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# A method to evaluate utility for architectural comparisons for a campaign to explore the surface of Mars

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ABSTRACT

There is a general consensus that Mars is the next high priority destination for human space exploration. There has been no lack of analysis and recommendations for human missions to Mars, including, for example, the NASA Design Reference Architectures and the Mars Direct proposal. These studies and others usually employ the traditional approach of selecting a baseline mission architecture and running individual trade studies. However, this can cause blind spots, as not all combinations are explored. An alternative approach is to holistically analyze the entire architectural trade-space such that all of the possible system interactions are identified and measured. In such a framework, an optimal design is sought by minimizing cost for maximal value. While cost is relatively easy to model for manned spaceflight, value is more difficult to define. In our efforts to develop a surface base architecture for the MIT Mars 2040 project, we explored several methods for quantifying value, including technology development benefits, challenge, and various metrics for measuring scientific return. We developed a science multi-score method that combines astrobiology and geologic research goals, which is weighted by the crew-member hours that can be used for scientific research rather than other activities.


## 1. Introduction

There is a general consensus that Mars is the next high priority destination for human space exploration. However, the specific techniques for evaluating these missions are unclear. There has been no lack of analysis and recommendations for human missions to Mars, however, most of these recommendations either (a) focus on the analysis of a pre-selected architecture or (b) select a baseline architecture for the entire system, then trade off individual architectural decisions in that context.

For example, the NASA Design Reference Architecture 5.0 [1] executed very thorough trade studies across many mission systems, but these analyses were limited to the system at hand. Another example would be the Minimal Mars Architecture study by Price et al. [2] that came out of the JPL in 2015. In this case, the authors selected an architecture based on certain constraints (one of which was to reuse as many systems currently in development, in order to minimize the need for additional funding) and proceeded with an analysis and mission plan of the resultant architecture. While these are both important analyses, they fail to consider the potential benefits or pitfall of system-to-system interactions that were not considered as combinations.

The alternative is a complete trade-space study, such as the Apollo Architecture retrospective in chapter 14 of System Architecture by Crawley et al. [3]. In a study like this the researcher gathers all of the choices for each architectural decision, and defines their differing effects on the entire project and the other systems, as well as the impacts on evaluation metrics such as cost and benefit. Once these effects have been modeled, the entire trade-space can be enumerated and evaluated to see what combinations present as most desirable according to those metrics. A key feature of such an analysis is the ability to trade off the cost of the architecture with the delivered value, or utility, delivered by that architecture.

Cost metrics are relatively well defined; Initial Mass to Low Earth Orbit (IMLEO) which merely tracks the aggregate mass delivered to space, is widely applied, since the cost of the rocket launches is one of the most expensive components in a space campaign. There are also methods to estimate the actual cost of the elements delivered to space, as well as the development thereof, such as those applied in the NRC Pathways to Exploration [4] study.

However, there is no general consensus on the utility metrics for space missions, and human Mars missions in particular. There have been many recommendations for scientific inquiry and return on Mars, often related to site selection, such as the HEM-SAG [5] report which focuses on the possibility of locating sign of present or extinct life, and those that were used for site selection

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of the Mars Exploration Rover, as detailed in Golembek et al. [6] which focuses on xeno-geological factors.

While it is important and interesting to identify and rank Mars surface sites based on their scientific distinctiveness, this does not complete the picture in terms of enabling exploration. There are many other factors that can limit options, or provide incentives to go to sites that would not otherwise be selected. The intent of a complete trade-space study, as identified above, is to consider all of these factors, and weigh them against each other to identify the optimal mission architecture. Though the limitations of a site are considered in the costs of the systems needed to accommodate those specific difficulties (lower levels of sunlight, less regolith water content, etc.) the value of each site, and the ability to access that value must be measurable. Therefore, it is vitally important to characterize a thorough utility metric for the delivered value of a Mars campaign.

## 2. Potential metrics

A utility metric for uses such as trade-space analyses or other architectural comparisons necessarily excludes cost and risk, to focus on the returned value from the various architectures. This allows increases in utility to be traded off against increases in cost or risk, the identification of Pareto-optimal architectures, and ultimately keeps the decision making power in the hands of the researcher by cleanly separating these different metrics.

There are numerous potential metrics to measure the utility of Mars exploration architectures. The metric has to be quantitative, in order to be able to estimate, and measure the impact any given architectural decision will have. The metric also must be relevant to the decision makers who would be using these studies to inform their choices in guiding an exploration mission. As such, this paper focuses on metrics based on scientific return, and also gives a treatment to other potential metrics.

