCAM. Some of MCAM's terminology arose out of earlier modeling and simulation work performed under the Constellation Program, but we are not doctrinaire about it. Architectural terminology appropriate for human spaceflight architectures, and for a Mars Colony in particular, will naturally evolve on its own, and in the future may draw from NASA's Model-Based Systems Engineering (MBSE) initiatives. Table 2 provides a terminology cross-walk for many of the constructs in MCAM discussed above.[76]

Table 2: A Comparison of Terminologies

DoDAF 2.02	UPDM	MoDAF 1.3	MCAM
Node	Node	Node	Node
System	System or CapabilityConfiguration	CapabilityConfiguration	System
Needline (informal in v2.02)	Needline	Needline	Needline
Activity	Function	Function	Function
Measure	Measurement	MeasurableProperty	Measure Value
MeasureType	MeasureType	N/A	Measure
MeasureTypeUnitsofMeasure	SysML DimensionType (SysML 1.3 uses ValueType)	N/A	Unit Type
N/A	ActualProjectMilestone or DeployedMilestone or IncrementMilestone or NoLongerUsedMilestone	ProjectMilestone or DeployedMilestone or CapabilityIncrement or StatusAtMilestone	Milestone
Organization	ActualOrganization	ActualOrganisation	Partner
locationNamedByAddress	LocationKind or GeopoliticalExtent	N/A	Node Location
Performer	Participant or PhysicalResource or LogicalArchitecture or Performer	Node or PhysicalAsset or LogicalArchitecture	Performer Class
whole part of a PersonRoleType	PersonType	N/A	Person Type (by BLS Standard Occupation Classification)
Representation	Alias	Alias	Short Name
Resource	ExchangeElement	ResourceType	Resource

I. DoDAF Views Enabled By MCAM

Traditional DoDAF views are narrative, graphical, tabular, and /or matrices. Table 3 describes some of these traditional views, but how they actually appear is left to each architectural team to decide based on architectural needs, audience, preferred presentation software, etc. Perhaps unbeknownst to the reader, we have already presented the CV-1 view as Figure 1. In Part V of this paper, we will develop a simple example of a Mars Colony architecture, and we will show using MCAM portions of the AV-2 Integrated Dictionary, the resulting OV-2 graphic, OV-3 table, SV-1 graphic, and SV-6 table. Ultimately, we will create new viewpoints and views (e.g., business case views) and use the downstream models to provide the attendant quantitative analyses.

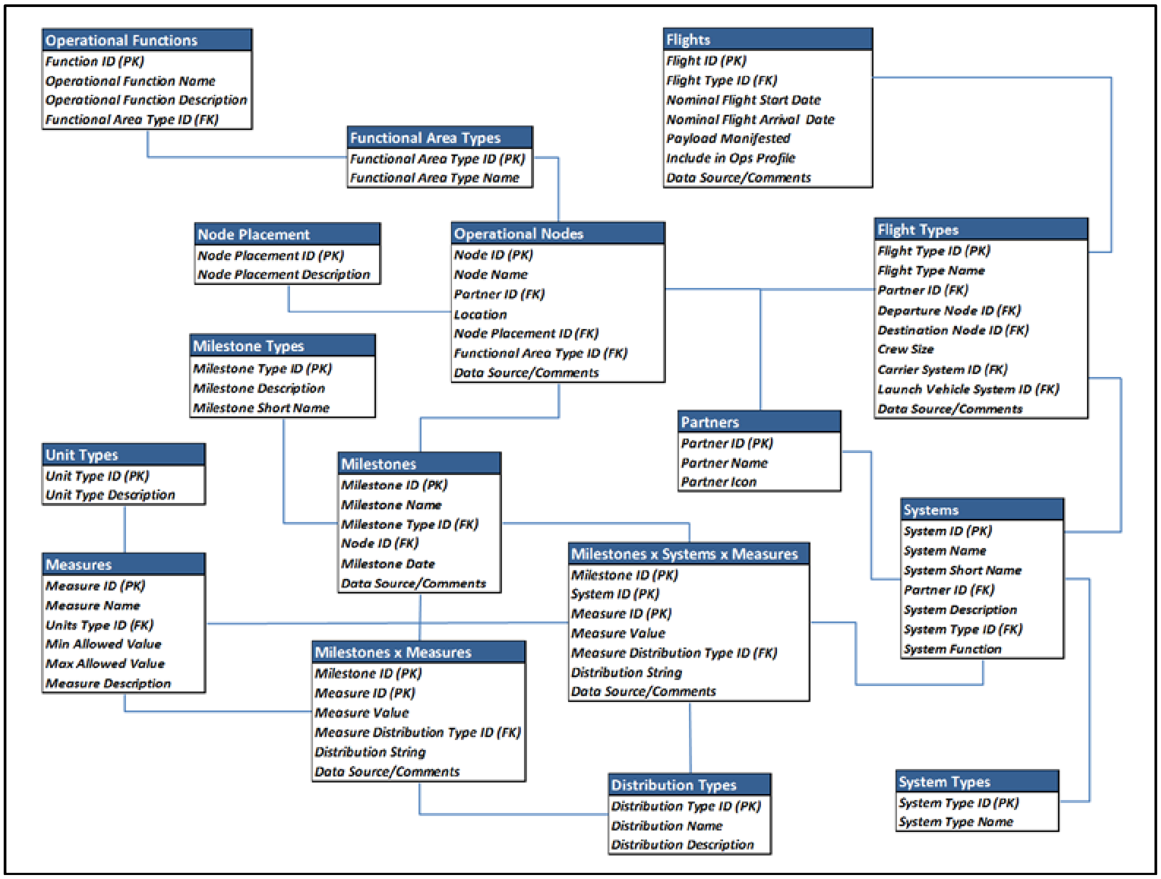
Table 3: Description of Some Basic DoDAF Views

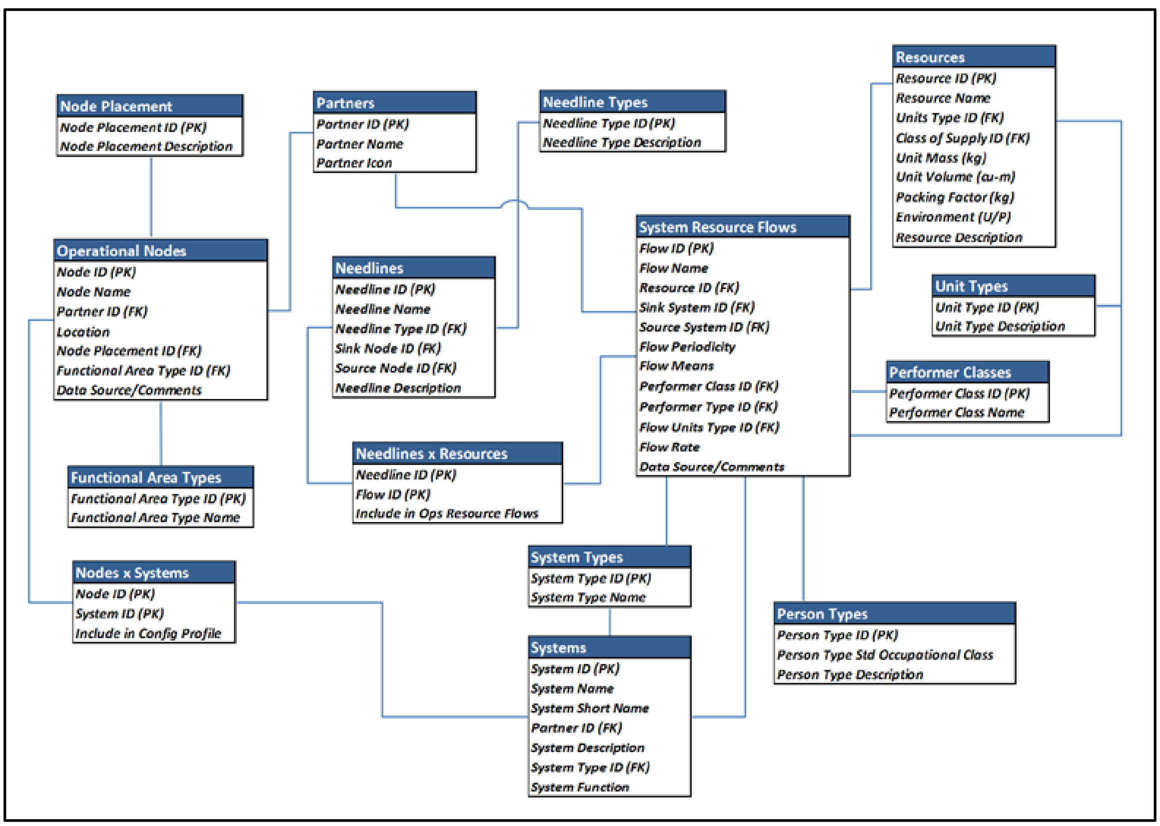
DoDAF Views	Description
AV-1	Provides scope, overview, key assumptions for the architecting effort
AV-2	Defines the architecture artifacts (operational nodes, systems, etc.)
CV-1	Communicates the strategic vision regarding capability development
OV-2	A graphic that shows 'needlines' between operational nodes
OV-3	Breaks needlines into component classes (various resources)
OV-5a	Describes functions/activities (ops functions, mining functions, etc.)
SV-1	A graphic shows a solution space generally in terms of an integrated SoS
SV-3	A matrix shows system interfaces
SV-5b	Maps systems back to functions/activities
SV-6	Describes the physical flows from one system to another
PV-2	Describes the deployment timing for systems

