Technology and Architecture: Informing Investment Decisions for the Future of Human Space Exploration

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ABSTRACT

NASA's detailed programmatic goals, system architectures, and mission designs for future human spaceflight beyond Earth orbit remain unspecified. Given this uncertainty, it is not clear exactly which technologies are necessary for enabling future exploration. The process of establishing technology development strategy relies on methods to evaluate the benefits and cost of potential investments. While the cost of technology development is often the primary uncertainty, in this application it is particularly difficult to quantify the benefit of technology development without a clear understanding of the system architecture to which it is being applied. With destinations and exploration strategy left to be determined, the potential benefits of any given technology can not be stated with certainty. While challenging, it is necessary to identify a prioritization of these development projects for early investment before the system architecture is defined.

This thesis develops a framework for evaluating technologies in the context of long term system architecture planning for the future human space exploration transportation system. An abstracted solution-neutral formulation of the transportation architecture to any arbitrary destination is defined as a combination of multiple architectural sub-problems. To evaluate technologies within the tradespace, two measures are adapted from design of experiments literature. Main effects analysis is used as a measure of a technology's influence on the best architectures. Similarly, the strength of coupling effects between two technologies is captured by interaction effects. The measures of technology influence and coupling enable architects to prioritize technologies based on their performance, and to organize investment decisions by those that must be treated together and those that can be taken in parallel.

The system architecture tradespace for Mars, the Moon, and two representative Near-Earth Asteroid (NEA) missions are explored and presented. Results from the proposed influence and coupling measures are used to evaluate technologies considered in the tradespace and to understand the benefits and tradeoffs presented by investing in different technologies in relation to each destination. Following the results from each tradespace, some suggestions of favorable pre-cursor missions to the Moon or NEAs are proposed as preparation for a future Mars exploration mission.

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LIST OF ACRONYMS AND ABBREVIATIONS

ACap	Aerocapture
ADG	Architecture Decision Graph
Arr	Arrival
Asc	Ascent
BO Ctrl	Boil-off control
CER	Cost Estimating Relationship
CH4	Methane- referencing LOX-CH4 liquid oxygen-liquid methane chemical propellant
CSTI	Civil Space Technology Initiative
Desc	Descent
DRA	Design Reference Architecture
EDS	Earth Departure Stage
EELV	Evolved Expendable Launch Vehicle
ESAS	Exploration Systems Architecture Study
GA	Genetic Algorithm
HAT	Human spaceflight Architecting Team
HSF	Human Spaceflight
ICA	Independent Cost Assessment
IMLEO	Initial Mass in Low Earth Orbit
IS (Out/Ret)	In-Space (Out/Return)
ISRU	In-Situ Resource Utilization
ISS	International Space Station
KSC	Kennedy Space Center
LCC	Life Cycle Cost
LH2	Liquid hydrogen- referencing liquid oxygen-liquid hydrogen propellant
LLO	Low Lunar Orbit
LMO	Low Mars Orbit
LOI	Lunar Orbit Insertion
LOR	Lunar Orbit Rendezvous
MOI	Mars Orbit Insertion
mt	metric tons (1000 kg)
NASA	National Aeronautics and Space Administration
NEA	Near-Earth Asteroid
NRC	National Research Council
NTR	Nuclear Thermal Rocket
OART	Office of Advanced Research and Technology
OAST	Office of Aeronautics and Space Technology
OCT	Office of the Chief Technologist
PICA	Phenolic Impregnated Carbon Ablator
PVS	Property Variable Sensitivity
SAP	System Architecting Problem
SEP	Solar Electric Propulsion
SLS	Space Launch System
TEI	Trans Earth Injection
TIM	Technology Influence Measure

TMI	Trans-Mars Injection
TCIM	Technology Coupling Interaction Matrix
TCIE	Technology Coupling Interaction Effects
TPM	Technical Performance Measure
TRL	Technology Readiness Level

1 INTRODUCTION

Between 1961 and 1969 the United States went from suborbital human space flight capability to landing astronauts on the Moon and returning them safely. During those eight years impressive progress was made in several fields including propulsion, guidance navigation and control, life support systems, and other fields of engineering that required new advanced technologies to provide the capability for one of the greatest achievements of the twentieth century. While the human space flight industry has significantly evolved since the Cold War era, technology development remains an essential part of enabling future exploration. The technology development enterprise within NASA has had long history with inconsistent levels of funding and support. NASA currently finds itself in a position where it must plan for a highly uncertain long term exploration program while making near term investment decisions that will help to prepare for those long term goals.

This introductory chapter provides the motivation for this thesis as it relates to current NASA planning activities, a discussion of selected relevant literature, the research objectives for this thesis, and it concludes with an overview of the rest of the work.

1.1 MOTIVATION

1.1.1 CURRENT STATE OF HUMAN SPACE EXPLORATION

The International Space Station (ISS) has been a permanently occupied functioning orbital laboratory for over a decade sitting in Low Earth Orbit (LEO). Through the late 2000s NASA's Constellation Program pursued development of the systems needed for a long term campaign of exploration beyond Earth orbit. While stated goals of the program were to explore the Moon in preparation for human expeditions to Mars, in that time frame earnest development work was focused entirely on lunar exploration missions.

In 2009, the Review of U.S. Human Spaceflight Plans Committee found that human space flight in the U.S. was on an unsustainable trajectory, "pursuing goals that do not match allocated resources" .

Subsequent to the release of this report, the Constellation Program was cancelled and replaced by a new overall strategy for the future of human spaceflight. The general strategy was outlined by President Obama in a speech at the Kennedy Space Center in April 2010 , and was heavily adapted from the "Flexible Path" alternative proposed in the U.S. Human Spaceflight Plans Committee Report. This was followed up by an entirely new National Space Policy explicitly mentioning the Moon, asteroids, and Mars as destinations for future human space exploration

As described in the current National Space Policy, stated goals of the U.S. human spaceflight program are to execute a series of to-be-defined missions to a number of possible destinations, particularly Near Earth Asteroids (NEA), that ultimately prepare for a long term exploration program at Mars. In addition to these undefined missions, a more specific overall strategy was defined to prepare for future exploration. Major points of this strategic plan include reliance on commercially operated launch vehicles, development of a heavy-lift launch capability for larger monolithic payloads, and an investment into fundamental research and technology development .

1.1.2 AMBIGUITY AND UNCERTAINTY IN THE SYSTEM TO DEFINE

While a sustained human presence on Mars is often cited as a very long term goal of human space exploration, there is no consensus that current planning should be for a Mars surface mission. The most recent major development towards future human space exploration was for a Lunar surface architecture as part of the Constellation Program. Since the cancellation of the program, much discussion has focused on missions to various NEAs, the moons of Mars, and other destinations.

While cancellation of the Constellation program may have been necessary due to the previously discussed programmatic issues, there is somewhat of a void in the long term goals of human space exploration, making it difficult for systems engineers to plan an exploration campaign. An example of the multiple destinations available for exploration is provided by the "Flexible Path" option in the Review of Human Spaceflight Plans Committee Final report as displayed in Figure 1-1.

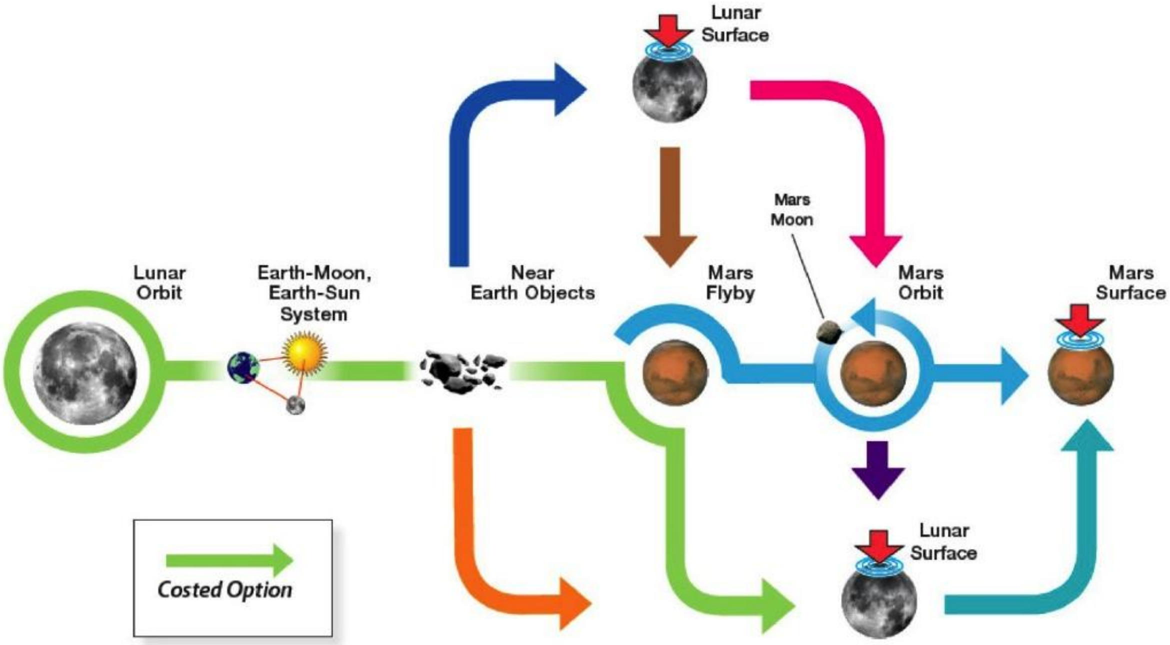

Figure 1-1 Flexible Path of future exploration with multiple destinations from

While a large number of mission opportunities are available for consideration, it is not clear which destinations will be on the path of future space exploration or over what timescale those missions will be executed. Defining this exploration campaign will be the result of extensive system analysis that considers not only science and engineering perspectives but the social, political, and economic factors that allow for a sustainable program.

In addition to ambiguity of the destinations to explore, the strategy in designing transportation architecture remains a broad tradespace defined by many different technical decisions. While reference missions to various destinations have been described in literature, these represent the results of trade studies with certain assumptions that vary from one study to another. Ultimately a good system will be defined by a hierarchy of thousands of decisions being refined as analysis and design proceed iteratively into concepts with increasingly detailed levels of definition. The system will have to fulfill requirements from stakeholders with criteria relating to science, engineering, politics, and economics. To claim any detailed knowledge of what the system will look like at this point in time would be unrealistic.

An example of how technology development relates to system architecture can be seen in the definition of the Apollo mission architecture. One major decision was to determine if the overall strategy would include a Lunar Orbit Rendezvous (LOR) or if the mission would be a “direct” architecture as envisioned by Werner von Braun and . LOR was an elegant and efficient solution relying on the capability to develop precise lunar orbit rendezvous and docking capability. The direct approach required development of a very large launch vehicle that could loft the enormous payload required. Figuring out the overall mission architecture was an important decision that would direct strategic development of certain capabilities to support that architecture. While LOR was obviously selected for the Apollo mission architecture, the direct approach may have been preferable to LOR if the rendezvous and docking risk was thought to be higher than large launch vehicle development risk.

The Apollo LOR decision example highlights the major uncertainty related to the performance of potential technologies that are required for certain architectures. On the one hand system designers must evaluate these architectures to determine investment to develop the required technologies, while on the other hand the expected cost and performance uncertainty of those technologies may be so high as to obfuscate the best system architecture.

Given the ambiguities in goals for a transportation system for human space exploration and the uncertainties in the associated mission architecture to different destinations, current architecting activities must consider multiple exploration objectives and destinations, several technologies that would need to be developed, and as a result different operational strategies for getting to each destination.

1.1.3 HISTORY OF NASA TECHNOLOGY DEVELOPMENT ACTIVITIES

The history of NASA's investment in fundamental research and technology development precedes its own formation. Through the National Advisory Committee for Aeronautics (NACA), which became NASA, the government began investment in high risk, long term technology development activities for the aerospace industry. Moving through the history of the organization, NASA has had a number of different internal offices explicitly tasked with activities related to fundamental research and technology development. While in reality research and development activities get spread through different projects within the organization it is most relevant to consider those bodies within NASA explicitly tasked with maintaining investment in technology development activities. At the agency-wide level several organizations have been explicitly created to pursue research and development within NASA. From 1969 to 1972 the Office of Advanced Research and Technology (OART) was provided limited funding as the Apollo program was ending. Then from 1972 through at least the end of the 1980s the Office of Aeronautics and Space Technology (OAST) assumed the task of technology development. OAST advanced many of the system capabilities that enabled important NASA programs and missions through the 1970s and 1980s. OAST technologies supported development of Space Station Freedom (now ISS), the space shuttle, and missions such as the Voyagers .

