IDENTIFYING TECHNOLOGY INVESTMENTS FOR FUTURE SPACE MISSIONS

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ABSTRACT

Advancement of critical technologies is a key factor in enabling future space missions. Yet, there is clearly a mismatch between the available funding and the cost of pursuing all technologies that have been identified as critical. Therefore, a process is needed to select the technologies that can provide the highest return on investment. In this paper, a systems engineering model is presented that identifies the technologies that provide the most significant impact for a given mission. The model is composed of three distinct areas: the objective of the mission, a mission model, and the technology investment. Depending on the desired investments, the resulting technology parameters ripple through the model, producing overall differences in mission value. These differences are measured to identify the technologies that produce the highest impact per dollar. In this fashion, technology investments may be optimized to maximize value for a single mission or a portfolio of missions.

INTRODUCTION

Part of systems engineering is the determination of whether to invest in a particular technology that will enable some future capability. The answer is often heavily dependent on engineering assumptions and analyses, as well as programmatic considerations.[1] In this paper, the use of a systems engineering model is evaluated to show how it can be used to guide technology investment in the context of limited NASA funding for critical technologies.

Scope

The study of optimal technology investment is not new, and other approaches (such as the real-options model) have been discussed in current literature[1]. Figure 1 shows the relationship between a real-options approach and the approach evaluated in this paper (that is, the "broad mission model"). The real-options approach considers a single technology in the context of its impact on multiple missions. In contrast, the broad mission model considers a set of technologies within a single mission. The models may then be applied to, respectively, multiple technologies or multiple missions to develop the full technology investment trade space. If the results of these two approaches agree, it would provide validation for both methods, assuming that a consistent set of missions and technologies is chosen for each approach.

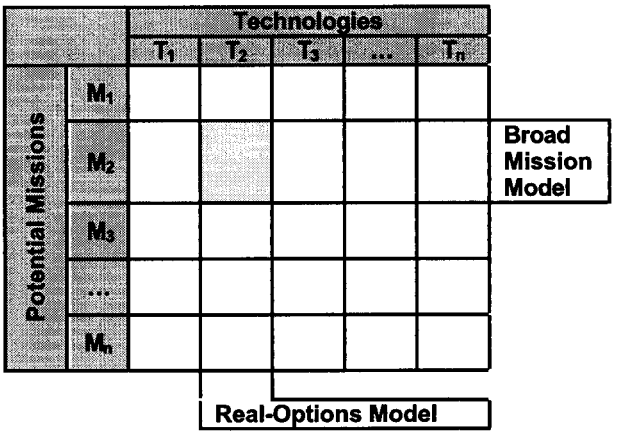

Figure 1: Tech. Investment Models

This paper presents a technology investment approach that emphasizes the broad mission model. The scope of this assessment is limited to high-level conceptual design associated with early mission architecture studies. Thus, the technology development efforts included in this research represent large-scale subsystems (such as the aeroshell, parachutes, or drill). This approach allows for a broad study of alternative mission architectures, at the exclusion of detailed technology development.

Background

The research presented here is founded on two previous efforts: the real-options model mentioned earlier[1] and an optimal technology portfolio assessment model developed by Elfes et al[2]. The latter effort was applied to determine optimal investments in long-range roving and precision landing technologies for a reference Mars exploration mission. It emphasized the technology investment, risk, and performance of the two systems, and the resulting analysis showed the optimal investment allocation for a range of technology budget options. However, there remains a need for a comprehensive

and "rapid prototyping" approach to mission and technology assessment. Thus, this paper presents such an approach that will enable the rapid analysis of a wide range of technology investment options.

The interactions between a set of new technologies for a future mission is complex and involves a number of challenges. Research in this area is ongoing and falls under the purview of the Project Trades Model (PTM). "A PTM is a collection of tools/simulations linked together to rapidly perform integrated system trade studies of performance, cost, risk, and mission effectiveness"[3]. While only a simplified PTM was used for this study, the ongoing development of larger, more complex PTMs should provide an opportunity for studying technology investment.