J. Entity-Relationship Diagram.

MCAM consists of datatables constructed as a relational database. The E-R diagram in Figure 6 shows the tables and their relationships to each other. The attributes of each table are described in the MCAM Data Dictionary, v.1.1.[77] The figure is presented in three parts simply because of its size. Consequently, several tables, e.g., Operational Nodes and related tables, appear in all three parts just to make the figure more readable.

Some guiding criteria for MCAM's development were (a) consistency, (b) compactness, and (c) auditability. Consistency is based on the relational structure of the database and strict control of attribute definitions. Brevity and conciseness were important, but the database must foremost support the analytics—that is, MCAM must support the analytic models that need to be exercised. MCAM is currently realized as an Excel © workbook. This enables and simplifies the exchange of the information from MCAM to other analytic models. Auditability was introduced by embedding VBA code so that the Excel spreadsheets display not just the unique identifiers for attributes within a record, but also the human-readable names and descriptions associated with each identifier.


Operational Functions
Function ID (PK)
Operational Function Name
Operational Function Description
Functional Area Type ID (FK)
Flights
Flight ID (PK)
Flight Type ID (FK)
Nominal Flight Start Date
Nominal Flight Arrival Date
Payload Manifested
Include in Ops Profile
Data Source/Comments
Functional Area Types
Functional Area Type ID (PK)
Functional Area Type Name
Node Placement
Node Placement ID (PK)
Node Placement Description
Operational Nodes
Node ID (PK)
Node Name
Partner ID (FK)
Location
Node Placement ID (FK)
Functional Area Type ID (FK)
Data Source/Comments
Flight Types
Flight Type ID (PK)
Flight Type Name
Partner ID (FK)
Departure Node ID (FK)
Destination Node ID (FK)
Crew Size
Carrier System ID (FK)
Launch Vehicle System ID (FK)
Data Source/Comments
Milestone Types
Milestone Type ID (PK)
Milestone Description
Milestone Short Name
Partners
Partner ID (PK)
Partner Name
Partner Icon
Unit Types
Unit Type ID (PK)
Unit Type Description
Milestones
Milestone ID (PK)
Milestone Name
Milestone Type ID (FK)
Node ID (FK)
Milestone Date
Data Source/Comments
Systems
System ID (PK)
System Name
System Short Name
Partner ID (FK)
System Description
System Type ID (FK)
System Function
Measures
Measure ID (PK)
Measure Name
Units Type ID (FK)
Min Allowed Value
Max Allowed Value
Measure Description
Milestones x Systems x Measures
Milestone ID (PK)
System ID (PK)
Measure ID (PK)
Measure Value
Measure Distribution Type ID (FK)
Distribution String
Data Source/Comments
Milestones x Measures
Milestone ID (PK)
Measure ID (PK)
Measure Value
Measure Distribution Type ID (FK)
Distribution String
Data Source/Comments
Distribution Types
Distribution Type ID (PK)
Distribution Name
Distribution Description
System Types
System Type ID (PK)
System Type Name


Resources
Resource ID (PK)
Resource Name
Units Type ID (FK)
Class of Supply ID (FK)
Unit Mass (kg)
Unit Volume (cu-m)
Packing Factor (kg)
Environment (U/P)
Resource Description
Node Placement
Node Placement ID (PK)
Node Placement Description
Partners
Partner ID (PK)
Partner Name
Partner Icon
Needline Types
Needline Type ID (PK)
Needline Type Description
System Resource Flows
Flow ID (PK)
Flow Name
Resource ID (FK)
Sink System ID (FK)
Source System ID (FK)
Flow Periodicity
Flow Means
Performer Class ID (FK)
Performer Type ID (FK)
Flow Units Type ID (FK)
Flow Rate
Data Source/Comments
Operational Nodes
Node ID (PK)
Node Name
Partner ID (FK)
Location
Node Placement ID (FK)
Functional Area Type ID (FK)
Data Source/Comments
Needlines
Needline ID (PK)
Needline Name
Needline Type ID (FK)
Sink Node ID (FK)
Source Node ID (FK)
Needline Description
Unit Types
Unit Type ID (PK)
Unit Type Description
Performer Classes
Performer Class ID (PK)
Performer Class Name
Needlines x Resources
Needline ID (PK)
Flow ID (PK)
Include in Ops Resource Flows
Functional Area Types
Functional Area Type ID (PK)
Functional Area Type Name
Nodes x Systems
Node ID (PK)
System ID (PK)
Include in Config Profile
System Types
System Type ID (PK)
System Type Name
Person Types
Person Type ID (PK)
Person Type Std Occupational Class
Person Type Description
Systems
System ID (PK)
System Name
System Short Name
Partner ID (FK)
System Description
System Type ID (FK)
System Function

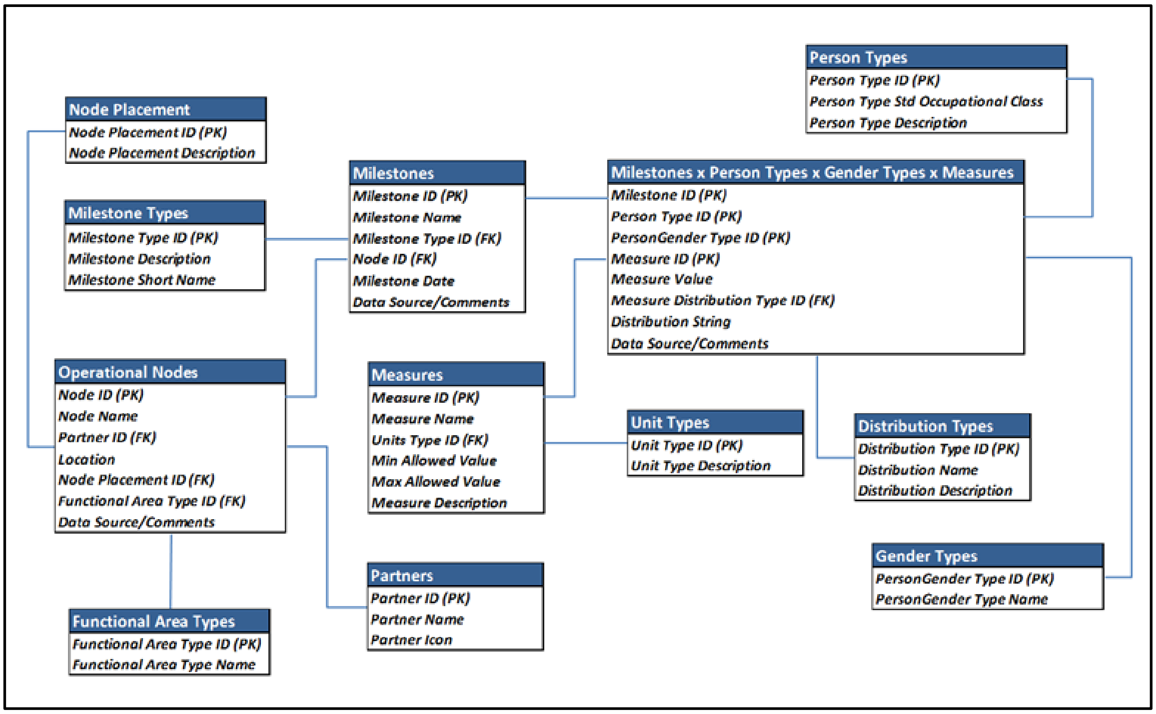


Figure 6: MCAM Entity-Relationship Diagram (Parts A, B, and C)