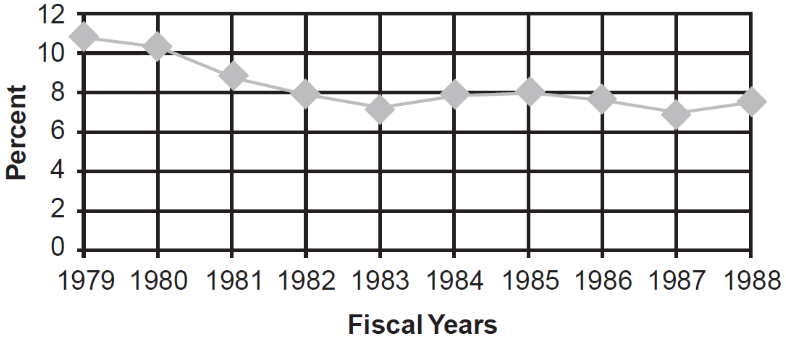

Figure 1-2 OAST funding as a percentage of total NASA budget taken from

Through the 1980s technology development was a high priority at NASA as demonstrated by both having a dedicated organization for that purpose and the associated funding levels shown in Figure 1-2.

Moving into the 1990s, the technology development enterprise within NASA was fractured into several programs with no dedicated entity to lobby for and manage funding at an agency-wide level. The Civil

Space Technology Initiative (CSTI) was intended to "revitalize technology for Low Earth Orbit applications," the Pathfinder program was intended to "develop technology for exploration of the solar system," and other stated goals were to maintain fundamental research, invite the participation of academia, develop in-space experimentation, and facilitate technology transfer to industry and . Throughout the following decade, reports such as the "Integrated Technology Plan" sought to focus agency-wide technology priorities. While expenditure on technology development remained as high as 10% of the total NASA budget these expenditures were distributed across different arms of the agency. Technology development was centrally coordinated but executed through multiple offices, limiting the ability for strategic technology portfolio management. In 1997 for example there was an Office of the Chief Technologist staffed with only four people who did not have their own explicit budget to spend on technology development .

It was not until the 2010 redefinition of national space policy that technology development was again supported as its own independent activity within NASA at the agency-wide level with both a politically and financially supported separate office to oversee execution of technology development expenditure. In February 2010, the Office of the Chief Technologist (OCT) was re-established to advocate technology policy and programs, manage those programs, coordinate investments in technology, and facilitate and communicate the realization of benefits of NASA technology into society . As a relatively new organization within NASA directed at long term goals, the OCT has to execute a strategic plan with a time horizon of at least two decades that is flexible enough to be updated regularly. This strategic plan includes selection of technologies to develop based on the needs of the whole agency. Prioritization of investments is centrally controlled by the OCT, balancing the areas in which they pursue development and the readiness level of projects pursued. Current estimates for explicit agency-wide technology expenditure have risen from about 2.5% of NASA's budget in 2011 to a request for over 3.5% in the 2013-2017 timeframe .

KEY POINTS

- *Current U.S. human spaceflight plans are vaguely defined but generally consist of a series of missions that will prepare for future Mars surface exploration missions.*
- *The ultimate goal of NASA's OCT is to define a portfolio of technology investments to support future missions while considering the needs of multiple stakeholders.*
- *When architecture design is uncertain, early investment decisions are made with limited knowledge of the benefits of those investments.*

1.2 RELEVANT LITERATURE

1.2.1 NASA SPACE TECHNOLOGY PRIORITIZATION

One of the major tasks for the OCT is to prioritize technologies and allocate funding that helps to develop technologies into capabilities available for future NASA missions. As of writing this thesis, the current incarnation of the OCT has just begun to receive and allocate funding and is still refining the framework with which they will execute their stated objectives. The OCT recently published a strategic investment plan outlining the process by which they would pursue their goal of developing technology . The overall investment framework is displayed in Figure 1-3.

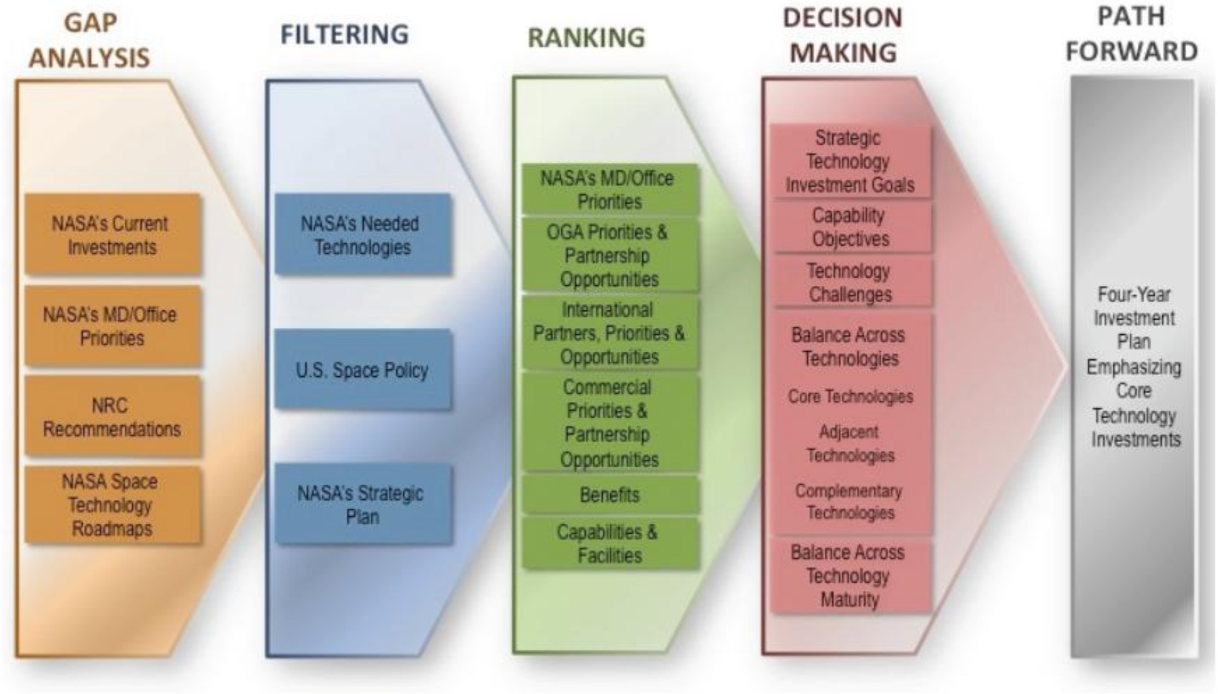

Figure 1-3 NASA OCT process to develop Strategic Technology Investment Plan from

The “gap analysis” which is currently in progress , is designed to identify the overall technical goals of the technology program. As a national scale effort, it is then important that the OCT’s process includes all relevant stakeholders, their needs, and an understanding of the value proposition of investments. Non-NASA stakeholders are considered mostly during the “filtering” and “ranking” phases of technology selection. Finally the “decision making” segment is where an integrated portfolio is designed. At this point in the process there are at least four major characteristics that must be defined for the technology portfolio.

1. Expected performance of the technologies
2. Expected cost of the technologies
3. Risk associated with the development and realization of the capabilities in the portfolio
4. Opportunities for flexibility and an associated implementation framework to maximize return over the uncertain development process

In the “decision making” phase, performance and cost are accounted for in meeting the strategic goals and capability objectives that have been previously defined. There is also an explicitly stated need to balance risk of different projects (across technology maturity). The concept of flexibility does not explicitly appear in Figure 1-3, however current materials released by the OCT indicate there will be detailed updates to technology roadmaps every four years and progress updates and allocation adjustments every two years . The resulting framework is fairly generic but highly inclusive in its inputs and intended to ensure the most benefit possible is derived from investments made. At the level of the framework provided no details have been included on specific quantitative tools that may or may not be used throughout the overall process.

Historically NASA studies provide quantitative justification of technology prioritization. By considering the beneficial influence of certain technologies on a reference mission, one can prioritize the major investments that will enable and improve the mission objective being pursued. Figure 1-4 demonstrates the benefits of various potential technology investments associated with the NASA Mars Design Reference Architecture (DRA) 5.0 .

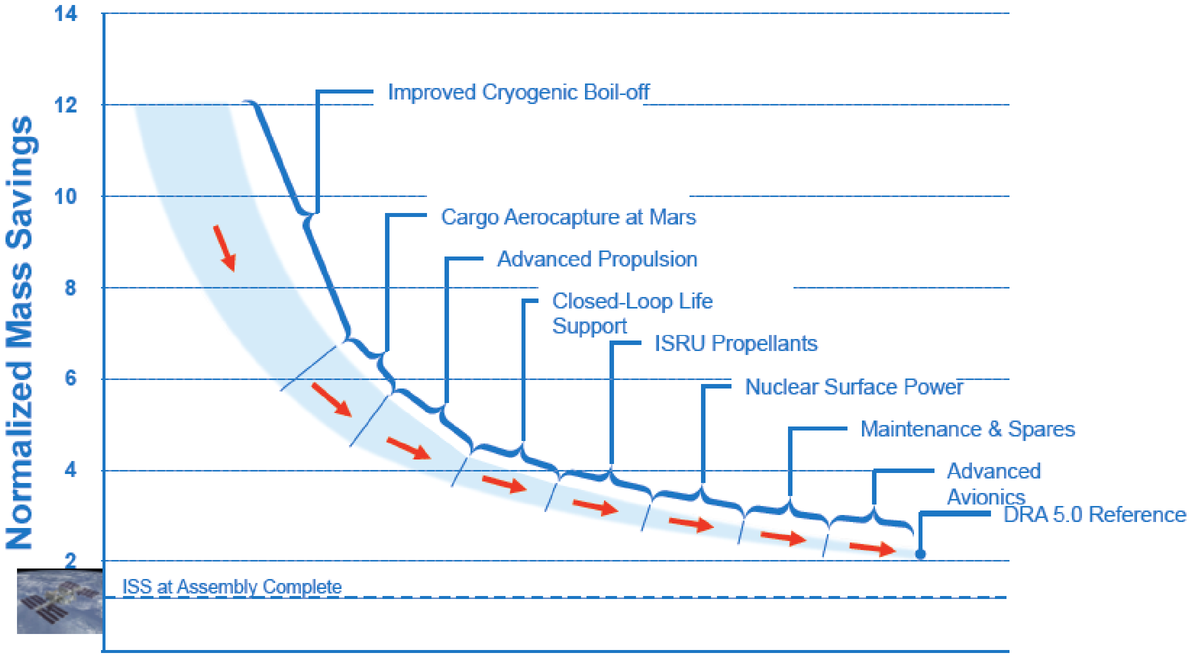

Figure 1-4 Technology prioritization based on the NASA DRA 5.0 study from

Using the metric of mass (as a proxy for cost), benefits are demonstrated as mass savings associated with each technology. While it is valuable to gain an understanding of technology benefits based on traceable physical modeling (rather than subjective opinions) some problems quickly become clear with this prioritization. The results presented in Figure 1-4 are entirely based on the DRA 5.0 reference mission. These technology benefits may significantly change if a different exploration strategy is pursued. If the overall design of the system considered or the exploration destination change, the entire technology prioritization becomes irrelevant. While consideration of a single design reference mission may not be sufficient to prioritize technology investments, measuring benefits from a quantitative understanding of mission performance is desirable.

NASA's current architecting activities are relevant to NASA's technology development efforts. Given the potential range of missions and destinations being considered, efforts to downselect a specific campaign of missions will greatly help the OCT to prioritize investments. At the time of writing this thesis the NASA Human Space Flight Architecting Team (HAT) is developing a series of reference missions to multiple destinations . The process of campaign design and mission downselect remains to be completed. The output from the HAT team will be important as inputs to the "filtering" and "ranking" phases of the NASA OCT technology investment process.