METHODOLOGY

The technology investment approach studied in this paper is described in Figure 2. It illustrates the structure of the broad mission model, along with how this model is divided into a graphical user interface and an analytical engine. The high-level graphical interface allows the representation of inference graphs that capture the computational steps for modeling the desired mission. Thus, investments, technologies, or mission subsystems may be more easily reconfigured to analyze alternative mission scenarios. Once this architecture is designed, a resulting mathematical description of the model is sent to the analytical engine (that is, a symbolic computational software). This engine provides a sophisticated level of analysis for evaluating the entire model.

The model is composed of four sections: technology investment, a technology database, the mission model, and science value. The technology investment portion represents alternative levels of investment for each technology. This includes the case of not funding the technology, and relying instead on the current state of the art. The technology database includes data from current efforts to develop new capabilities or subsystems for future missions. For this research, representative technology and mission data was used to exercise the model. The mission model contains the appropriate subsystems and their relationships, representing the heart of this analytical approach. Finally, the science value is the measure used for assessing alternative technology investments and the resulting mission effectiveness. Combined, these elements allow the technology investment levels to create a ripple effect

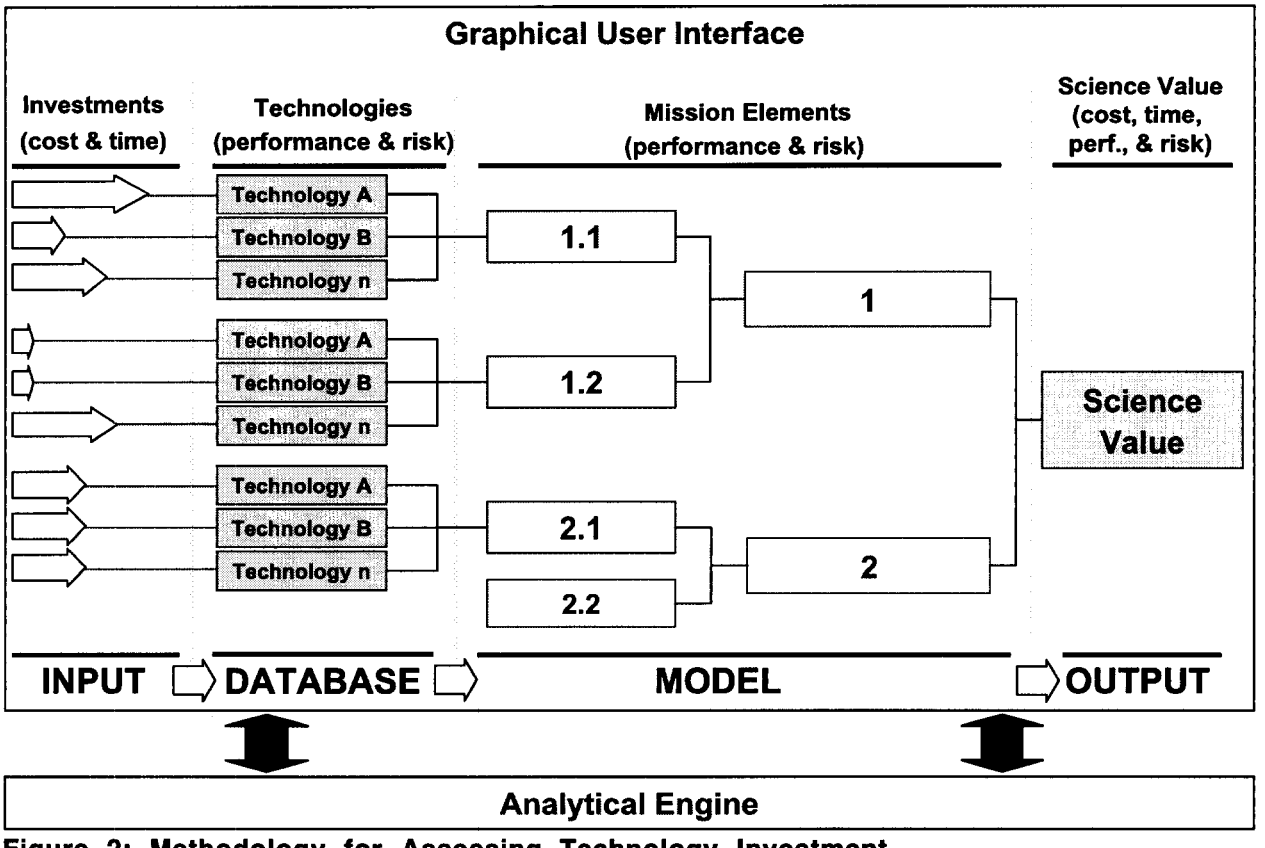

Figure 2: Methodology for Assessing Technology Investment

that results in overall differences in science value. These differences are measured to identify the technologies that produce the highest impact per dollar. In this fashion, technology investments may be optimized for a single mission or a portfolio of missions.

Technology Investments & Parameters