Node ID	Node Name	Partner ID	Location	Node Placement ID	Node Placement Description	Functional Area Type ID	Functional Area Description	Data Source/Comments
0	Disposal	0	Various	1	Terrestrial	12	Other	
1	Orion Recovery Site	1	Various	1	Terrestrial	4	Ground Ops	
2	DSN Ground Station	0	Goldstone, Madrid, and Canberra	1	Terrestrial	6	Communications and Tracking	
3	HEO Mars Transfer Orbit	0	200 km x 340,000 km, highly elliptical	2	CisLunar	8	Rendezvous	Earth departure to Mars
4	LEO Rendezvous Orbit	0	300 km alt circular 28.5 deg	2	CisLunar	8	Rendezvous	
5	NASA Program Office	1	JSC	1	Terrestrial	1	Management	
6	Mission Control Center, Hou	1	JSC	1	Terrestrial	3	Mission Ops	
7	Training Center, Hou	1	JSC	1	Terrestrial	3	Mission Ops	
8	Mission Control Center, Mos	2	Moscow, Russia	1	Terrestrial	3	Mission Ops	
9	Training Facility, FP	2	Star City, Russia	1	Terrestrial	3	Mission Ops	
10	Launch Facility, KSC	1	KSC	1	Terrestrial	4	Ground Ops	
11	Launch Facility, Baik	2	Baikonur, Khazakstan	1	Terrestrial	4	Ground Ops	
12	Launch Facility, Kou	3	Kourou, French Guiana	1	Terrestrial	4	Ground Ops	
13	Launch Facility, Tan	4	Tanegashima, Japan	1	Terrestrial	4	Ground Ops	
14	Logistics Facility	1	KSC	1	Terrestrial	5	Integrated Logistics Support	
15	Mars Comm Relay Orbit	0	1 sol orbit at altitude = 17,030 km	4	Deep Space	6	Communications and Tracking	Areostationary orbit
16	Mars Parking Orbit	0	250 km x 33,793 km	4	Deep Space	8	Rendezvous	
17	Mars Settlement Site A	0	Isidis Planitia 12°54'N 87°00'E	5	Mars Surface	7	Settlement	SP-2009-566 ADD, Human Exploration of Mars DRA 5.0 Addendum
18	Mars Settlement Site B	0	N. Amazonis Planitia 35°00'N 145°00'W	5	Mars Surface	7	Settlement	Website http://marsbase.org/location, accessed 27 Feb 2015
19	Mars Settlement Site C	0	Utopia Planitia 42°00'N 150°00'E	5	Mars Surface	7	Settlement	Website http://marsbase.org/location, accessed 27 Feb 2015
20	Mars Settlement Site D	0	Isidis Basin 18°30'N 77°30'E	5	Mars Surface	7	Settlement	Website http://marsbase.org/location, accessed 27 Feb 2015
21	Mars Water Mining Site	0	Panchaia Rupes 64°14'N 146°00'E	5	Mars Surface	9	ISRU-Type 1 (Volatiles)	Thierry de Roche, UNSW, School of Mining, 2015
22	Distant Retrograde Lunar Orbit	0	70,000 km alt from lunar surface, near circul	2	CisLunar	8	Rendezvous	Asteriod Redirect Mission (ARM) Feasibility Study, v2.0, 24 May 20
23	Low Lunar Orbit (LLO)	0		2	CisLunar	8	Rendezvous	
24	Geostationary Orbit (GEO)	0	35,786 km alt, circular	2	CisLunar	8	Rendezvous	
25	Geostationary Transfer Orbit (GTO)	0	185 km x 35,786 km alt	2	CisLunar	8	Rendezvous	
26	Earth-Moon Langrange Point 1 (EML1)	0		2	CisLunar	8	Rendezvous	
27	Earth-Moon Langrange Point 2 (EML2)	0		4	Deep Space	8	Rendezvous	
28	Earth-Moon Lagrange Point 4/5 (EML4/	0		2	CisLunar	8	Rendezvous	
29	Lunar South Pole	0	Shackleton Crater region	3	Lunar Surface	9	ISRU-Type 1 (Volatiles)	
30	Lunar Transfer Orbit	0		2	CisLunar	8	Rendezvous	
31	Phobos Transfer Orbit	0		4	Deep Space	8	Rendezvous	
32	Low Phobos Orbit	0		4	Deep Space	8	Rendezvous	
33	Phobos Site of Interest	0		4	Deep Space	9	ISRU-Type 1 (Volatiles)	
34	Deimos Transfer Orbit	0		4	Deep Space	8	Rendezvous	
35	Low Deimos Orbit	0		4	Deep Space	8	Rendezvous	
36	Deimos Site of Interest	0		4	Deep Space	9	ISRU-Type 1 (Volatiles)	
37	Low Mars Orbit	0		4	Deep Space	8	Rendezvous	
38	High Mars Orbit	0		4	Deep Space	8	Rendezvous	
39	Mars Settlement Site E	0	Henry Crater 10°54'N 10°42'E	5	Mars Surface	7	Settlement	Project Aldrin-Purdue Final Report, April 9, 2015
40	Mars Settlement Site F	0	Elysium Planitia 3°00'N 154°00'E	5	Mars Surface	7	Settlement	Project Aldrin-Purdue Final Report, April 9, 2016
41	Mars Settlement Site G	0	Casius Quadrangle 35°00'N 75°00'E	5	Mars Surface	7	Settlement	Project Aldrin-Purdue Final Report, April 9, 2017
42	Mars Settlement Site H	0	Arcadia Planitia 50°00'N 173°00'E	5	Mars Surface	7	Settlement	Project Aldrin-Purdue Final Report, April 9, 2018
43	S1L1 Orbit	0		4	Deep Space	8	Rendezvous	Project Aldrin-Purdue Final Report, April 9, 2019

Figure 7: A Portion of the Operational Nodes Table

V. An Illustrative Example of a Mars Colony Architecture Description

In Part V, we illustrate by a simple example how MCAM is used to describe a Mars Colony architecture consisting of a Mars settlement (and its systems), an areographically separated water mining site, and a communications/navigation link between them. The relationships and data captured in various MCAM datatables in the presented example are either DoDAF views in tabular form, or can be used to construct certain standard DoDAF graphical views.

A. Building an Architecture--Operational Nodes and Needlines

The three nodes in this example are listed in the Operational Nodes Table along with additional architectural information about each node. A portion of the Operational Nodes Table is shown in Figure 7, which currently contains over 50 potential Operational Nodes of interest. Adding a new Operational Node to the architecture may be needed, for example, if the architecture is expanded to include a new future destination. In Figure 7, the three nodes in this simple example have been highlighted.

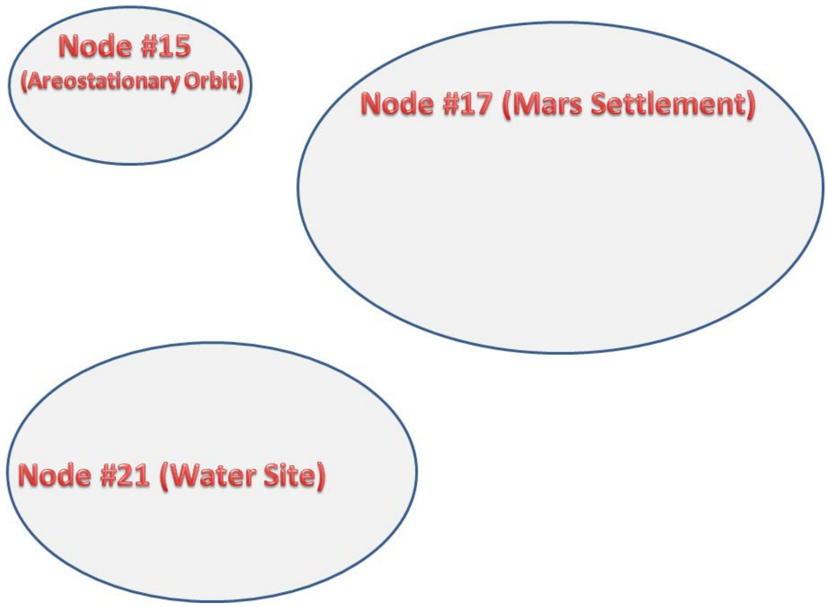


Figure 8: A Simple Mars Colony with Three Operational Nodes

Figure 8 is a graphical view that we will use to add architectural information and build up other views. In the next step, we add Needlines. The Needlines between the Operational Nodes are represents in Figure 9 as arrows. Typically these are annotated, as we have done, with some sort of information regarding the nature of each Needline. The figure is typical of a DoDAF OV-2 graphic. A matrix version of this information (without annotations) has been called an adjacency matrix[v] in graph theory.[78]

The Mars settlement site's principal need from the water mining site is of course water, but in this example, it also includes telemetry to indicate status (e.g., health and safety) information for any Systems sent there. The water mining site might need to receive commands and maintenance services (labor) from the Mars settlement site for those (as yet unspecified) Systems. The annotations also indicate that both sites need to receive Positioning, Navigation, and Timing (PNT) information from orbit. We have identified four Needlines, to which we have given unique IDs #3 through #6 in Figure 9. (As we already used unique IDs #1 and #2 for interplanetary logistics and general communications Needlines, those IDs were unavailable and are not shown. MCAM only requires that IDs are indeed unique.)