1.2.2 NRC SPACE TECHNOLOGY PRIORITIZATION

Periodically the National Research Council (NRC) is called upon to aid in technology prioritization for NASA. Their recommendations are marked as an input to the OCT process in Figure 1-3. Most recently the NRC Study on Space Technology Roadmaps and Priorities was published to support the OCT allocation of funding in the coming years. Unlike the model-based quantitative measures often used by NASA to prioritize technology benefits, the NRC study has a more holistic approach based on expert opinions. A series of experts that span the domain of the various technology areas in consideration were surveyed and asked to rank all the relevant technologies by multiple criteria. Their responses were compiled to produce non-dimensional multi-objective relative ranking of each technology. After the scoring system was completed, a final set of selected technologies was recommended that span various readiness levels and different technology areas.

This group decision making process does not provide a thorough treatment of the influence each technology has on a system being designed. In fact the investment decisions are not made with any particular explicit set of goals or missions in mind as these considerations are left to individual experts to determine. While the NRC process encompasses a vast array of knowledge encoded in several expert opinions, it is difficult to trace the final set of recommendations back to specific influences in the desired system. The group ranking process is subject to bias in the initial categorization and listing of technologies, the evaluation process, and weighting factors of different criteria. Despite its flaws, this process provides a unique way to incorporate the detailed knowledge of a large group of people that would not otherwise be possible with a detailed system model developed by a small number of engineers.

1.2.3 TECHNOLOGY EVALUATION AND PORTFOLIO SELECTION

The evaluation of future technologies is a challenging field filled with many uncertainties. When deciding how to make investments, it is necessary to understand the value proposition of major investments or the expected benefits at cost. Historically, a measure of technology readiness contributes to defining cost and/or risk. A common measure of readiness used is the Technology Readiness Level (TRL) system. An assessment of the TRL framework is provided in . Due to the high uncertainty of both costs and benefits of future technologies, TRL is often used when constructing measures of cost and risk or involved with modeling those parameters such as in .

A broad historical perspective of dealing with the development uncertainty related to large technology development projects is provided in . Based on several case studies of government projects, it provides an excellent evidence-based view of managing development uncertainty in the federal acquisition atmosphere. More abstract frameworks have been proposed to deal with development uncertainty including strategies such as real-options. A framework to apply real-options for NASA technology assessment is provided in . The further application of real options in technology portfolio selection is then given in . While dealing with development uncertainty is not specifically addressed in this thesis, the historical and proposed methods can be included in future work.

The field of portfolio design is extremely rich with different methodologies and it is broad in its various applications. provides an extensive overview of the literature that considers the selection of a portfolio of technology development projects. The methods covered include single and multi-objective comparative rating criteria, economic methods that relate benefits to financial success, real-options that optimize value in the face of development uncertainty, group decision techniques that leverage expert knowledge, various mathematical programming methods, decision trees and game theory, simulation, and heuristic modeling. While many of these methods are touched upon in the other literature discussed in this thesis, they are not all applicable to the NASA space technology context.

Some of the context-specific issues with portfolio design of space technology development projects are related to project success being dependent upon mission success. Additionally, successful technology maturation is often dependent on multiple other technologies due to the nature of tightly coupled integrated systems. Finally, uncertainties associated with political and other non-technical issues can be difficult to integrate in portfolio design, as well as a quantification of success criteria when benefits are often difficult to relate with economic terms. A specific technology portfolio design method review paper that considers these issues is . In addition to reviewing the literature it provides assessment of various methodology as applicable to NASA. While full portfolio design is outside the scope of this thesis it is relevant as the methodology presented is an input to the process of portfolio definition.

Holistic frameworks have been proposed that integrate several of the aspects of analysis required for technology development. The Jet Propulsion Lab's Strategic Assessment of Risk and Technology (START) office reports to the JPL chief technologist and is dedicated to building these frameworks. The JPL START team focuses on providing quantitative methods and traceable recommendations to support technology investment activities. Their approach is fully quantitative but still attempts to include the associated "intangible benefits" of technology. Their framework leverages many of the previously discussed methods including a treatment of uncertainty through measuring sensitivity in results, expert knowledge through interviews, and physics based simulation and modeling that supports their analysis and . While the START methodology provides a rich set of tools in preparing recommendations for technology portfolio design, it does not provide a framework to enumerate different system architectures.

1.2.4 TECHNOLOGY IN SYSTEM ARCHITECTURE

While the bodies of literature that cover system architecture and technology development are both extensive, the literature that explicitly addresses the interaction of these two fields is limited. However the evaluation and downselection of technology is highly coupled to the system to be defined, and technology portfolio management and system architecture tradespace exploration both occur long before the system is actually implemented and operated. An attempt to evaluate the cost and risk of technologies by accounting for internal system interfaces and a discussion of the resulting implications for technology infusion is provided in and . While these methods allow for comparison across technologies with very different system interactions (changing performance and interfaces) it requires knowledge of a reference baseline architecture that can be incrementally modified. While the methodology is powerful, it can be challenging to implement for systems that do not yet exist in any form and have no baseline with which to compare.

A more general framework for system architecting decision support is provided by the Architecture Decision Graph (ADG) described in . In this reference the definition of system architecture is viewed as a series of decisions that must be made, defining the various parameters that distinguish one architecture from another. As part of his framework, Simmons provides measures of Property Variable Sensitivity

(PVS) and connectivity that are defined for each decision in the architectural space. PVS is the average measure of how much a system metric can change based off a change in assignment of a property variable. The connectivity measure is a function of constraints enabled between assignment decisions and the number of alternatives the assignment decision has. The combination of PVS and connectivity provides a view of each architectural decision, categorized according to Figure 1-5.

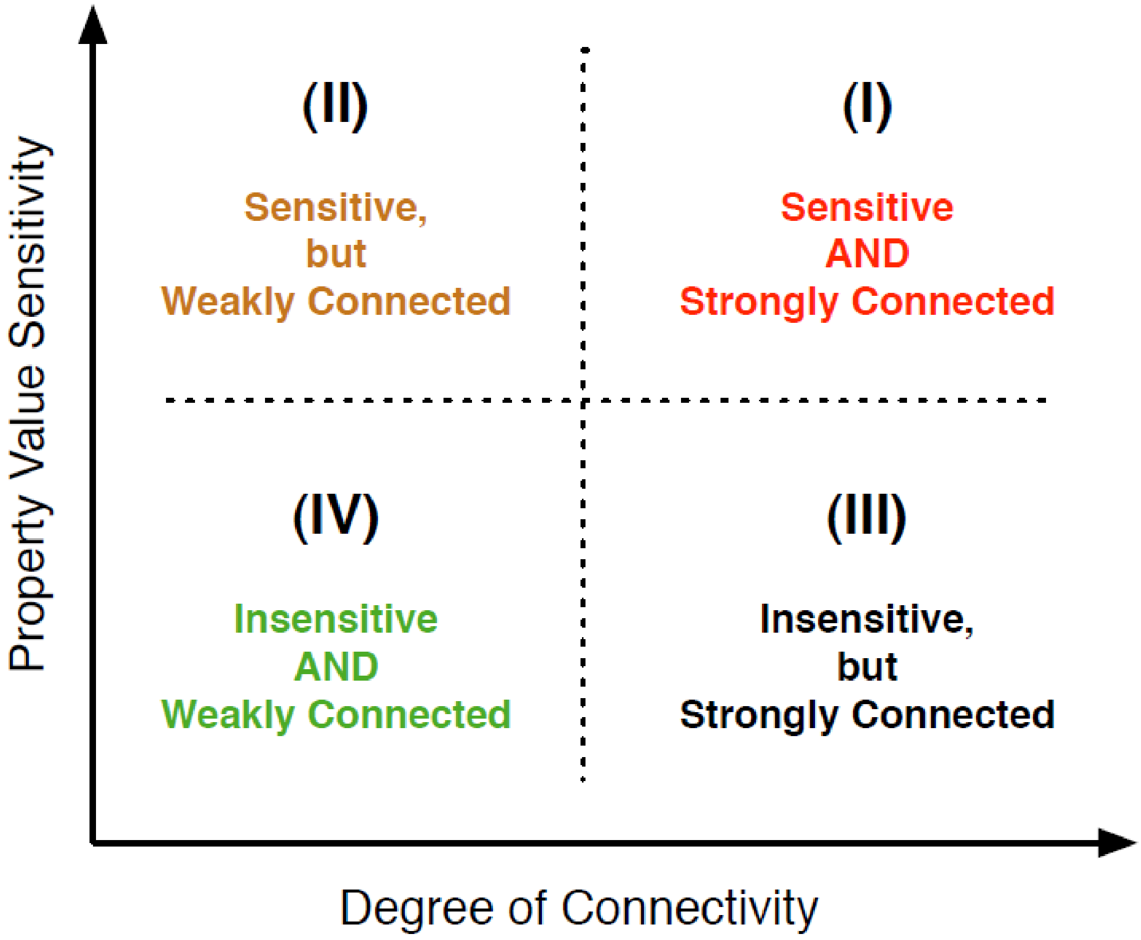

Figure 1-5 Categorizing architecture decisions by PVS and connectivity according to

In the ADG framework, connectivity is defined by the system modeler, while PVS is a result of model evaluation. While these are very important aspects of architectural decisions to capture, they have some limitations. Sensitivity as defined does not provide an understanding of the influence a decision has on architecture because it provides a magnitude but no direction. Also, connectivity of decisions within a tradespace may be unknown before model evaluation. Much of the methodology throughout this thesis builds upon Simmons's ADG, and a thorough treatment of the differences will be discussed in Chapter 4.

The ADG framework assumes a very specific approach to system architecture problem formulation. However more recent work provides a framework that demonstrates there are inherently multiple types of System Architecture Problem (SAP) classes . These different types of architecture sub-problems combine to formulate an entire architecture tradespace, and as a result aspects of the architecture may not be encoded as the assignment problem formulation that is assumed in the ADG. The architecture measures of PVS and connectivity are not necessarily defined for other SAP classes.

To develop measures of how technology influences architecture and the coupling that occurs between different technologies, we rely heavily on design of experiments literature . While it is intended to understand influences of variables on observed behavior, it can similarly be applied to the influence of defined variables on measured or calculated behavior in terms of the architecture tradespace exploration. As applied to an architectural tradespace, each evaluated architecture is treated as a single experiment. Similar to the ADG view of PVS, the design of experiments literature provides a measure of main effects. The key to applying main effects analysis is that it measures the difference between two averages. While normally the two averages would be applied to high and low states of a variable within an experiment, this can correlate to the binary states of an architectural feature either including the feature or not. For an arbitrary SAP, an architect may have an arbitrary number of alternatives rather than a series of binary decisions. A discussion of how to apply main effects analysis to particular technologies and architectural features will be presented in Chapter 4.

The same body of design of experiments literature provides an explicit measure of interaction effects. This is a measure of the strength of two variables interacting. By extending the previous logic of relating experiments to individual architectures, we can use interaction effects to measure the strength of coupling that occurs between different technologies or other architectural features. Relying on the design of experiments literatures helps to solve the problems of the ADG of being limited in problem formulation and requiring a priori system knowledge. The complete extension of design of experiments literature to the presented framework is detailed in Chapter 4.

1.3 RESEARCH OBJECTIVES

The general objective of this thesis is to develop a framework for technology evaluation in the context of long term system architecture planning for the future human space exploration transportation system. Given the literature discussed there are several specific objectives within that goal. The specific objectives are organized into those that provide methodology that is applicable to the fields of system architecture and technology evaluation generally. These contributions are expected to provide value in future analysis of other related problems. The specific application objectives define the goals for understanding the specific problem of defining a transportation system for future human space exploration.

1.3.1 METHODOLOGY OBJECTIVES

Provide an understanding of the influence that technologies have on system architecture considering the following attributes of the tradespace:

- There is ambiguity in the definition of the system
- The measure must be applicable to an arbitrary architecture problem formulation
- The measure can be calculated independent of a priori system knowledge

Provide a measure of coupling in architecture between technologies or other architectural features considering the following attributes of the tradespace:

- There is ambiguity in the definition of the system
- The measure must be applicable to an arbitrary architecture problem formulation
- The measure can be calculated independent of a priori system knowledge

1.3.2 SPACE TRANSPORTATION ARCHITECTURE OBJECTIVES

Create a framework for defining an architecture that describes a transportation system to an arbitrary destination beyond Earth.