### 2.1. *Scientific return*

The scientific return of any endeavor is difficult to predict, much less than that of the exploration of a world upon which no human has ever set foot. Many efforts to measure the value of scientific research, such as the *h*-index, consider the impact only after the fact [7]. The *h*-index is citation based, and other citation and coauthorship network [8] based metrics have been used to predict the impact of scientific research. However, such methods cannot be used in the case of evaluating Mars exploration campaigns, since the evaluation is focused on the impacts of the Mars architecture, and not the scholar who publishes the report.

There can be quantitative, non-citation based methods as well, such as the one proposed by Sutherland William et al. [9] in 2011 which evaluates the impact of a piece of research based on a clearly defined policy objective. The proposed methodology could be a useful starting point in assessing the reasoning behind going to Mars, by [taking] the issues society wants to be answered as a starting point and [asking] how much each piece of research [could] contributes to answering them. However, since the research that would take place by a human settlement on Mars is not yet completed, this would still be a speculative means to estimate scientific return.

Since these methods have been ruled out because they focus on the scholars' past work, the remaining option is to look at the potential for scientific impact.

In order to look at the potential impact of scientific research on Mars, we need to be able to score the scientific interest of potential research sites against one another. There have been a wealth of analyses and proposals that evaluate different landing sites for scientific interest, and we summarize a sampling of the options below.

**Table 1**
HEM-SAG rankings for the potential of finding signs of extinct (EL) and present (PL) life at a selection of landing sites on Mars.

| Site | EL | PL | Lat. | Lon. |
|---|---|---|---|---|
| Holden Crater | 4 | 1 | −26.09 | −34.02 |
| Gale Crater | 4 | 1 | −5.41 | 137.81 |
| Meridiani Planum | 5 | 1 | −0.09 | −3.41 |
| Gusev Crater | 3 | 1 | −14.58 | 175.52 |
| Isidis Planitia | 5 | 1 | 13.89 | 88.38 |
| Elysium Planitia | 5 | 2 | 2.93 | 154.74 |
| Mawrth Vallis[a] | – | – | 22.38 | −16.97 |
| Eberswalde Ellipse | 4 | 1 | −24.02 | −33.30 |
| Utopia Planitia | 2 | 1 | 46.69 | 117.52 |
| Hellas Planitia | 5 | 3 | −42.48 | 70.50 |
| Chasma Boreale | 5 | 4 | 82.49 | −47.64 |

[a] Site not scored for EL/PL.

#### 2.1.1. *HEM-SAG*

The HEM-SAG [5] white paper, published by the Mars Exploration Program Analysis Group (MEPAG) sets out a thorough ranking (on a 1 to 5 scale) of the likeliness of finding present life (PL) and extinct life (EL) at 58 sites on the Mars surface. For example, this study places Chasma Boreale at EL5, due to the possibility that it was formed by a flooding allowing early habitability, and PL4, due to proximity to polar ice, and the chance that the obliquity of Mars allows for regions of liquid water. This report could be used to quantitatively compare the interest of each of those 58 sites based on a combination of its PL and EL scores. Table 1 presents the EL and PL scores for 11 potential landing sites. However, due to lingering uncertainties, some of the 58 sites did not receive firm EL or PL scores, so care must be taken when working with this metric (Fig. 1).

#### 2.1.2. *Proximity to special regions*

Another way to numerically compare research potential on the Martian Surface would be to characterize the access to special regions that would be afforded by a given architecture. Determining the distance between landing sites and special regions can be completed relatively simply using data from, for example, Rummel et al. [10]. In addition to the landing site, any specific architecture would also differentiate between the constraints and capabilities for exploration range. For example, an architecture that selects a site that is 100 km from a special region might not be more desirable when an alternate architecture places the landing site 500 km from two separate special regions, but also provides the ability to travel these distances.

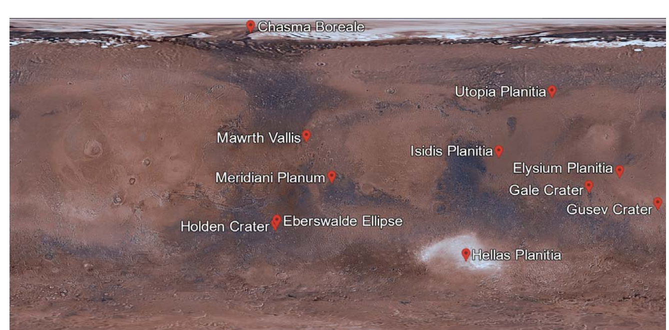


**Fig. 1.** Location of sites listed in Table 1, Courtesy NASA.