These Needlines are captured in MCAM's Needlines Table, shown in Figure 10. The actual data is structured as in the E-R Diagram of Part IV, but by design MCAM displays the human-readable text associated with each unique ID.

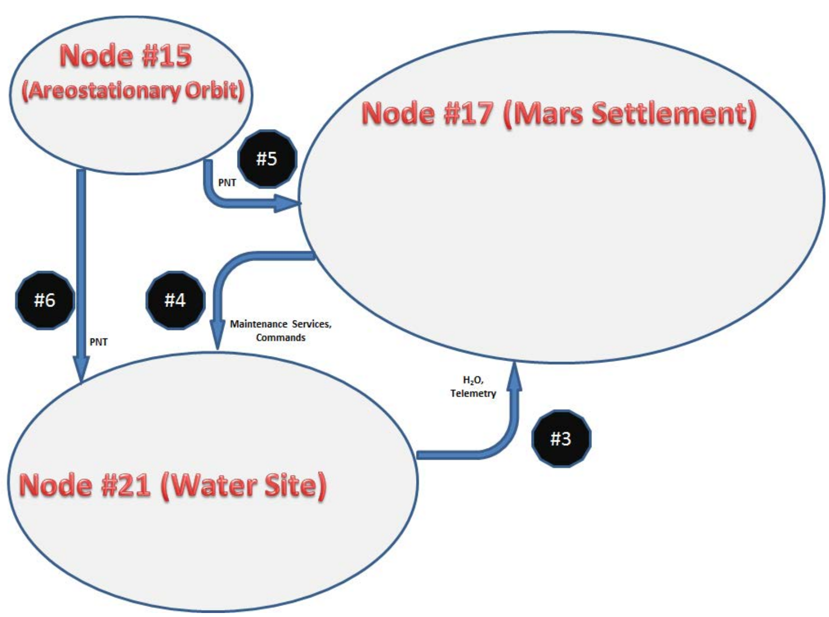


Figure 9: OV-2 Mars Colony Operational Nodes with Their Needlines

So far, we have identified some Needlines between Operational Nodes, and have represented those Needlines in an MCAM datatable. This datatable has the information needed to generate an OV-2 graphic using whatever graphical software a system architect may wish to employ. To preview a bit here, we will later add additional qualitative data that will enable an OV-3 view of each Needline in terms of operational resource flows; and we will add quantitative data that will enable calculation of the total demand for various resources. To do that, we first add some Resources and Systems to our simple example.

Needline ID	Needline Name	Needline Type ID	Needline Type Description	Sink Node ID	Sink Node Name	Source Node ID	Source Node Name	Needline Description
1	HEO-HMO	1	Logistics (LOG)	38	High Mars Orbit	3	HEO Mars Transfer Orbit	
2	Colony-DSN	6	General Communications (COMM)	2	DSN Ground Station	17	Mars Settlement Site A	
3	Water Mining-Colony	1	Logistics (LOG)	17	Mars Settlement Site A	21	Mars Water Mining Site	Water from ISRU systems
4	Colony-Water Mining	1	Logistics (LOG)	21	Mars Water Mining Site	17	Mars Settlement Site A	Maintenance services for ISRU systems
5	Positioning Satellites-Colony	5	Positioning, Navigation, and Timing (PNT)	17	Mars Settlement Site A	15	Mars Comm Relay Orbit	
6	Positioning Satellites-Water Mining	5	Positioning, Navigation, and Timing (PNT)	21	Mars Water Mining Site	15	Mars Comm Relay Orbit	

Figure 10: MCAM OV-2 Needlines Representation in Tabular Form

B. Adding Resources and Systems to the Architecture

The Resources Table in MCAM provides a list of all the Resources we seek to track in an architecture. As previously mentioned, earlier versions of DoDAF had essentially one resource—information—so this has been accorded the unique ID = 0. Beyond information, a Mars Colony architecture would need to track those Resources essential to human life, as well as surface power, propellants, other materials extractable from the Mars environment, etc. The Resources Table, a portion of which is shown in Figure 11, identifies each Resource with a unique ID and the units in which it is measured.

Resource ID	Resource Name	Units Type ID	Units Type	Class of Supply ID	Unit Mass (kilograms)	Unit Volume (cubic meters)	Packing Factor (kilograms)	Environment (U/P)	Resource Description
0	Information	32	Gb						
1	Labor	39	workhours						
2	Water	8	kg	201	1	0.001			
3	Oxygen	8	kg	203	1				
4	Hydrogen	8	kg	203	1				
5	Carbon Dioxide	8	kg	203	1				
6	Electric Energy	58	kWh						
7	Mars Icy Regolith	8	kg		1				
8	Lunar Ice/Icy Regolith	8	kg		1				
9	Food from Plant Sources	8	kg	202	1				
10	Food from Animal Sources	8	kg	202	1				
11	Nitrogen	8	kg	203	1				
12	Methane	8	kg	104	1				