Explore the tradespace for human exploration transportation systems to multiple destinations.

Define and then find "good" architectures to multiple exploration destinations.

Evaluate the influence of a set of potential technologies for future human spaceflight transportation systems across multiple destinations.

Identify some initial candidates of precursor mission architectures that might lie on the development pathway to a future Mars mission architecture.

1.4 THESIS OVERVIEW

Chapter 2 presents a motivating case study that is used to define metrics in the tradespace exploration that follows. Chapter 3 provides a detailed description of the problem formulation and approach to tradespace exploration of the transportation system architecture. Chapter 4 provides a detailed view of the contributions made in measuring influence and coupling of architectural features across the tradespace. Chapter 5 provides a detailed view of the analysis executed for the transportation system to Mars and Chapter 6 provides results from applying the methodology to other destinations. Chapter 6 also provides some insights into the future exploration campaign and identifies some of the inputs to technology portfolio design. Finally Chapter 7 wraps up with a summary of conclusions and contributions.

2 TECHNOLOGY LIFE CYCLE EVOLUTION

2.1 OVERVIEW

The goal of this chapter is to develop an understanding of the overall history, development, and evolution of a piece of space propulsion technology over time through a single detailed case study. Particular emphasis is placed on measuring performance and cost while also tracking non-technical issues related to the procurement environment of the piece of technology.

The scope of this thesis is dedicated to understanding major technology investment decisions for space transportation considering ambiguity of system architecture definition and long term programmatic goals. Beyond simply understanding their potential performance, a major consideration for evaluating technologies is understanding their life cycle in terms of performance evolution and Life Cycle Cost (LCC). While a generic model that integrates detailed understanding of these issues into the associated cost and performance modeling of various technology elements is desired, developing such a model would require a level of analysis across several major pieces of technology that is outside the scope of the work presented.

Several of the metrics that define performance and cost are often tightly coupled. In addition to the technical interactions that occur within the system that defines a piece of technology, these metrics can be strongly influenced by factors in the surrounding environment such as fluctuations in the demand for a technology element, changes in the procurement of related technologies, the emergence of disruptive technologies, and the changing needs of customers of the technology. This is a short sample from the list of factors that can make it difficult to track, let alone predict, the evolution of performance and cost over the lifetime of a technology element. Since there are complex interactions that drive evolution of technology over time, it makes sense to investigate a single project to try and extract some of the high-level influences for a technology element in the environment of low-procurement rate in-space propulsion technologies.

In this chapter a single case study is presented on the Pratt and Whitney RL-10 liquid oxygen-liquid hydrogen in-space engine. Issues associated with performance evolution and life cycle cost are considered, and some observations are made on the influence of various factors over the life of this piece of technology. Recommendations are made for evaluative metrics based on the general conclusions from the case study. These metrics are then used in later chapters when evaluating high-level architectural concepts.

2.2 CHALLENGES OF ASSESSING COST/RISK

Section 1.1.2 provides a discussion of some of the various uncertainties related to the definition of system architecture. In addition to ambiguous system goals and undefined system architecture, it can be a challenge for system designers to define expected cost and risk associated with incorporating technology elements into design. These uncertainties occur in both the development and operation of technologies.

A common tool used to evaluate technologies is the Technology Readiness Level (TRL) used by NASA and defense organizations. TRL as defined by details this ordinal metric of the maturity of a system. However, multiple sources document this metric as an inadequate measure of resources required to develop the technology. A detailed treatment of the difficulties of tracing technology development is provided in . While a measure of readiness will be introduced later on, the detailed discrimination between TRL levels is not used.

2.2.1 COSTING AND ARCHITECTURE

The inherent difficulty in costing future systems to develop is that these systems do not currently exist. All costing methodologies gather knowledge of systems that have already been implemented and develop some kind of model that extends this knowledge to predict costs of future systems. This information, based on a variety of assumptions, is then used to make decisions on the system being developed. Depending on the design phase and level of definition of the system, the costing methodology and resulting decision support required of this process varies. Costing activities can be used for everything from precise allocation of budgets to high-level decision support tools when defining overall system architecture.

Figure 2-1 Technology costing in systems engineering

In general there are three basic methodologies to predict future costs. Ground-up costing requires detailed knowledge of the system and assigns costs to every component and process required, assuming previous knowledge at the component level. Costing by analogy requires knowledge of similar projects or programs that can be appropriately scaled to derive an expected cost for the system under consideration. Finally, parametric costing relies on one or more Cost Estimating Relationships (CER) that relates aspects of system performance to cost from historical projects that have relevant design and operational histories to the system under consideration. Since CERs rely on statistical relationships they also provide relative uncertainties based on the fit of the data used to develop the relationship.

When it comes to long-term development planning and predicting operations costs of systems that do not yet exist, there is often very little previous knowledge to support any precise costing methodology. This analysis is often done early on, in support of high-level architecture and program level decisions. Given the lack of knowledge of the systems in consideration, parametrics based on various CER are often the tool of choice. Designers consider the most relevant systems (however that may be defined) and perform parametric analysis relating cost to properties of the system to be built such as size, performance or complexity. While the level of precision associated with these methods is limited, it is important as a decision support tool that the major distinguishing differences between alternatives can be captured by the coarse parametrics used. When considering systems that will be procured and operated over decades, it is particularly important that cost metrics capture the aspects of the system that will drive cost over the lifetime of the system including development, operations, and retirement (if applicable). Some of the major issues in designing appropriate parametrics can be found in and .

2.2.2 CONSIDERING LIFE CYCLE COST

It is important to understand the cost impact of integrating various technologies into a system. Often technologies are seen as an investment that can improve performance, or they can increase efficiency for the same performance of a system with the added cost and risk associated with the technology. Ideally, the costs to be considered are Life Cycle Costs (LCC), including analysis of issues that span the lifetime of the system. This means the major considerations include both development of the capability that does not currently exist, and the operational segment of the technology when elements are being manufactured, procured, and flown.

At the system architecture level, the parametrics and CERs previously discussed are used to predict both development and operations costs. While development costs are highly uncertain, this is often acknowledged and taken into consideration (see Section 1.2.3). The problem with estimating operations costs, is the low level of system definition. Defining the relevant set of previous technologies from which a parametric can be built is difficult when the system and its surrounding operational environment have yet to be defined. This further motivates the presented case study which has detail of the operational life of a piece of technology that evolves over time in different systems and procurement atmospheres. A good example of the difficulty in estimating future operational cost is demonstrated by life cycle cost estimate performed for the Space Shuttle during the design phase. The following quotation is taken from the 1971 Mathematica, Inc[1] study that was intended to find the most cost-effective solution to U.S. space transportation needs.

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[1] Mathematica refers to the research organization now known as Mathematica Policy Research. There is no relation to the software produced by Wolfram Research.

> *“[The cost estimator] stated that it tested its cost estimating relationships by estimating costs of well known aerospace systems with good approximation of actual costs. On the other hand, it must be recognized that the fully reusable Space Shuttle Transportation system advances major new areas of technology, and therefore involves cost uncertainties not easily related to present aircraft or spacecraft costs.”*

The report proceeded to estimate an incorrectly high budget for NASA, a flight rate for the shuttle that was at least an order of magnitude too high, and as a result provided an estimate of incremental flight costs of the re-usable space shuttle that was three orders of magnitude lower than for the realized system . The results of this report were included in reports to Congress and were used in determining budgets for the shuttle program .

Similar difficulties continue to be a problem. In a more recent Independent Cost Assessment (ICA) of the Space Launch System (SLS), it is noted:

> *“All three Program estimates assume large, unsubstantiated, future cost efficiencies leading to the impression that they are optimistic.”*

It remains a difficult task to predict the usage of a piece of technology and how that drives performance and cost evolution over time. In the following case study both performance and procurement issues will be tracked for a single piece of technology over a long lifetime of use.

KEY POINTS

- *Available documentation highlights that part of the difficulty of Life Cycle Cost estimation for future technologies comes from the lack of relevant systems that can inform the estimate, and the difficulty in predicting flight rate of the system to be designed.*

2.3 LIFE-CYCLE TECHNOLOGY EVOLUTION CASE STUDY

The rest of this chapter will discuss details of the Pratt & Whitney RL-10 rocket engine. This engine is a liquid hydrogen-liquid oxygen in-space engine that has flown in different launch vehicles since the early 1960s.

2.3.1 WHY RL-10?

Given the previously described difficulties in estimating technology element LCC and the desire to understand what factors might drive this cost, it is important to carefully select a case study that is representative of the type of projects to be considered in the rest of this thesis.

There are four aspects to the Pratt & Whitney RL-10 liquid hydrogen rocket engine that make it a good candidate for a detailed case study.

1. **In-space propulsion**

   The RL-10 is primarily an in-space propulsion technology. As a result, the overall types of projects that included the RL-10 as a system element had properties inherent to space projects such as high risk, low procurement rates, and complex integration schemes. The focus of this thesis is the in-space exploration transportation system, and the technologies considered will generally be subject to similar complex systems issues.

2. **Technology evolution over time**

   The RL-10 began as a piece of technology development, creating a capability that was previously little more than a theoretical possibility. Over time it developed a rich history of performance evolution with many variants serving different customers. Variants included both incremental performance optimization and overall engine functionality upgrade. The engine is no longer seen as an experimental element, but rather an operational capability. While the readiness of technologies considered in this thesis varies, most are early concepts with various levels of demonstration. If included in an exploration campaign, these concepts must be developed into operational system elements with well understood and repeatable performance.

3. **Procurement evolution**

   Over the lifetime of the engine, the procurement environment surrounding the RL-10 has drastically changed. The engine has served multiple customers and procurement has been done under different contracting schemes. In addition the rate of procurement has fluctuated in response to the changing volume of different systems in which the engine is integrated.

4. **Data availability**

   Beyond high level technical specifications, data availability is often a problem when considering technology development activities, especially those that began as secret defense projects. However, having its history in both a defense and a civil agency, the RL-10 has a large amount of unclassified (or declassified) publicly available data. It is also helpful in gathering data that despite the consistent restructuring, mergers, and acquisitions of the space industry, the engine remains a product of the initial developer, Pratt & Whitney.

This case study will provide an understanding of the overall history of the engine, tracking its development and evolution over time. Particular emphasis is placed on measuring performance and cost of the engine while also tracking non-technical issues related to the procurement environment.

N.B. The analysis that follows in the rest of section 2.3 comes from a wide variety of sources. All data collected is from unclassified and declassified sources including , , , , , , , , . The aggregated data was verified with proprietary documents and reports held internal to the Aerospace Corporation. Due to the proprietary nature of some of the data in its aggregate, several figures particularly those relating to development spending and engine price, have had their axes removed. All monetary data values are presented in constant-year relative dollars and are presented only for the overall trends present.

2.3.2 DESIGN AND DEVELOPMENT

By 1957 engineers at Pratt & Whitney were testing the first jet engine specifically developed for liquid hydrogen. The P&W model 304 engine was the powerplant for a then-secret reconnaissance aircraft program codenamed "Suntan." While the vehicle development was eventually cancelled in favor of the Lockheed U-2 and other reconnaissance alternatives, the engine development that took place during this period directly allowed for the development of the RL-10 engine.