The principal model input is technology investment (as shown in Table 1). Alternative levels of funding provide differences in technological capabilities. For this study, the amount of investment was assumed to vary incrementally between a minimum value (usually $0) and a maximum value. This incremental variation is a simplification of the actual process, which is usually dependent on the type of technology.

Table 1: Tech. Investment Parameters

Parameters	Value	Units
Investment Minimum	$Tech_{investment\text{-}min}$	$K
Investment Maximum	$Tech_{investment\text{-}max}$	$K
Investment Increment	$Tech_{investment\text{-}inc}$	$K

In Table 2, the technology parameters are shown. Often, most or all of these parameters are functions of the technology investment. For example, an increase in funds may help improve the mass, power, cost, reliability, readiness date, lifetime, and/or performance. Thus, the effect of the technology on the future mission may be highly variable. For this study, it was assumed that investment, however, would only have an effect on reliability and performance. This influence will be expanded to the other technology parameters in future studies.

Table 2: Technology Parameters

Parameters	Value	Units
Mass	$Subsystem_{mass}$	kg
Power	$Subsystem_{power}$	W
Cost	$Subsystem_{cost}$	$K
Reliability	$= f(Tech_{investment})$	0-1
Readiness Date	$Subsystem_{date}$	year
Lifetime	$Subsystem_{lifetime}$	days
Performance	$= f(Tech_{investment})$	-

Figure 3 and Figure 4 illustrate some of the typical types of influence that technology investments will have on reliability and performance. For example, Figure 3 shows the reliability increasing as the funding increases. However, the improvement diminishes until large investments are needed to produce even slight gains in reliability.

Similarly, the improvements in performance also diminish for each of the curves (a, b, and c). Curve (a) shows fixed investment levels necessary to produce any improvements, whereas curves (b) and (c) show continuous change. Curve (b) represents increasing performance, where higher is better (such as telecom data rates). And, curve (c) illustrates increasing performance, where lower is better (such as in minimizing landing uncertainty).