Figure 11: A Portion of the MCAM Resources Table

System ID	System Name	System Short Name	Partner ID	System Description	System Type	System Type Name	System Function
1	Space Launch System (Block 1A)	SLS (Blk 1A)	1		1	Launch Vehicle	70 MT to LEO
2	Space Launch System (Block 1B)	SLS (Blk 1B)	1		1	Launch Vehicle	105 MT to LEO
3	Orion Lunar Variant (Block 1)	Orion (Blk 1)	1		2	In-Space Transportation	Earth
4	Orion Mars Variant (Block 2)	Orion (Blk 2)	1		2	In-Space Transportation	Transports crews from Earth to Mars orbit and returns them to Ear
5	Space Launch System (Blk 2)	SLS (Blk 2)	1		1	Launch Vehicle	130 MT to LEO
6	DRA5 NTR Departure Stage - Cargo	NTR	1		2	In-Space Transportation	
7	DRA5 LH2 Tank - Cargo	LH2 Tank	1		2	In-Space Transportation	
8	DRA5 Mars CargoLander	DAV	1	Common LOX/CH4 descent stage mated to an ascent stage without LOX	21	Mars Surface Logistics	
9	DRA5 Mars HabLander	SHAB	1	Common LOX/CH4 descent stage mated to a long-term crew surface habitat	15	Mars Surface Habitation	
10	DRA5 LH2 Drop Tank w/Long Saddle Truss	LH2 Drop Tank	1		2	In-Space Transportation	
11	DRA5 Mars Transfer Vehicle	MTV	1	Consists of 3 segments: TransHab, short saddle truss w/DM, consumables module	2	In-Space Transportation	
12	Mars Communications Relay Satellite	MARSAT	1		4	Deep Space Communications	
13	DRA5 Pressurized Rover		1		16	Mars Surface Mobility	
14	DRA5 Unpressurized Rover		1		16	Mars Surface Mobility	
15	DRA5 Robotic Rover		1		21	Mars Surface Logistics	
16	DRA5 Utility Power Cart		1		20	Mars Surface Power	
17	DRA5 Dynamic Isotope Power System Cart	DIPS Cart	1	Advanced Stirling cycle power system with self-mobility	20	Mars Surface Power	
18	DRA5 ISRU Plant-Stationary		1	O2 production from atmospheric CO2	18	Mars Surface ISRU-Type 2	
19	DRA5 Traverse Cache Vessel		1		18	Mars Surface ISRU-Type 2	
20	DRA5 FSPS	FSPS (30kW)	1	Scaled version of lunar FSPS. Lunar variant is 40kW; Mars variant is 30 kW	20	Mars Surface Power	
21	DRA5 Towable Drilling Equipment		1		18	Mars Surface ISRU-Type 2	
22	Mars Systems Simulation and Integration Laboratory	MSSIL	1		5	Mission Operations	
23	Aeroshell		1		2	In-Space Transportation	
24	DRA5 NTR Departure Stage - Crew	NTR - Crew	1		2	In-Space Transportation	
25	DRA5 Inline LH2 Tank - Crew	LH2 Tank - Crew	1		2	In-Space Transportation	
26	DRA5 NTR Engine	NTR Engine	1		2	In-Space Transportation	
27	DRA5 Mars EVA Suit		1		22	Other Mars Surface System	
28	TMI Module	TMI Module	1		2	In-Space Transportation	
29	MOI Module	MOI Module	1		2	In-Space Transportation	
30	TEI Module	TEI Module	1		2	In-Space Transportation	
31	Mars Surface Habitat - Variant 1	MHAB-1	0	Dragon capsule based design from SpaceX, Available: http://www.spacex.com/dragon	15	Mars Surface Habitation	
32	Mars Surface Habitat - Variant 2	MHAB-2	0	Dragon capsule based design from SpaceX, Available: http://www.spacex.com/dragon	15	Mars Surface Habitation	
33	Mars Surface Habitat - Variant 3	MHAB-3	0	Dragon capsule based design from SpaceX, Available: http://www.spacex.com/dragon	15	Mars Surface Habitation	
34	Inflatable Mars Habitat Unit	IMHU	0	~500 cubic meters capable of connecting to any SpaceX Mars Surface Habitat	15	Mars Surface Habitation	
35	Falcon 9 Heavy	F9-H	8	Space X heavy lift launch vehicle	1	Launch Vehicle	53 MT to LEO
36	Mars In Situ Water Extractor	MISWE	1	Honeybee Robotics mining system; 6-wheeled rover powered by 2 ASRGs	17	Mars Surface ISRU-Type 1	Icy soil acquisition/delivery, volatiles extraction/capture, water stora
37	100kWe SEP Tug	SEP100	1	SEP unit with 8 Hall thrusters w/16mt Xenon	2	In-Space Transportation	Transports uncrewed modules to Mars
38	DSN 34m Antenna Complex	DSN34	0		4	Deep Space Communications	
39	DSN 26m Antenna Complex	DSN26	0		4	Deep Space Communications	
40	Deep Space Habitat	DSH	1	Supports 4 crew for 500 days; 30mt vehicle w/SAs, batteries, ACS provided by Orion or prop m	2	In-Space Transportation	Transports crew only from HEO to HMO and return
41	Mars Surface Greenhouse Facility	MSGF	2	Supports 0.01 hectares (100 m-sq) of greenhouse environment	15	Mars Surface Habitation	Grows vegetables for colony
42	Mars In Situ Water Transporter	MISWT	1	Includes self-contained power system for thermal regulation and mobility	16	Mars Surface Mobility	Stores and transports large quantities of water to settlement sites

Figure 12: A Portion of the MCAM Systems Table

The Systems Table in MCAM provides a list of all the Systems that we may want to include in an architecture. MCAM currently contains more than 100 identifiable Systems. These were culled from a variety of sources, including Mars DRA 5.0, Inspiration Mars[45], Project Aldrin-Purdue[71], Mars One[79], etc. as well as from systems currently operational or under development. A portion of the Systems Table is shown as Figure 12 with seven Systems highlighted. These were selected for our simple example to be physically associated with the three Operational Nodes. (A logical association is also representable in MCAM, as for example, when a System is associated with its terrestrial developer.) These associations are captured in an MCAM table called Nodes × Systems.

One of the Systems selected for our simple example is called the Mars *In Situ* Water Extractor (MISWE) from Honeybee Robotics.[39] This proposed system consists of the Icy-Soil Acquisition and Delivery Subsystem (ISADS) and the Volatiles Extraction and Capture Subsystem (VECS), as shown in Figure 13. The ISADS is a deep fluted auger that drills into the ice or icy-soils and retains material on its flutes. Upon material acquisition, the ISADS is retracted into the VECS and sealed. The VECS consists of a cylindrical heat exchanger and volatiles transfer system (a reactor). The material on the deep flutes is heated via conduction. However, once some water sublimes and pressure inside the reactor increases, the further heat transfer is accomplished via very efficient convection. Vapor is bled into a water collection canister by a one way valve where it condenses. The heat from the canister can be transferred back to the reactor.

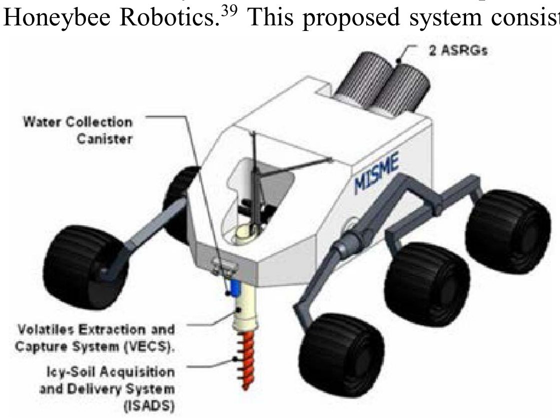


Figure 13: MISWE from Honeybee Robotics

After water extraction the ISADS is lowered towards the ground and spun at high speed to eject the dry soil via centrifugal action. Meanwhile, the collected water is pumped from the canister into a storage container within the rover's Warm Electronics Box. The MISWE rover then moves to the next location and the operation is repeated.

The other selected Systems consist of a Mars Surface Habitat, a Mars Surface Greenhouse Facility, a Fission Surface Power System, an O_2 Extraction System (for breathable air), a Communications/Positioning Satellite, and a

Mars *In Situ* Water Transporter (MISWT). (The quantity of each System will be determined later using the downstream analytic models, but these numbers are not needed at this stage to build DoDAF views. Naturally, the quantities are functions of the Mars Colony “size” to be supported.)

C. Building DoDAF Views

In Figure 14, we show the Systems we associated with each Operational Node. We have also identified the Resources that flow between these Systems. Figure 14 is typical of a DoDAF SV-1 diagram, though sometimes the identification with specific Operational Nodes is left vague. The Resources represented in the flows are information (PNT, telemetry, commands), labor (maintenance services), water, power, etc. from the Resources Table. To enhance stakeholder understanding, it is common in an SV-1 diagram to use color and different styles of lines to make these flows clearer, as the number of resources and kinds of resource flows can be daunting for more complex architectures.

Even in this simple example, there are 22 Resource Flows, which we have labelled in Figure 15. These are captured in System Resources Flow Table in MCAM. Figure 16 shows the 22 Resource Flows in tabular form, which in DoDAF is typically called an SV-6 table. This table uniquely identifies each flow, the specific Resource involved, and the source and sink Systems. Additional qualitative and quantitative information regarding each flow is captured in this table, which is shown in two parts for readability. Such information includes the flow periodicity, as for example, whether the flow is continuous, periodic (i.e., occurring at regular intervals), or irregular (e.g., as might occur with random failures). The flow means provides descriptive information about how the flow occurs, and the flow Performer Class indicates who or what is responsible for the flow (i.e., whether the performer is one of the Systems involved, a person, or an organization). Once the Performer Class is identified, the table allows for the identification of the performer in more detail, when that is known. (See Performer Classes and Types above.)