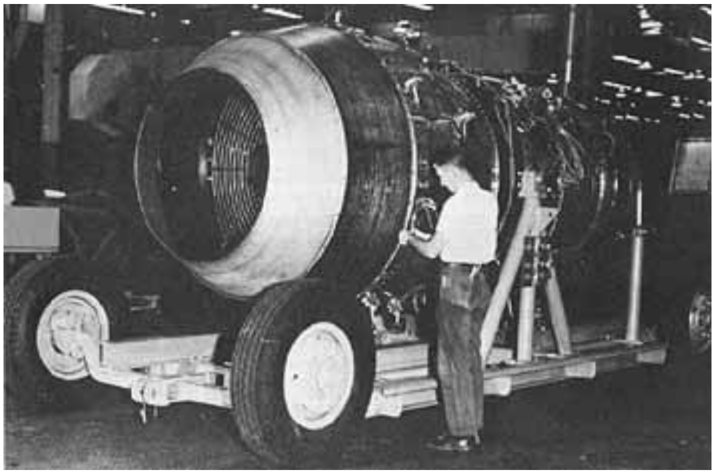


Figure 2-2 Pratt & Whitney model 304 engine, liquid hydrogen turbojet engine

The 304 engine required engineers to develop liquid hydrogen (LH2) handling techniques and greatly increased the demand for its production. This alone was significant as at the time LH2 was mostly available only in very small quantities in the few cryogenic labs that existed at the time in the United States. Furthermore the 304 engine development had produced a very efficient heat exchanger that brought the fuel from 20 K to 1000 K, extracting energy from the combustion products and greatly increasing the overall engine efficiency . This efficient heat exchanger would become essential to the design of the RL-10 engine.

Around the same time as the development of the 304 engine, a national need emerged for high performance upper stages on multiple launch vehicles. Relative to existing hypergolic and solid propellants, a high performance upper stage would use liquid hydrogen fuel and would need a propulsion system, (rocket engine) that would be reliable and restartable. While different launch vehicles had different structural requirements for the overall stage tank design, there were two customers for a liquid hydrogen engine. The Air Force was developing the high performance LOX-LH2 upper stage that would become the Centaur upper stage, and needed an accompanying engine. Meanwhile NASA was developing the Saturn V launch vehicle. While development work on the much larger J-2 upper stage hydrogen engine had begun, it would not be available for initial development flights of the Saturn family of rockets. The RL-10 served as the LOX-LH2 propulsion system for the Saturn I S-IV upper stages, each with a cluster of 6 engines. By the mid 1960s variants of the RL-10 had been produced for both the Air Force and NASA, and testing had been pursued on other variants that were never completed, demonstrating flexibilities in the engine such as different propellant types and deep throttling.

Evolving from the 304 turbojet engine, the simple design of the RL-10 is largely what led to its success. The engine takes advantage of an expander cycle as shown schematically in Figure 2-3.

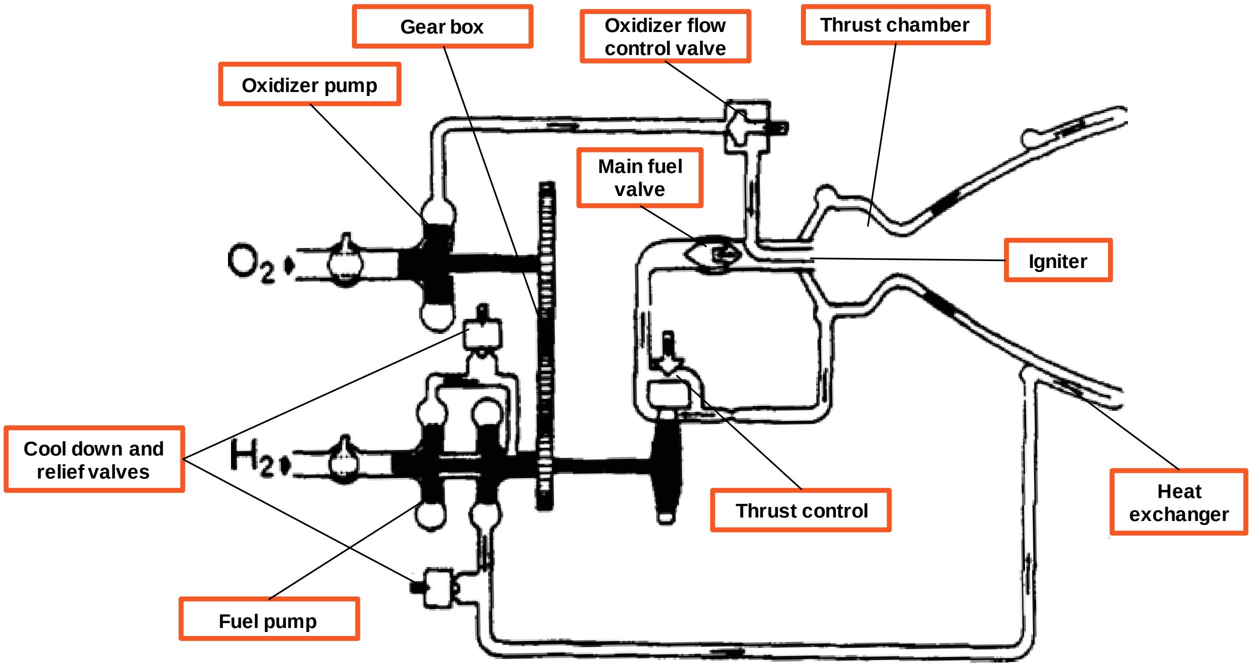


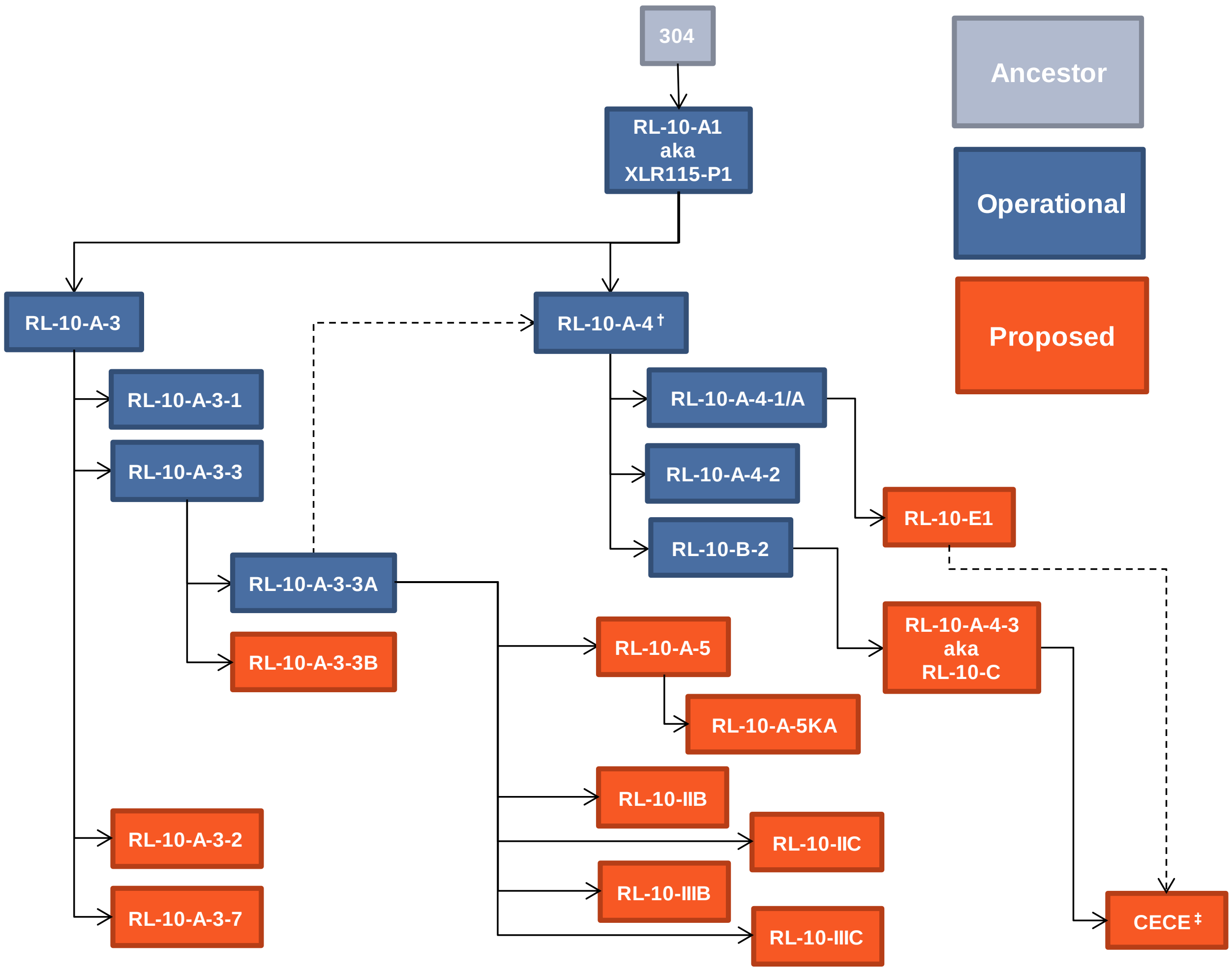
Figure 2-3 RL-10 engine expander cycle schematic

Usually a regenerative rocket engine uses propellant as a coolant surrounding the combustion chamber and nozzle. This cooling prevents melting and degradation of internal components while imparting energy into the propellants before combustion. However in the case of the expander cycle, this pre-heating of liquid hydrogen produces a phase change with enough energy to power the fuel and oxidizer pumps. The RL-10's expander cycle required fewer moving parts as compared to other regenerative liquid rocket engines because the liquid hydrogen phase change removed the need for a gas generator to drive propellant pumps.

When starting the RL-10 all that is required is a single ignition point and mechanically opening the fuel valve. Even after coasting in deep space, ambient heat in the engine inherently heats up the cryogenic hydrogen, and pumps are able to spin up without a separate energy source (a pre-combustor phase). The intended primary advantage of this system was the reliability in starting the engine for critical maneuvers. This startup reliability has since been proven through the engine's rich flight history and multiple deep-space engine restarts. In addition the relatively low temperature requirement of the turbines allows them to be made of lightweight aluminum rather than steel.

2.3.3 ENGINE VARIANTS AND FLIGHT HISTORY

The RL-10 liquid hydrogen rocket engine has a rich history of performance upgrades since its initial design during the early 1960s. Tracing the exact performance parameters associated with different engine upgrades can be difficult, as inconsistent variant names were used in documentation of development activities. The inconsistent record-keeping is a result of program cancellations and the integration of partially developed upgrades into later projects. To create a thorough timeline of engine developments, a detailed breakdown of engine variants must be created that details engine improvements among both proposed and operational variants. A fairly detailed map of the major variants (both those that were brought to production and those cancelled in various stages of development) is shown in Figure 2-4. This map will be used as a basis to place major performance upgrades into a timeline associated with various development costs and engine prices.



† RL-10-A4 combustion chamber and nozzle modifications taken from RL-10-A3-3A

‡ Throttling from work for Atlas Reliability Enhancement Program (AREP) for Common Extensible Cryogenic Engine- Altair Descent Module Engine

Figure 2-4 RL-10 "family tree" describing variant history

Since funding, procurement, and performance parameters all vary for different engine variants, defining the distinct engine variants to consider is the first step to tracking the evolution of the engine over time. Brief descriptions of the overall purpose of each variant are provided in Table 2-1. Non-operational engines were never qualified for flight although some prototypes did fly on test vehicles. Most non-operational engines were cancelled during varying phases of design and ground testing.

Table 2-1 RL-10 Variant Descriptions

Variants	Operational?	Description

A1, A3, A3-1, A3-3	Yes	Original in-space (upper stage) hydrogen engines. Developed for Atlas/Centaur and Saturn I, S-IV upper stage.
A3-2, A3-7	No	90% throttling capability demonstrated for lunar lander
A3-3A	Yes	Centaur stage for Atlas G, I, II and Titan IIIE, IV 3rd stages.
A3-3B	No	Engine for modified Centaur for both space shuttle and Air Force.
IIB, IIC, IIIB, IIIC	No	Orbital Transfer Vehicle engine concepts
A4, A4-1/A, A4-2	Yes	Centaur stage for Atlas IIA, IIAS, IIIA, IIIB, V. Lower shuttle flight rate drives need for increased upper stage production rate and capacity. Higher thrust, Isp.
A5, A5-KA	No	Launch engines for DC-X and Kistler launch vehicle. Sea-level operation and throttle capability, reusable.
E1	No	Atlas Reliability Enhancement Program (AREP). Throttleability and reliability improvements
B2	Yes	Upper stage engine for Delta III, IV. Large nozzle extension, higher thrust.
A4-3 aka -C	No	Shuttle derived Heavy Lift Vehicle upper stage, and replacement for A4-2 engine in Centaur.
CECE	No	Common Extensible Cryogenic Engine- Altair Descent Module Engine (deep throttle capability)

Figure 2-5 indicates the rough timeline for the development of each variant. Note that at the time of writing this thesis, no RL-10 development work has produced a new operational engine in the last two decades, despite significant development work that has been pursued on new engine variants.