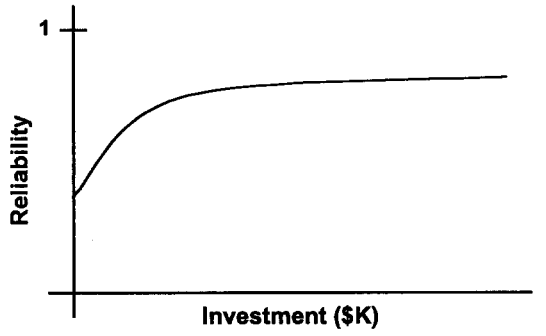

Figure 3: Investment vs. Reliability

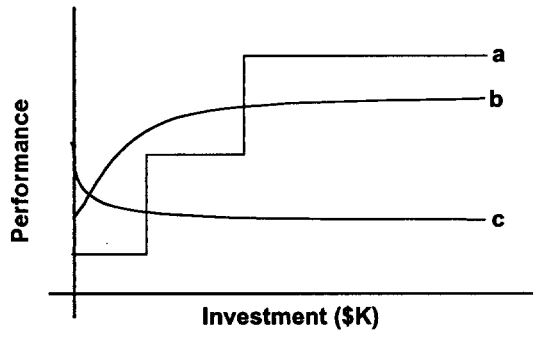

Figure 4: Investment vs. Performance

By varying each of the investment levels to produce alternative technologies, the reliability and performance differences ripple through the mission model, producing concomitant changes. In general, however, since the technologies experience diminishing returns from investment, there will be some optimal investment distribution, assuming a limited technology investment budget.

Mission Model

The mission model is composed of specific subsystems that carry out the activities associated with the mission timeline, shown in Figure 5. The subsystems are formed by two equations, described in Table 3. The first equation dictates the operation of the subsystem, and is dependent on the environment, lifetime, reliability, and power received. The second equation determines the actual

performance of the subsystem. It receives inputs from the environment, technologies, and other subsystems, and then determines a desired output. For example, sunlight, solar-cell efficiency, and solar array size determine the power produced. Thus, the operation of the subsystems produces outputs that correspond with the mission timeline.

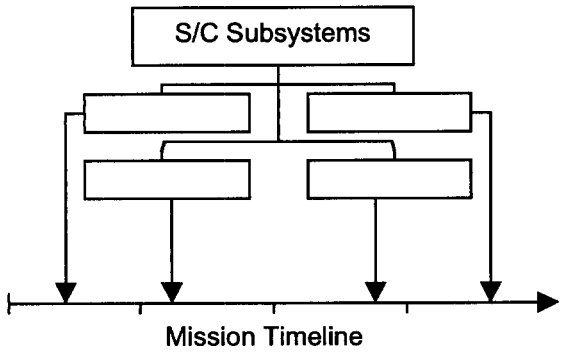

Figure 5: Structure of Mission Model

Table 3: Subsystem Parameters

Parameters	Value	Units
Operation	$= f$(Environment, $\text{Subsystem}_{\text{lifetime}}$, $\text{Subsystem}_{\text{reliability}}$, $\text{Subsystem}_{\text{actual-power}}$)	on/off
Actual Performance	$= f$(Environment, $\text{Subsystem}_{\text{operation}}$, $\text{Subsystem-n}_{\text{performance}}$)	-

Science Value

The subsystem operations and mission timeline ultimately lead to the collection of science. This science data represents a portion of the value of the mission. Measuring this (often subjective) value is exceedingly difficult[4]. For example, one bit of data signaling life could make the mission a success, whereas a gigabyte of low-resolution photos may not justify the mission. The result is continued skepticism on how to measure science value. Nevertheless, a measure (or objective function) for value can be helpful in the early stages of selecting missions and their supporting technologies. And, more specifically, a quantitative definition of science value in this study is essential to determining which technologies are likely to provide the greatest future value. Therefore, the objective function in Equation 1 was used for this study. This equation has been modified slightly from a more commonly used form of risk times benefits divided by cost[5].

$$\textit{Objective Function} = \textit{Science Return} / \$$$

$$= \frac{\textit{Reliability} \times \textit{Science_Quantity} \times \textit{Science_Quality}}{\textit{Mission Cost} + \textit{Technology Investment}}$$

Equation 1: Objective Function

In Equation 1, the science return is divided between *Science_Quantity* (from 0 to 1) and *Science_Quality* (from 0 to 1). Cost is composed of the mission cost and technology investment. Although this equation (and particularly science quantity and quality) is still subjective, it is helpful for comparing alternative mission scenarios. Additionally, this equation may be changed to suit individual preferences.