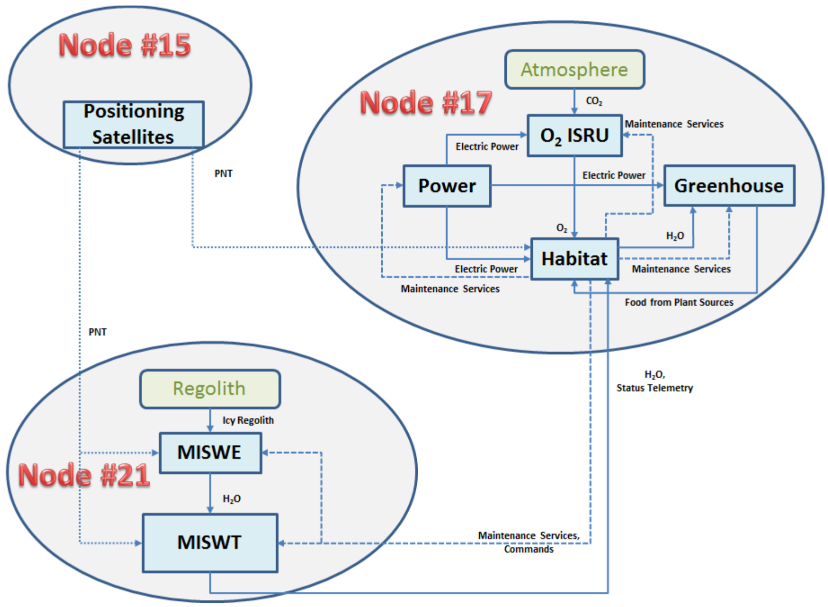


Figure 14: SV-1 Architecture with Systems and System Flows

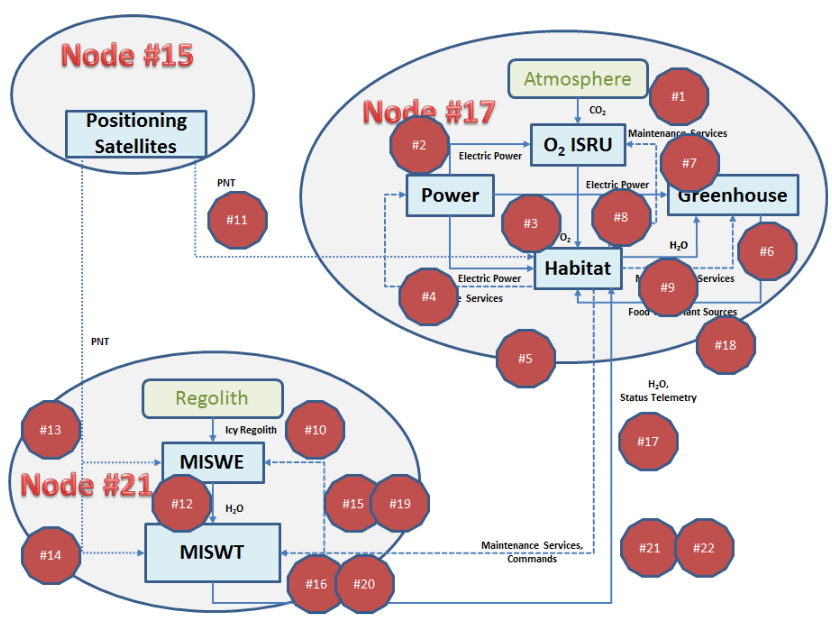


Figure 15: Identifying Resource Flows Between Systems

The table also captures the anticipated or required flow rate with the units associated with that flow. Taken together, this quantitative information is intended to permit an analysis of the total demand for a Resource at an Operational Node against the available supply, as for example, by summing power loads and comparing that to the available power generating capability. To compute the latter, however, we need to add data regarding the deployment and capability of any power-generating Systems. The table that captures that information is discussed in the next section.

Flow ID	Flow Name	Resource ID	Resource Name	Sink System ID	Sink System Name	Source System ID	Source System Name	Flow Periodicity	Flow Means
1	Mars Atmosphere to O2 Generator	5	Carbon Dioxide	18	DRA5 ISRU Plant-Stationary			Continuous	
2	Power to O2 Generator	6	Electric Power, DC	18	DRA5 ISRU Plant-Stationary	20	DRA5 FSPS	Continuous	Power Cable
3	O2 Generator to Habitat	3	Oxygen	31	Mars Surface Habitat - Variant 1	18	DRA5 ISRU Plant-Stationary	Continuous	Pipe
4	Power to Habitat	6	Electric Power, DC	31	Mars Surface Habitat - Variant 1	20	DRA5 FSPS	Continuous	Power Cable
5	Habitat to Power	1	Labor	20	DRA5 FSPS	31	Mars Surface Habitat - Variant 1	Irregular	EVA
6	Habitat to Greenhouse	1	Labor	41	Mars Surface Greenhouse Facilit	31	Mars Surface Habitat - Variant 1	Irregular	IVA
7	Habitat to O2 Generator	1	Labor	18	DRA5 ISRU Plant-Stationary	31	Mars Surface Habitat - Variant 1	Irregular	IVA
8	Power to Greenhouse	6	Electric Power, DC	41	Mars Surface Greenhouse Facilit	20	DRA5 FSPS	Continuous	Power Cable
9	H2O to Greenhouse	2	Water	41	Mars Surface Greenhouse Facilit	31	Mars Surface Habitat - Variant 1	Periodic	
10	Mars Regolith to H2O Extractor	7	Mars Icy Regolith	36	Mars In Situ Water Extractor			Periodic	Deep Fluted Auger
11	PNT to Habitat	0	Information	31	Mars Surface Habitat - Variant 1	12	Mars Communications Relay Satellite	Continuous	
12	H2O Extractor to H2O Transporter	2	Water	42	Mars In Situ Water Transporter	36	Mars In Situ Water Extractor	Periodic	Hose
13	PNT to H2O Extractor	0	Information	36	Mars In Situ Water Extractor	12	Mars Communications Relay Satellite	Continuous	
14	PNT to H2O Transporter	0	Information	42	Mars In Situ Water Transporter	12	Mars Communications Relay Satellite	Continuous	
15	Habitat to H2O Extractor	1	Labor	36	Mars In Situ Water Extractor	31	Mars Surface Habitat - Variant 1	Irregular	EVA
16	Habitat to H2O Transporter	1	Labor	42	Mars In Situ Water Transporter	31	Mars Surface Habitat - Variant 1	Irregular	EVA
17	H2O Transporter to Habitat	2	Water	31	Mars Surface Habitat - Variant 1	42	Mars In Situ Water Transporter	Periodic	Hose
18	Food to Habitat	9	Food from Plant Sources	31	Mars Surface Habitat - Variant 1	41	Mars Surface Greenhouse Facility	Periodic	IVA
19	H2O Transporter Telemetry to Habitat	0	Information	31	Mars Surface Habitat - Variant 1	42	Mars In Situ Water Transporter	Periodic	
20	H2O Extractor Telemetry to Habitat	0	Information	31	Mars Surface Habitat - Variant 1	36	Mars In Situ Water Extractor	Periodic	
21	Commands to H2O Transporter	0	Information	42	Mars In Situ Water Transporter	31	Mars Surface Habitat - Variant 1	Periodic	
22	Commands to H2O Extractor	0	Information	36	Mars In Situ Water Extractor	31	Mars Surface Habitat - Variant 1	Periodic	

Performer Class ID	Performer Class Name	Performer Type ID	Performer Type Name	Flow Units Type ID	Flow Units Type	Flow Rate	Data Source/Comments
1	System			38	kg/hour	0.8	Not real data
1	System	20	Mars Surface Power	31	watts	3	Not real data
1	System						
1	System	20	Mars Surface Power				
2	Person	20	Installation, Maintenance, and Repair Occupation	18	workhours/year		
2	Person	20	Installation, Maintenance, and Repair Occupation	18	workhours/year		
2	Person	20	Installation, Maintenance, and Repair Occupation	18	workhours/year		
1	System	20	Mars Surface Power	31	watts		
1	System						
1	System			38	kg/hour	18	Not real data
1	System	4	Deep Space Communications	40	kb/sec		
1	System						
1	System			40	kb/sec	0.0002	Not real data
1	System			40	kb/sec		
2	Person	20	Installation, Maintenance, and Repair Occupation	18	workhours/year		
2	Person	20	Installation, Maintenance, and Repair Occupation	18	workhours/year		
1	System						
2	Person	18	Farming, Fishing, and Forestry Occupations	18	workhours/year		
1	System	19	Mars Surface Comm/Nav	40	kb/sec		
1	System	19	Mars Surface Comm/Nav	40	kb/sec		
1	System	19	Mars Surface Comm/Nav	40	kb/sec		
1	System	19	Mars Surface Comm/Nav	40	kb/sec		

Figure 16: SV-6 System Resource Flows in Tabular Form

Using the data in the System Resource Flows Table (Figure 16) and the Needlines Table (Figure 10), we can now establish a view of operational resource flows, which in DoDAF is called an OV-3. This tabular view, presented as Figure 17, shows the decomposition of the Needlines between Operational Nodes into the individual Resource Flows for our simple example.