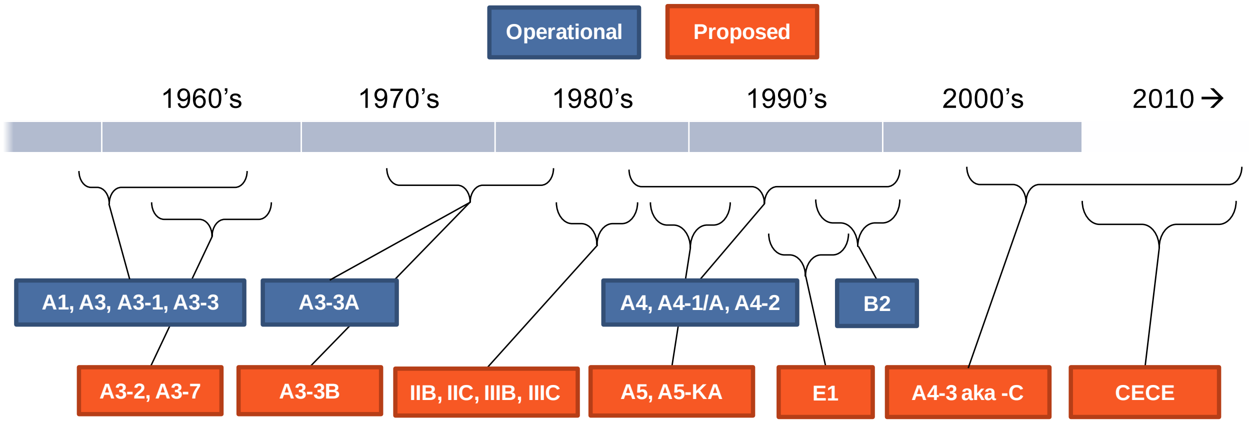


Figure 2-5 RL-10 development timeline by variant

Most of the analysis in the rest of this chapter will focus on the nine engine variants that were operational. The flight history of these engines is shown below in both Figure 2-6 and Figure 2-7 indicating the years of first and last flights and the quantity of each engine variant flown (to date) respectively. Data collected accounts for flights through August 2011.

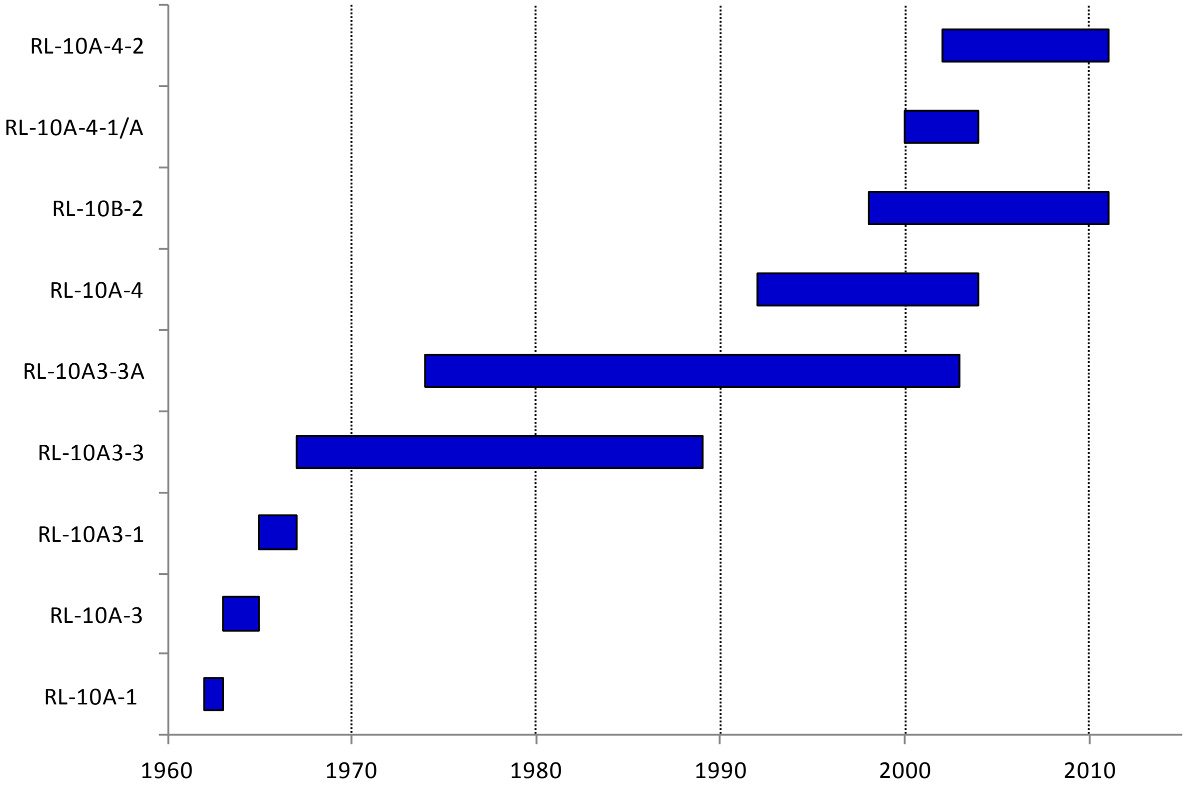


Figure 2-6 RL-10 operational flight history by variant indicating years of first and last flights

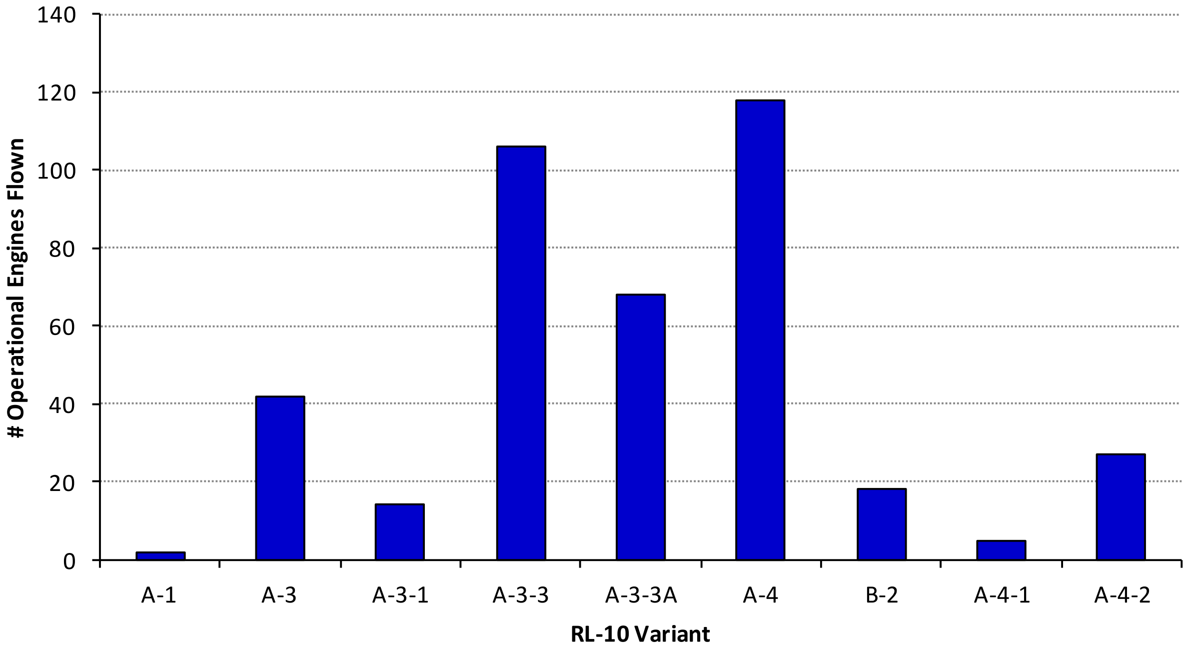


Figure 2-7 Number of each operational RL-10 variant flown

As the data cataloging all engine variants and missions was collected from several sources a quick validation was done to make sure most operational, flown engines were accounted for. Several overall reference points on the total number of successfully flown engines in space came from Pratt & Whitney papers and promotional materials. While the definition of "successful flight" was inconsistent and resulted in slight accounting discrepancies of one or two engines, overall publicly available sources were able to capture missions including all RL-10 starts through history. This validation is presented in Figure 2-8.

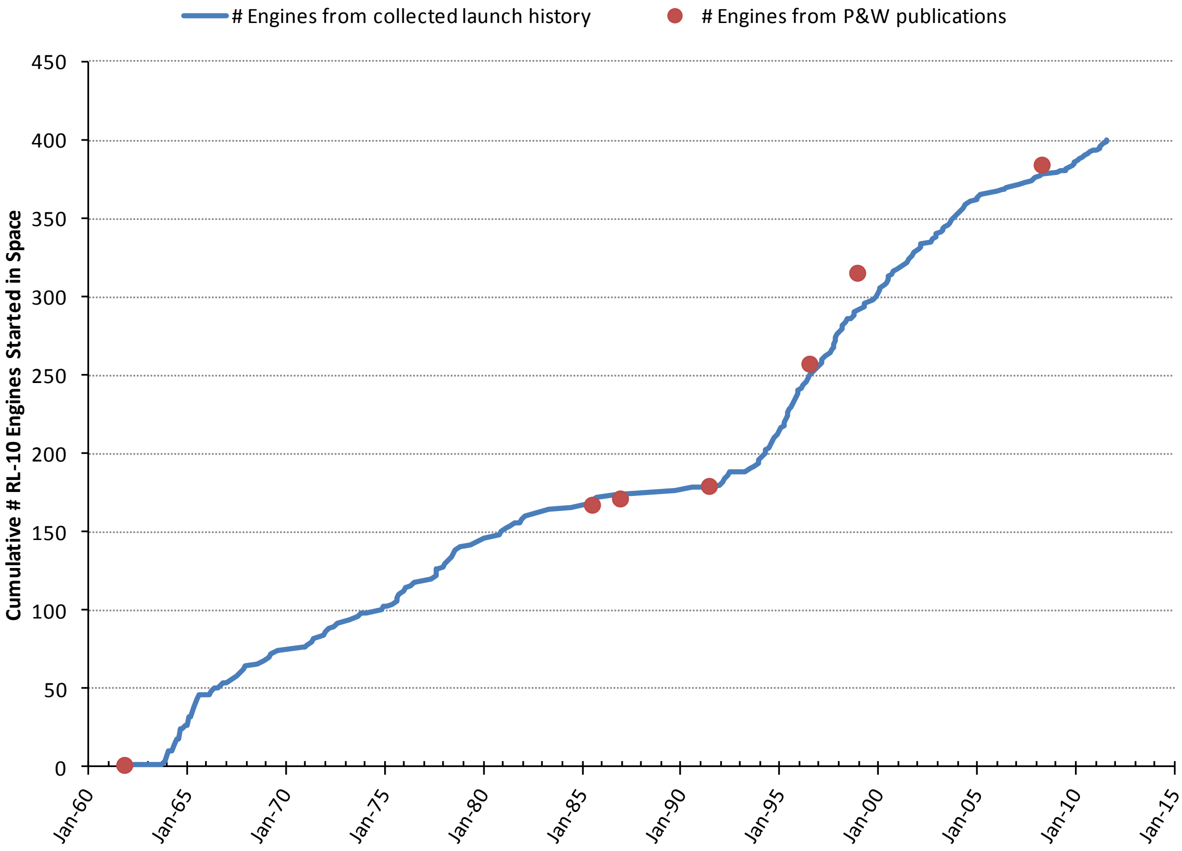


Figure 2-8 Successfully operated RL-10 engines compiled from publicly available sources against P&W reference values

As of this writing, around 400 RL-10 engines have been flown of different variants and performance. With an understanding of the actual different engines that have been developed and flown, the rest of this chapter will look at some of the performance and cost drivers of the engine.