EXAMPLE: MARS SURFACE MISSION

To demonstrate the application of this approach, a reference Mars surface mission was selected. The mission involves three phases: cruise; entry, landing, and descent (EDL); and surface operations. To accomplish this mission, a simplified set of thirteen subsystems was selected. The objective of this study was to determine the appropriate level of funding for maximizing mission value given constraints on the overall technology budget.

Assumptions

For the reference Mars surface mission example, a number of assumptions were made, as described below.

- The technology and subsystem data have been created for this case study, although it is illustrative of a future reference Mars mission.
- As described in the previous section, only the technology reliability and performance are influenced by the investment level.
- The structure and relationships of the thirteen subsystems within the mission model remain constant (ie, the structure does not vary depending on the capability of the technologies).
- Five surface sites have been chosen, 20 km apart, and the *Science_Quality* metric varies linearly from 0 to 1 with respect to these five sites. It is assumed that after investigating these five sites, full science diversity has been achieved.
- In the illustrative results presented below, technology investment was varied between $0 and $1M for each of the subsystems. An investment analysis over a wider range might yield different results.

These assumptions are important to reduce the complexity and running time of the model. However, as the model continues to develop, some of these assumptions will become more realistic, so that the results of the model can be used for technology investment allocation decisions.

Mission Subsystems

Thirteen subsystems were selected for this example (see Table 4). Seven were chosen for the carrier vehicle, covering the mission phases of cruise and EDL, and six were chosen for surface operations. Additionally, there are currently new technologies being studied to upgrade or replace each of these subsystems.

Table 4: Mission Subsystems

Carrier Vehicle	
Thrusters	Guidance during cruise
Flight S/W	Guidance during cruise
Guidance Sys.	Guidance during cruise & EDL
Aeroshell	Guidance during entry & descent
Parachute	Guidance during descent
Retrorockets	Guidance during descent &landing
Airbags	Guidance during landing
Rover	
Solar Array	Power generation
Battery	Power storage
Avionics	Navigation guidance
Drill	Sample collection
Laboratory	Sample analysis
Telecom	Data transmission

Technology Investments & Parameters

For each of the thirteen subsystems, individual reliability and performance functions were chosen depending on the current state of technology development for that subsystem. For example, thrusters are a more proven technology compared to other EDL technologies. Therefore, while there might be some technological progress, the increase in reliability and performance for thrusters will be relatively limited. Figure 6 and Figure 7 show the reliability and performance functions for the aeroshell, which guides, protects, and slows the carrier vehicle during entry and descent.

Since aeroshells are a relatively new technology, Figure 6 shows a significant jump in reliability (0.95 versus 0.60) for an investment of $1M. Similarly, the performance of an aeroshell (expressed using the uncertainty of the landing ellipse, measured through the semi-major axis) increases dramatically over the first $500K investment (see Figure 7).

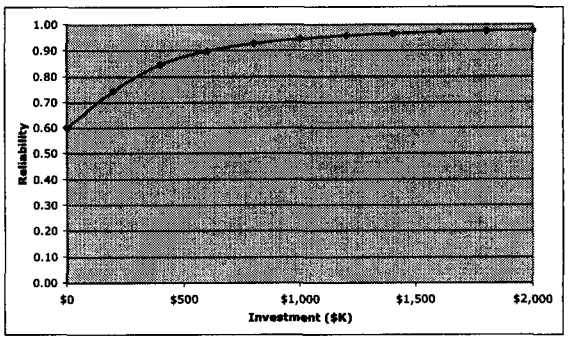

Figure 6: Aeroshell Reliability

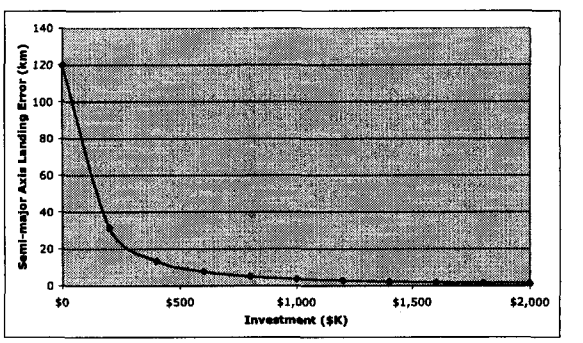

Figure 7: Aeroshell Performance

Mission Model

Using the mission timeline and the thirteen subsystems, the mission model was created (see Figure 8). This model shows all of the elements, including the links between the subsystems. It also displays the definition of value used for this study.