This table shows that there may be different "flavors" of information being exchanged between Operational Nodes. These differences may be in the types of information, the required bandwidth, the refresh rate, and/or other characteristics. Similarly, there may also be different flavors of labor (i.e., different skills) needed. The SV-6 System Resource Flows provides the detailed characteristics of these flows, including any standards that may apply (via flow means).

Needline ID	Flow ID	Resource Name	Sink Node Name	Source Node Name	Include in Operational Resource Flows (T/F)
3	17	Water	Mars Settlement Site A	Mars Water Mining Site	TRUE
3	19	Information	Mars Settlement Site A	Mars Water Mining Site	TRUE
3	20	Information	Mars Settlement Site A	Mars Water Mining Site	TRUE
4	15	Labor	Mars Water Mining Site	Mars Settlement Site A	TRUE
4	16	Labor	Mars Water Mining Site	Mars Settlement Site A	TRUE
4	21	Information	Mars Water Mining Site	Mars Settlement Site A	TRUE
4	22	Information	Mars Water Mining Site	Mars Settlement Site A	TRUE
5	11	Information	Mars Settlement Site A	Mars Comm Relay Orbit	TRUE
6	13	Information	Mars Water Mining Site	Mars Comm Relay Orbit	TRUE
6	14	Information	Mars Water Mining Site	Mars Comm Relay Orbit	TRUE

Figure 17: OV-3 Needlines x Resources Table

D. Adding Quantitative Measures

Quantitative data must be unambiguous with regard to its meaning. Consequently, adding such data for Systems must combine a unique Measure identification with a unique System identification and with a unique time and place identification. This is accomplished in an MCAM table called Milestones × Systems × Measures, a portion of which is shown in Figure 18. The Measures Table provides the parameter of interest and by reference the units by which it is quantified. The Systems Table provides the System of interest and the Milestones Table provides the Operational Node and time. Once this triple is established, the measure's value is recorded in the table. (This value persists until it is updated by another table entry.) One important use of this table is to track quantities, so the 'quantity' Measure is accorded a unique ID = 0. From this table then, we can track the growth in the Mars Colony's Systems at each Operational Node. This view can be likened to an assembly sequence or to a DoDAF PV-2.

Milestone ID	System ID	Measure ID	Milestone Name	Node Name	System Name	Measure Name	Measure Value	Measure Distribution Type ID	Distribution String	Measure Units Type	Data Source/Comments
1	12	0	First Deployment of Mars Comm Infrastructure	Mars Comm Relay Orbit	Mars Communications Relay Satellite	quantity	1			integer, dimensionless	
3	36	0	First Deployment of Water Extractors	Mars Water Mining Site	Mars In Situ Water Extractor	quantity	1			integer, dimensionless	
3	36	13	First Deployment of Water Extractors	Mars Water Mining Site	Mars In Situ Water Extractor	drill_rate	1			m/hour	
3	36	14	First Deployment of Water Extractors	Mars Water Mining Site	Mars In Situ Water Extractor	drill_diameter	0.127			meters	
3	36	15	First Deployment of Water Extractors	Mars Water Mining Site	Mars In Situ Water Extractor	system_avg_speed_over_terrain	0.04			m/sec	

Figure 18: A Portion of the Milestones x Systems x Measures Table

Another important use of this table is to capture the technical parameters of each System. The MISWE rover, described earlier, has technical parameters that are needed by the downstream Extraction Process Model. One example of a performance parameter is the Measure called 'drill rate' measured in meters per hour. The value of this parameter is captured in the table for the water mining site of our simple example, as shown in Figure 18. Because Milestones has a location component by definition, we are able to establish different values for the drill rate not only at different times, but at different locations on Mars.

A table similar to Milestones × Systems × Measures is used in MCAM to track human Measures. The Milestones × Person Types × Gender Types × Measures Table operates in the same way. Figure 19 shows a portion of this table, which is broken into two parts for readability. This table tracks the Mars Colony population growth (via the 'quantity' Measure) by skill (via Person Type) and gender at each Operational Node. It also provides technical parameters that are needed by the downstream Infrastructure and ILS Model.

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Milestone ID	Person Type ID	Gender Type ID	Measure ID	Milestone Name	Node Name	Person Type Name	PersonGender Type	Measure Name	Measure Value	Measure Distribution Type ID	Distribution String	Measure Units Type	Data Source/Comments
2	20	1	9	First Human Colonists Land	Mars Settlement Site A	Installation, Maintenance, and Repair Occupations	Female	person_food_con_rate	1850			kcal/day	
2	10	1	9	First Human Colonists Land	Mars Settlement Site A	Healthcare Practitioners and Technical Occupations	Female	person_food_con_rate	1800			kcal/day	
2	18	0	9	First Human Colonists Land	Mars Settlement Site A	Farming, Fishing, and Forestry Occupations	Male	person_food_con_rate	2300			kcal/day	
2	5	0	9	First Human Colonists Land	Mars Settlement Site A	Life, Physical, and Social Science Occupations	Male	person_food_con_rate	2150			kcal/day	
2	20	1	0	First Human Colonists Land	Mars Settlement Site A	Installation, Maintenance, and Repair Occupations	Female	quantity	1			integer, dimensionless	
2	10	1	0	First Human Colonists Land	Mars Settlement Site A	Healthcare Practitioners and Technical Occupations	Female	quantity	1			integer, dimensionless	
2	18	0	0	First Human Colonists Land	Mars Settlement Site A	Farming, Fishing, and Forestry Occupations	Male	quantity	1			integer, dimensionless	
2	5	0	0	First Human Colonists Land	Mars Settlement Site A	Life, Physical, and Social Science Occupations	Male	quantity	1			integer, dimensionless	

Figure 19: A Portion of the Milestones x Person Types x Gender Types x Measures Table

VI. An Overview of the Three Other Models

This section addresses the downstream models that are needed to conduct an end-to-end economic analysis via the Economics Integration Model. As described above, MCAM is used to export technical parameters to these downstream models.

A. Extraction Process Model

The Extraction Process Model calculates the rate at which Mars colonists can produce each mined Resource by the application of ISRU Systems and OEM best practices. This model collectively represents the economic production functions for mined Resources. These production functions can be thought of in the rather traditional way as mathematical functions of capital and labor, but with capital being replaced by the flow of services from deployed ISRU Systems. Typically then, the output of the Extraction Process Model is the quantity of each ISRU System needed to produce a given amount of the mined Resource per unit time. This result is then feed into the Economics Integration Model and combined with DDT&E cost, production unit costs, deployment, and recurring operating costs (feed from MCAM) to form the cost side of the profitability equation.

The spreadsheet in Figure 20 models the MISWE and MISWT approach to water mining in our simple example. The technical inputs for this Extraction Process Model are feed from MCAM, and the model computes the quantity of each System needed to support a Mars settlement with a population of L_M—in this run, $L_M = 8$. While this version of the model is deterministic, a future version could be set up to account for uncertainties in the technical parameters as well as in the Mars environment.