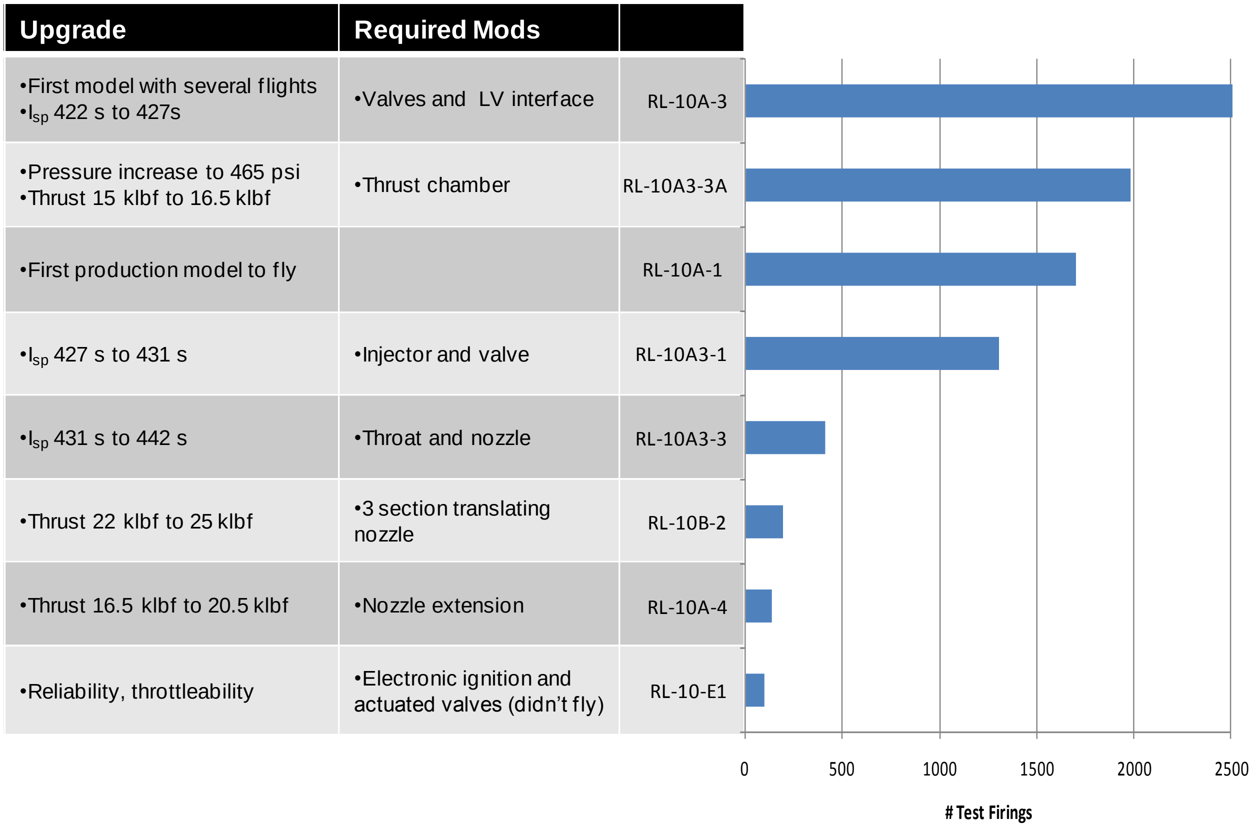
2.3.4 PERFORMANCE EVOLUTION

Each of the previously described engine variants are the result of specific changes and upgrades to the RL-10. While the nature of each variant's implemented changes is different, the resulting performance changes are categorized in Table 2-2. Additionally the number of development test firings that was required for engine certification was available for most engine variants.

Table 2-2 RL-10 Variant performance and size

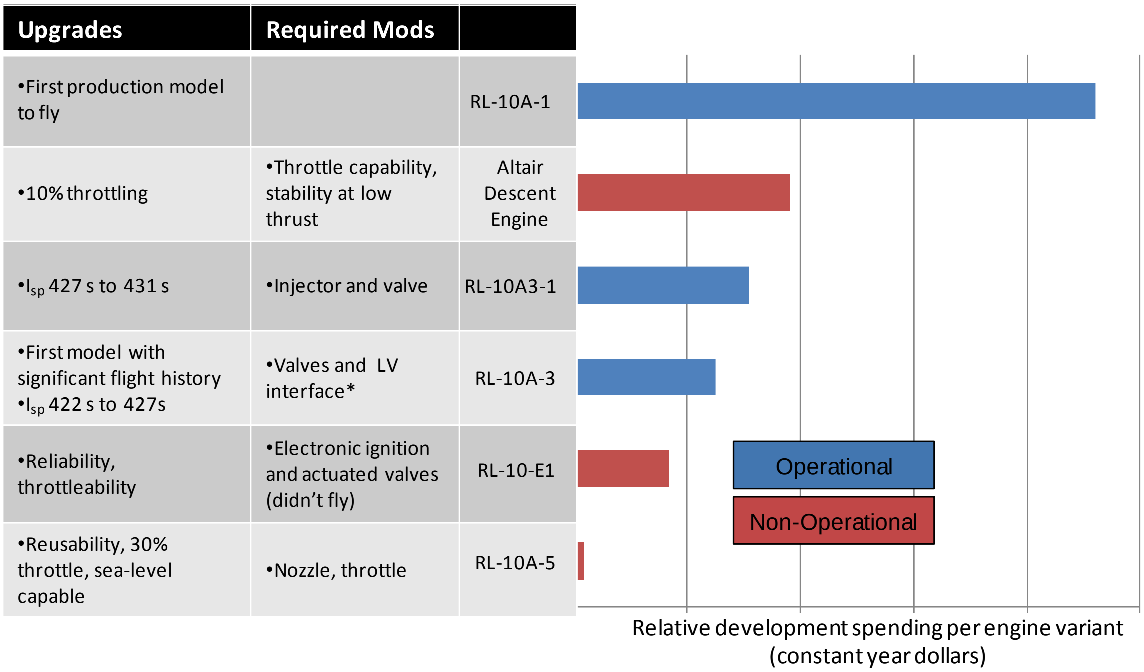
RL-10 Variant	**A1**	**A3**	**A3-1**	**A3-3**	**A3-3A**	**A4**	**A4-1**	**A4-2**	**B2**
I_{sp} (s)	422	427	431	442	444	449	451	451	466.5
Chamber Pressure (psi)	300	300	300	395	465	578	610	610	644
Area Ratio	40:1	40:1	40:1	57:1	61:1	84:1	84:1	84:1	285:1
Vac thrust (lbf)	15,000	14,750	15,000	15,000	16,500	20,800	22,280	22,280	24,720
Dry Weight (lbm)	NA	288	298	301	310	375	368	375	610
T/W ratio	50	51.2	50.3	49.8	53.2	55.5	60.5	60.5	40.5
Envelope: length; diam (in)	NA	98; 60	70; 40	70; 40	70; 40	90; 46	90; 60	90; 60	163; 84
# Dev Test Firings	1700	2527	1308	410	1984	136	NA	NA	194

Looking at the various engine upgrades in comparison to the number of development test firings and development spending might give a sense for the effort required to prove out various types of changes. It is expected the initial engine development took the most resources for qualification. While this data does not necessarily support any particular parametrics for resource expenditure in rocket engine development, it does suggest engine upgrades that can be more or less costly. The development test firings for several variants are shown in Figure 2-9 and the development spending for several variants is shown in Figure 2-10 below. While the number of development test firings was available for most of the operational engine variants, the development spending data are more sparse.



Upgrade	Required Mods	
•First model with several flights •I_{sp} 422 s to 427s	•Valves and LV interface	RL-10A-3
•Pressure increase to 465 psi •Thrust 15 klbf to 16.5 klbf	•Thrust chamber	RL-10A3-3A
•First production model to fly		RL-10A-1
•I_{sp} 427 s to 431 s	•Injector and valve	RL-10A3-1
•I_{sp} 431 s to 442 s	•Throat and nozzle	RL-10A3-3
•Thrust 22 klbf to 25 klbf	•3 section translating nozzle	RL-10B-2
•Thrust 16.5 klbf to 20.5 klbf	•Nozzle extension	RL-10A-4
•Reliability, throttleability	•Electronic ignition and actuated valves (didn't fly)	RL-10-E1

Figure 2-9 Engine upgrades and development test firings



Upgrades	Required Mods	
•First production model to fly		RL-10A-1
•10% throttling	•Throttle capability, stability at low thrust	Altair Descent Engine
•I_{sp} 427 s to 431 s	•Injector and valve	RL-10A3-1
•First model with significant flight history •I_{sp} 422 s to 427s	•Valves and LV interface*	RL-10A-3
•Reliability, throttleability	•Electronic ignition and actuated valves (didn't fly)	RL-10-E1
•Reusability, 30% throttle, sea-level capable	•Nozzle, throttle	RL-10A-5

Figure 2-10 Engine upgrades and (relative) development spending

Qualitatively it seems thrust chamber modifications require more test firings for engine certification than nozzle developments. More importantly however, after the first couple variants, both the number of test firings and amount of development spending was far lower than during the initial engine development.

Considering more carefully the development expenditure against various performance improvements it quickly becomes clear for this engine that there was no statistically significant correlation. Even the number of test firings, a possible measure of resources spent, does not seem closely correlated to the development spending for different engine variants. An example is shown in Figure 2-11.

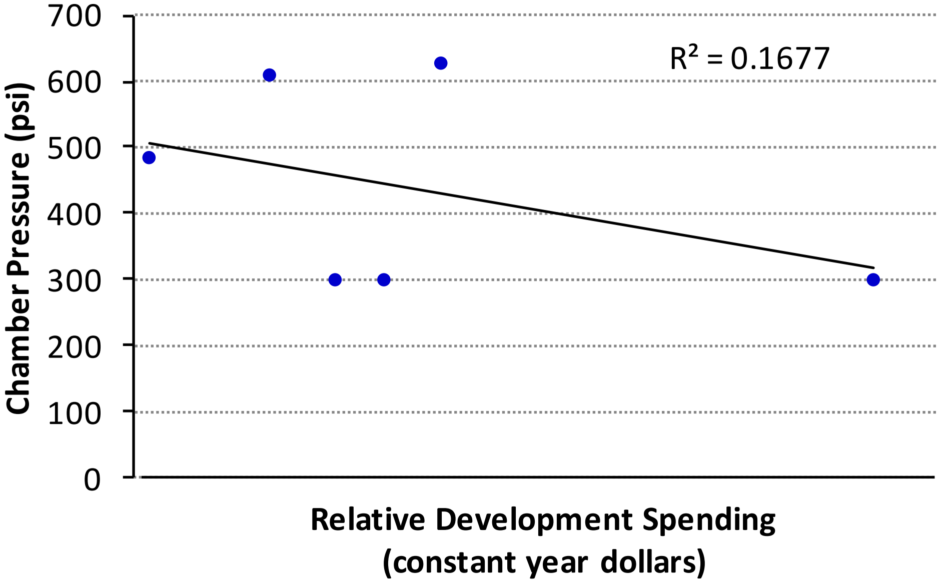


Figure 2-11 Chamber pressure vs relative development spending

Assuming increasing performance improvements should cost more, basic linear fits are presumed for each of the engine parameters tracked. The coefficient of determination, R is used to check how “good” the fit is. More simply, R^2 represents the percentage of the variation in one parameter that is accounted for by variation in the other parameter. Traditionally an R value of 0.8 indicates a “good” fit while an R value less than 0.5 indicates a poor fit. In this case all R values are less than 0.8 and in fact all R^2 values indicate less than 50% of variability in each variable can be accounted for by development spending.

Table 2-3 Lack of correlation between engine performance parameters and development spending

Engine Parameter	Development Spending: Linear Best-Fit R Value
I_{sp} (s)	0.451
Chamber Pressure (psi)	0.410
Area Ratio	0.618
Vac thrust (lbf)	0.195
T/W ratio	0.345

The correlations between development spending and all major performance improvements tracked are very low. Additionally we know that development spending was mostly from the first 2 variants. In considering the highest level drivers of life cycle cost, we do not expect these incremental performance improvements over time to drastically change the Life Cycle Cost of the engine.