The timeline of Figure 8 shows the three phases of the mission. These phases are broken into specific events, which are tied to one or more subsystems of either the carrier vehicle or the rover. Additionally, four other elements have been added, including the environmental inputs (that is, the Mars atmosphere, sunlight, and terrain) and the power distribution unit (PDU). The PDU is not associated with a specific technology, as it simply distributes the available power evenly between the avionics, drill, laboratory, and telecom.

The implementation of Figure 8 is divided between the graphical user interface and the analytical engine. For this study, Khoros™ was selected as the graphical interface, allowing the structure of the model to be easily constructed. Additionally, Mathematica™ was used as the analytical engine. This selection allowed greater capability for the analysis, since Mathematca uses symbolic relationships to represents the subsystem functions.

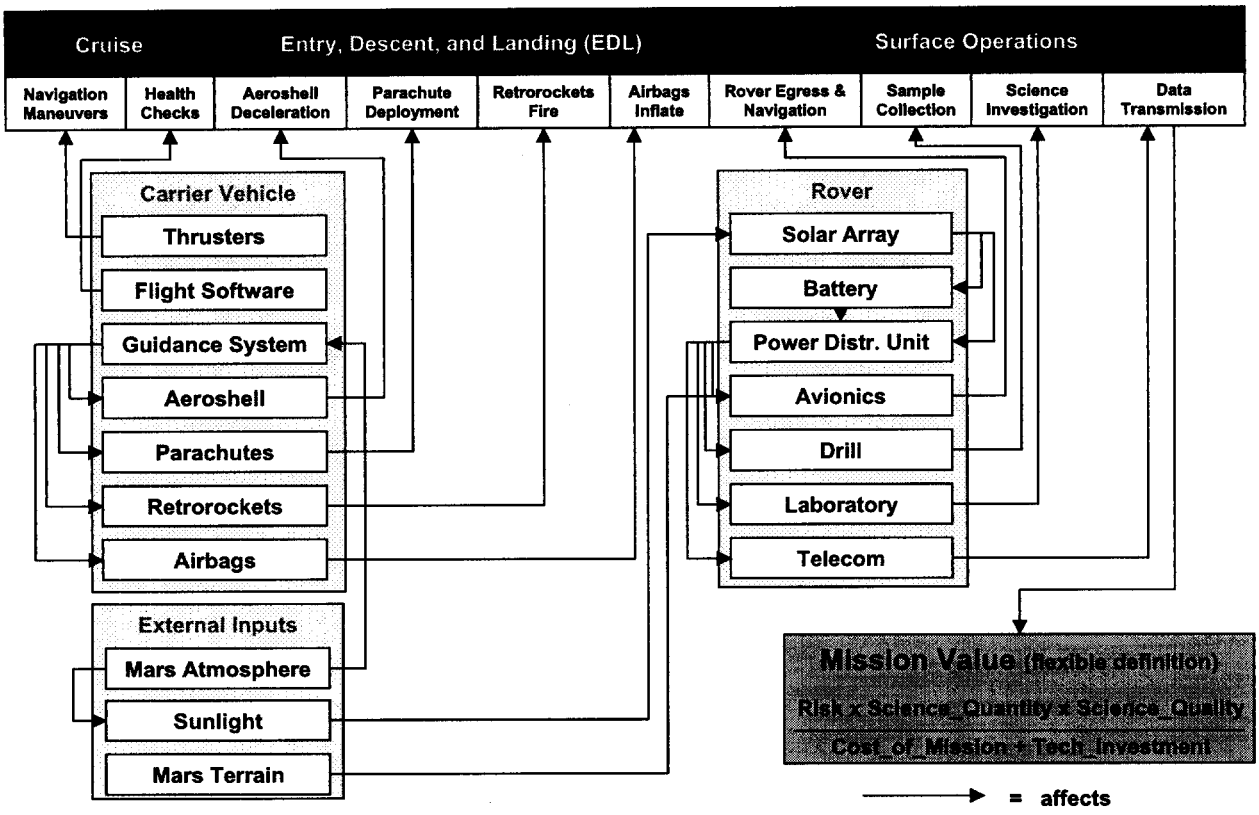

Figure 8: Mars Mission Model

Figure 10 is the same Mars mission model, but instead as it appears in Khoros. In this display, the model is divided into slightly different categories. At the highest level, it is split between (i) technology investment, (ii) Mars surface mission model, (iii) analysis, and (iv) results/science value. These, in turn, are separated into either different subsystems or functions. Additionally, the links do not present actual subsystem connections as they did in the previous diagram. Instead, the links in Figure 10 specify the order in which the computational analysis must be performed. In some parts of the program, the order is irrelevant (such as the order of the subsystems). In this fashion, it is possible to construct other mission models relatively easily.

Science Value

As described earlier, value is a function of the reliability, science quality and quantity, mission cost, and technology investment. Value can then become an implicit function of time (or distance traveled) as shown in Figure 9. As can be seen from the plot, value is increasing even prior to the first site being reached. This is because the rover has the option of stopping to collect samples at sites other than the designated sampling locations. Additionally, the plot shows the initial distance that the rover must navigate to the first site (~80 km). This large distance is due to the uncertainty in precision landing. In other words, it is assumed that the error in landing must be traveled to reach the first landing site. Finally, the plot shows how once the first site is reached, the value jumps due to the fulfillment of one mission objective. In this case, however, the large error in landing means that only the first site was reached.