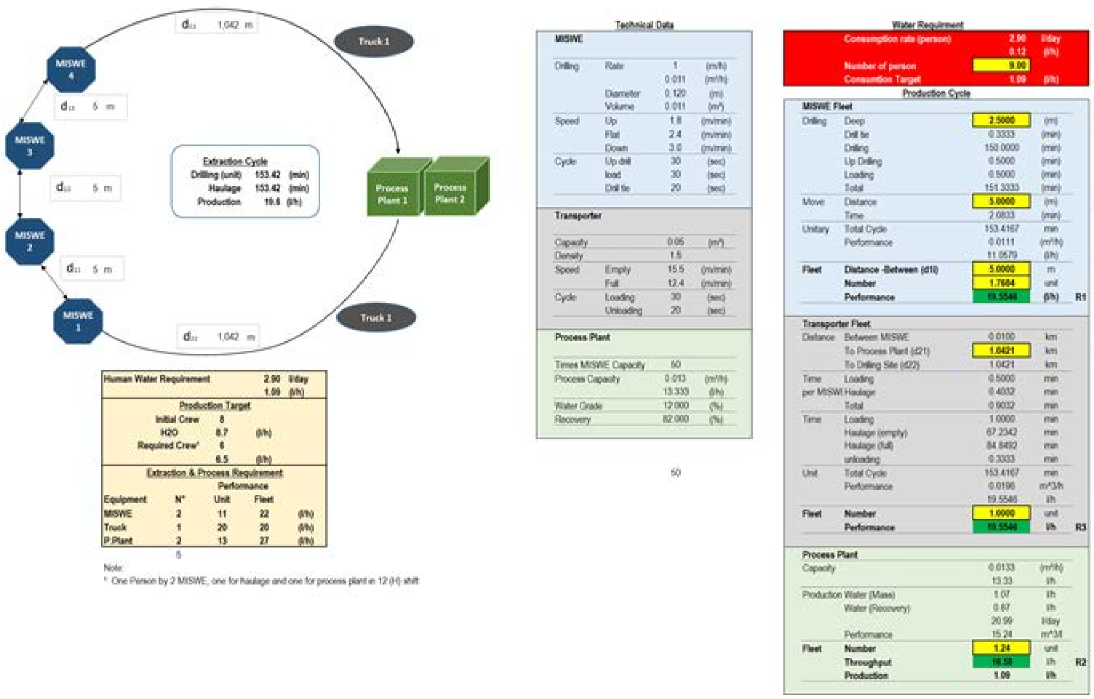

Figure 20: Spreadsheet Version of the MISWE Extraction Process Model

B. Mars Infrastructure and ILS Model

The Mars Infrastructure and ILS Model is currently under development. The model combines two simulations, *HabNet* (being developed at M.I.T.)[80] and *SpaceNet* (previously developed at M.I.T. and JPL under the Constellation Program).[81] The core of *HabNet* is its habitation module. This module is based on software called BioSim, whose source code is freely available under a GPL3.0 open source license.[82] BioSim is a mid-fidelity dynamic simulation, developed by TracLabs under a NASA contract, for the purpose of research on integrated ECLSS controls. *HabNet's* purpose in this research program is to quantify the demand for various Resources supporting a Mars Colony population.

SpaceNet is an integrated interplanetary supply chain management and logistics planning simulation. Instead of helping to design in-space transportation Systems in terms of propulsive and pressurized/un-pressurized cargo carrying capability, *SpaceNet* evaluates such vehicles in the context of a particular mission architecture (defined by MCAM Flight Types and Flights) and the supply chain strategy. The software allows the user to specify how the transportation and inventory holding capacity resulting from particular mission architectures will be used in terms of defined classes of supply (i.e., commodities like consumables, spare parts, Mars Colony infrastructure Systems, etc.). *SpaceNet* simulates the time-varying flow of in-space transportation Systems, commodities, and colonists through the Operational Nodes of a supply network within the Earth-Moon-Mars system, while taking into account feasibility (ΔVs, fuel levels) as well as on-board consumption and resupply via in-space depots. In this research program, *SpaceNet's* purpose is to track all such movements, both forward and reverse.

C. Economics Integration Model

The Economics Integration Model is also under development. The model consists of a set of cost models and a revenue simulation. With inputs from MCAM and the other models described above, the Economics Integration Model forecasts (for a given Resource, ISRU System, and OEM CONOPS) investment and operating costs and revenues over time, which will enable the calculation of NPV, ROI, breakeven points, sensitivities to changes in market parameters, and the likelihood of profitability. These outputs will be used to produce business case views in formats understandable (i.e., familiar) to the commercial mining industry.

The cost models will encompass the development, unit production, deployment to Mars, and recurring operating costs of ISRU Systems. Revenues from the production of Resources on Mars will be simulated based on a stochastic model of price drift and volatility. The initial reservation price for water mined on Mars, for example, can be set by the cost of delivering it from other locations in the solar system.

VII. Summary and Future Work

This paper has presented a progress report on our continuing research into the economic potential of ISRU in supporting a Mars Colony. As a first step, we must be able to formally describe how such a colony might be structured in order to address these questions quantitatively from the point of view of various stakeholders. In general, a Mars Colony architecture is largely driven by (in no particular order):

- orbital mechanics
- human physiology
- system technologies
- natural Mars environments
- economic constraints.[vi]

Consequently, analytic models that address stakeholder concerns must take these drivers into account. Four models being developed are discussed in this paper, with details presented on the Mars Colony Architecture Model (MCAM).

MCAM's purpose is to support an exploratory investigation of various architectures, CONOPS, and representative scenarios. MCAM houses architectural information in a structured way so as to allow some applicable DoDAF views to be constructed, and to pass quantitative data to downstream analytic models that enable more complex views to the developed. MCAM is consistent, concise, and auditable, and may be a starting point for the use of other Model-Based Systems Engineering modeling languages like SysML.

Future work will be directed at completing the downstream models already described, expanding the set of available downstream models, and integrating the ensemble of models so that various ISRU technologies and market scenarios can be simulated. Possible uses of the ensemble include determining which ISRU strategies (e.g., lunar mining for propellant) and technologies offer greater returns and economic benefits, and, perhaps even more important, use as a university-level educational device for future mining and aerospace engineers.

Acknowledgments

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[i] It is worthwhile in this regard to bring the reader's attention to the following paragraph from the Shames, et al. 2012 paper in which they discuss efforts to model the architecture of NASA's SCaN network:

> While developing models for single systems is becoming a common practice, doing the sorts of trade space and System of Systems modeling that was required for this task appears to be less well understood. There is little support for it or literature on how to implement it and very few worked examples have been published. It requires a different approach to modeling than monolith system models, and we are still learning how to do it. There is a challenge in finding an effective way to structure the model to effectively create the trade space models, and there is a challenge in identifying the right depth to drill down so that the model adequately discriminates among the options. What is clear is that these models appear to have a real value in helping distributed architecting and modeling teams document and understand complex system interactions and to explore a multi-dimensional trade space. It appears that these models, while they are complex, can be used with some success to communicate the technical details of a complex trade space effectively, even to stakeholders untutored in modeling, if sufficient care is taken to explain the modeling concepts and to produce technically correct and visually accessible model that resonates for the users.

[ii] Maier says: "DoDAF is a blueprint standard in that it defines how to represent a system's architecture, but it does not restrict the nature of the architecture of the underlying system." (p. 316) and points out that "DoDAF and MoDAF address [architectural] descriptions where the objects of interest are themselves significant systems and programs instead of the component-level elements that would occupy systems engineers in preliminary and detailed design phases." (p. 321).

[iii] From the Shames, et al. 2012 paper, the authors comment that "two groups of modelers had each adopted different UML profiles: one had been using the UPDM profile (based on DoDAF and MoDAF) and the other had been using the SysML™ profile. While the UPDM profile works well for operational models and high level views of architectures, its limitations for doing more detailed system and software views in this SoS trade space quickly became problematic."

[iv] The BLS Standard Occupational Classification major groups are:

11-0000 Management Occupations
13-0000 Business and Financial Operations Occupations
15-0000 Computer and Mathematical Occupations
17-0000 Architecture and Engineering Occupations
19-0000 Life, Physical, and Social Science Occupations
21-0000 Community and Social Service Occupations
23-0000 Legal Occupations
25-0000 Education, Training, and Library Occupations
27-0000 Arts, Design, Entertainment, Sports, and Media Occupations
29-0000 Healthcare Practitioners and Technical Occupations
31-0000 Healthcare Support Occupations
33-0000 Protective Service Occupations
35-0000 Food Preparation and Serving Related Occupations
37-0000 Building and Grounds Cleaning and Maintenance Occupations
39-0000 Personal Care and Service Occupations
41-0000 Sales and Related Occupations
43-0000 Office and Administrative Support Occupations
45-0000 Farming, Fishing, and Forestry Occupations
47-0000 Construction and Extraction Occupations
49-0000 Installation, Maintenance, and Repair Occupations
51-0000 Production Occupations
53-0000 Transportation and Material Moving Occupations
55-0000 Military Specific Occupations

In the BLS SOC, major groups are broken into minor groups, which, in turn, are divided into broad occupations. Broad occupations are then divided into one or more detailed occupations. For example, the 29-0000 major group would flow down to a detailed occupation as follows:

29-0000 Healthcare Practitioners and Technical Occupations
29-1000 Health Diagnosing and Treating Practitioners
29-1060 Physicians and Surgeons
29-1062 Family and General Practitioners

[v] Arney and Wilhite's 2012 paper uses the concept of an adjacency matrix in a different way, but the concept from graph theory is the same. An adjacency matrix is an n x n matrix, where $A_{i,j} = \begin{cases} 1 \text{ if there's an arc between source node i and sink node j in the graph} \\ 0 \text{ otherwise} \end{cases}$

[vi] Economic constraints may include broader, socio-political constraints and ethical issues regarding sending humans on one-way missions.