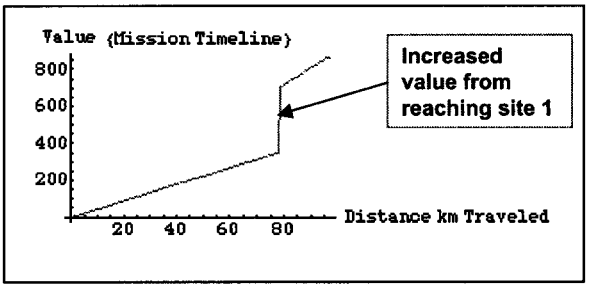

Figure 9: Value versus Mission Timeline

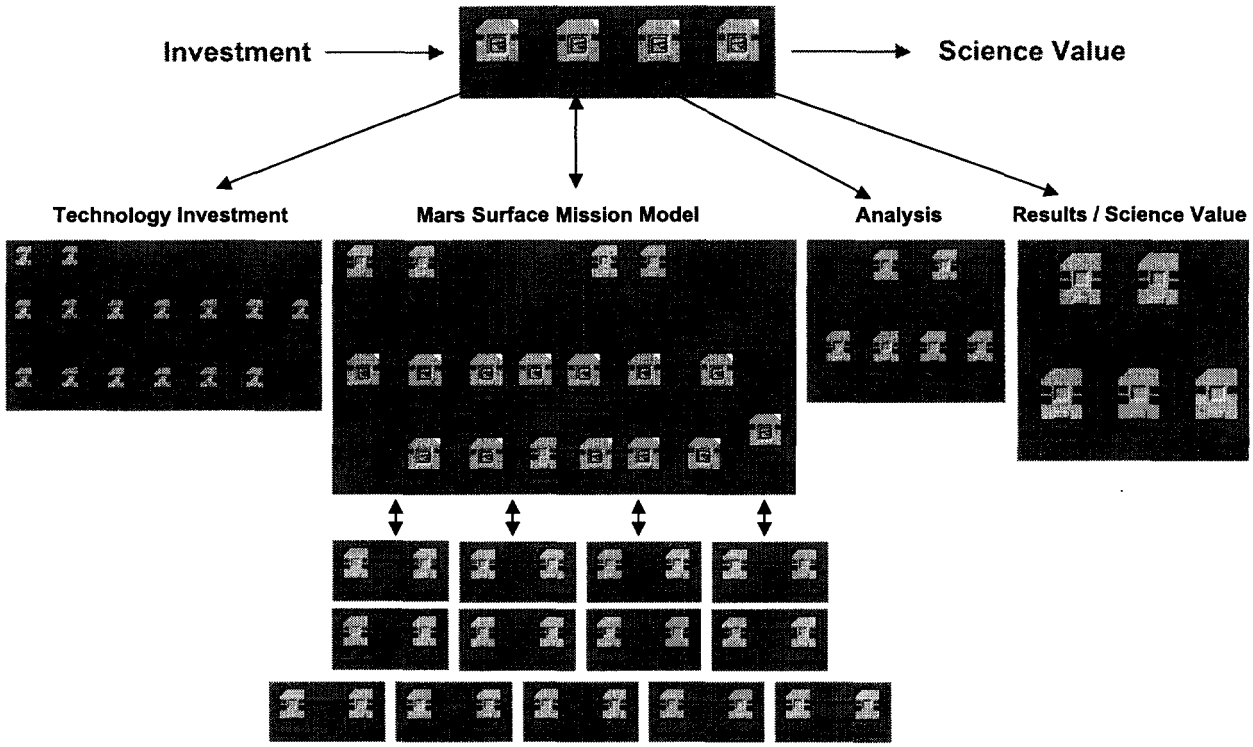

Figure 10: Mars Mission Model (in Khoros)

Results

Once the mission has been created in the graphical front end, the program can be run to determine the greatest mission value by varying the technology investments. To accomplish this, the visual editor outputs the software code (representing the model) to Mathematica, where it is executed. The results of all investment combinations specified are shown in Figure 11. The plot shows that value greatly increases at first, and then its increase slows near the higher investment figures.

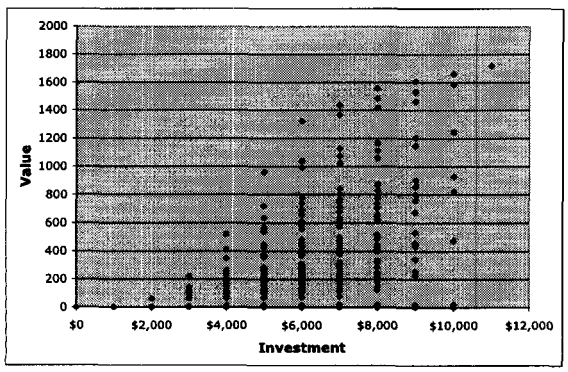

Figure 11: Results from the Analysis

Of all investment combinations studied, maximizing value (or the objective function) can be obtained from an investment of $12M, allocated as shown in Table 5. The table displays a summary of the information, along with the subsystem and mission characteristics. In particular, the distance traveled is 97 km. The science diversity is 0.4. The expected mission value is listed, but it is only meaningful in comparison to other missions. Finally, the total mission duration is 1,081 hours (or 45 days) to return 3.5 Mb of data.

CONCLUSIONS

The broad mission model has been presented in this paper as a relatively new model that offers insight into optimally investing in future technologies. The approach is relatively straightforward, and the results clearly differentiate the various allocations for investments. Ultimately, an optimal investment allocation is produced, which also provides the expected mission data return. Future research includes applying the model to a data set representative of a specific mission, applying this approach to other missions, and constructing a library of model elements (and subsystems) to more easily create alternative missions.