KEY POINTS

- *No significant correlation was found between performance measures and development resource expenditure through the available data for the RL-10 engine.*

2.3.5 PROCUREMENET HISTORY

Aside from the purely technical engineering specifications discussed, several issues related to the procurement of the RL-10 engine were also considered. While there are large gaps in the availability of this data due to the proprietary nature of procurement strategy, an overall picture of the procurement trajectory of the technology can be put together from the data that is available. The data in this section is only presented in relative magnitudes due to the sources being a mix of both publicly available and proprietary sources. Despite the limited data available it is desirable to create an understanding of some overall drivers of the life cycle cost of the engine. While the development costs have been discussed, for a piece of technology that will be operated over a long time, it is the procurement that dominates the life cycle cost of the engine. As a result the design of a long term system should avoid elements vulnerable to run-away cost growth over the lifetime of the technology. From the government's perspective, it is desirable to integrate systems that are robust to drastic price increases.

RL-10 variants were used in at least three distinct launch vehicle families. Many non-technical aspects of the economic and political environment surrounding these vehicles resulted in a volatile procurement atmosphere with inconsistent expectations on procurement volume from Pratt & Whitney's perspective. An excellent overview of major historical economic influences on the launch vehicle industry and the resulting impact on technical decision making is provided in . While it is difficult to know exactly what expected demand for engines managers at Pratt & Whitney used in internal decision making over time, a sense for the expected procurement of the engine can be gathered from the various announcements and press releases of intentions to procure different RL-10 variants. In many cases, these data points represent potential procurement of RL-10 engines that was either greatly reduced or never pursued at all. For the following analysis it is assumed these publicly announced figures were correlated to Pratt & Whitney's expectations for the engine. The relative magnitude of expected procurement is displayed in Figure 2-12.

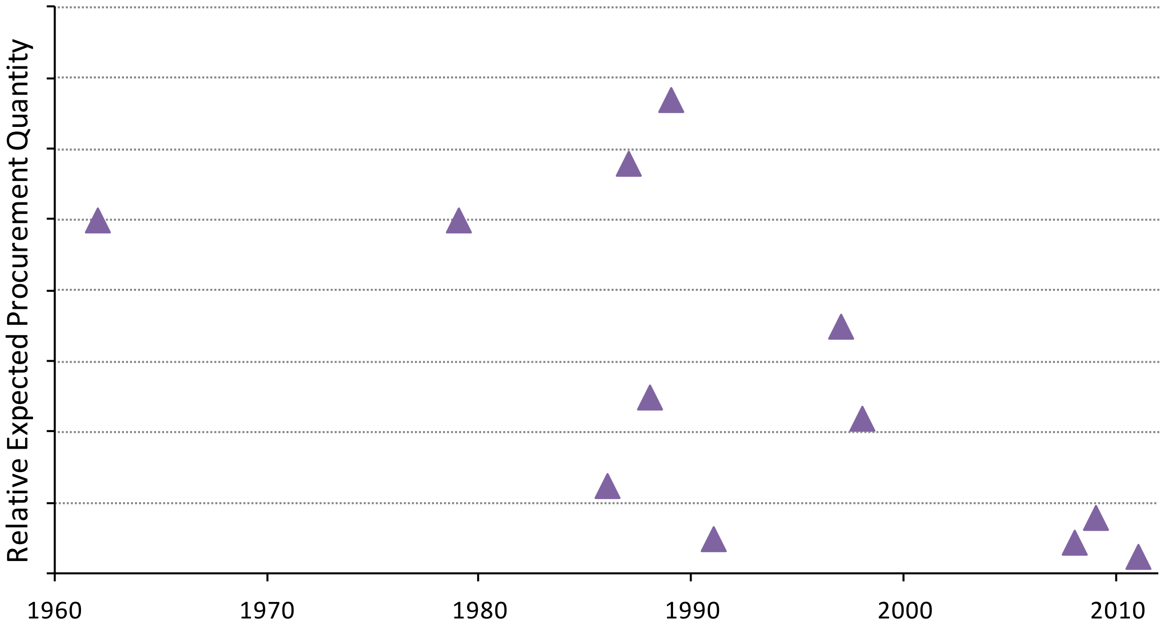


Figure 2-12 Relative expected quantity of engines to be ordered

The early development of the engine came with relatively high and consistent expected procurement. Engines were needed for early Saturn I flights and the frequent launch of Atlas rockets that were flying Centaur upper stages. Two other distinct periods in the procurement history of the RL-10 are captured in Figure 2-12. In the mid-1980's it was expected that the procurement rate would significantly increase as the shuttle would begin to carry the Centaur-G upper stage. This was a modified upper stage that would greatly increase the propulsive capabilities of payloads brought to orbit by the space shuttle. However after the Challenger disaster in 1986, this entire program was cancelled to avoid the extra risk of carrying the liquid hydrogen propulsion system on a crewed vehicle. In a short time frame, there were both some of the highest and lowest expected procurements of the engine. This rapid change in expected demand for the RL-10 certainly had significant implications for those managers planning its production.

The other interesting feature captured by this data set is the very low procurement rate over the last several years. In the late 1990s a large block buy of the B-2 variant for the Delta launch vehicle family occurred in preparation for the Evolved Expendable Launch Vehicle (EELV) program. The expected high flight rate for these vehicles never materialized and a large stockpile of engines ended up in storage. The stockpile accumulated as engines continued to be delivered at a rate higher than the flight rate of the engine through the 2000s. With a large aging stockpile of engines and a consistent but fairly low flight rate, there is not a significant need for the Air Force to procure many more RL-10 engines. The Air

Force has announced some “bridge” or smaller block buys of launch vehicles, specifically to maintain the industrial base production capability, but Pratt & Whitney recently announced they would reduce their rocket propulsion manufacturing resources by more than 50%. This is due to both the end of the space shuttle program and these issues with the RL-10 engine .

In the 1980’s there was a push to see competitive commercialization of the launch vehicle industry in the United States. On the government side, this was pushed forward by the Commercial Space Launch Act of 1984 defining and regulating the commercial launch industry in expectations of high procurement rates for the launch vehicle supply chain. In addition it also encouraged suppliers to assume more risk and lower overall costs in the provision of launch services. As a result, a shift occurred in the procurement of the RL-10 engine. Although it is not clear exactly which engines were procured under which contract types, overall there was a shift from being an engine that was predominantly procured under cost-plus fixed-fee contracts to being primarily procured under firm-fixed price contracts .

Figure 2-13 shows the relative price points of the engine to the government customer over time. These price points come from historic press releases and contract announcements, early NASA development budgets, and more recent specific contracts for individual group engine purchases. This data spans the life of the engine and multiple variants being procured in different economic environments.

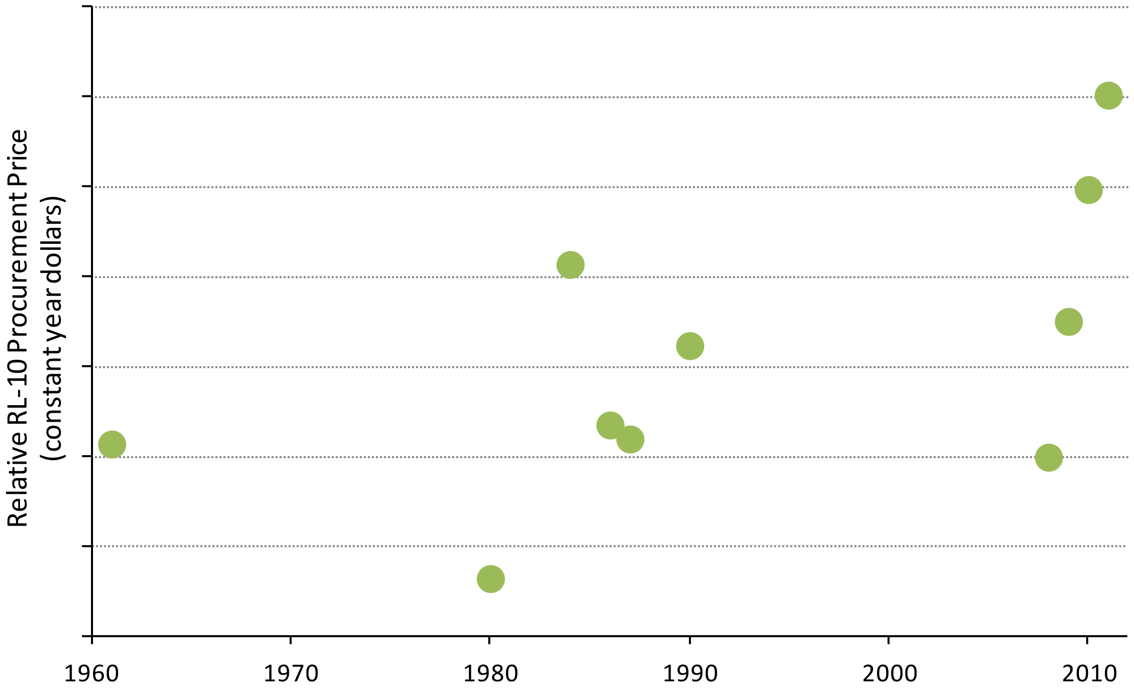


Figure 2-13 Relative price points of the RL-10 engine over time

There are insufficient data points to claim any particular effects from the contracting changes of the 1980’s previously discussed; however since the highest relative price points have been recent we can conclude that the changes in contracting mechanism did not effectively result in a long-term price reduction on the engine.

By interpolating the engine price point data we can combine this with the expected procurement data and look at a very rough estimate of possible correlations between the expected procurement and engine price. These data, shown in Figure 2-14, may indicate something about the relationship between procurement rate and engine price. In general when very few engines are expected to be ordered, there are more price spikes. Likewise the lowest engine prices are associated with the highest expected order quantities.

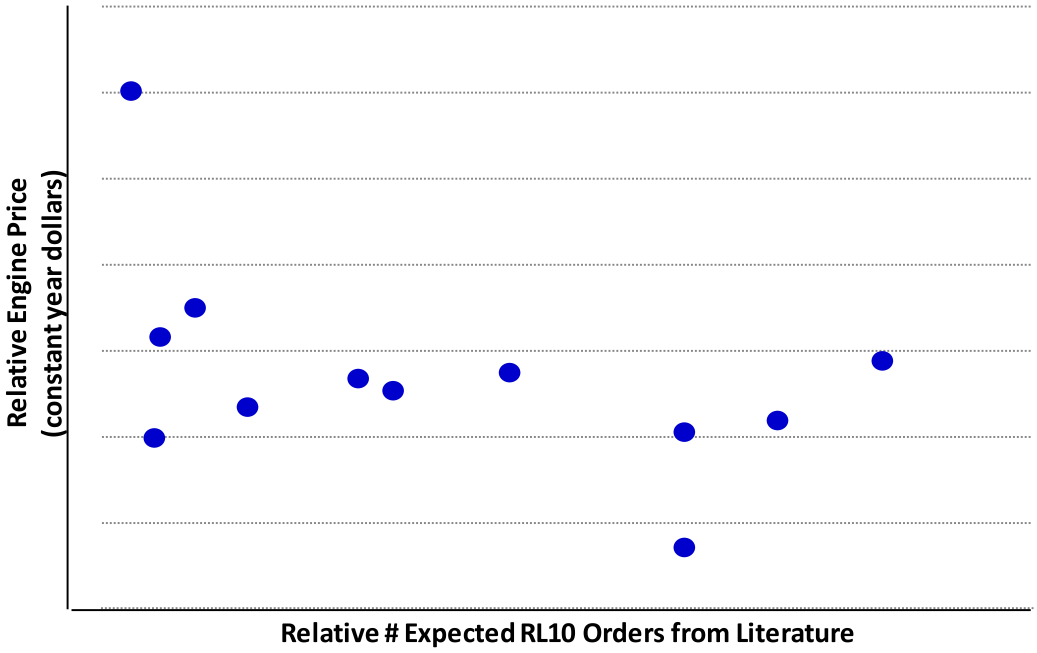


Figure 2-14 Relative engine price vs relative expected procurement quantity

The uncertainty in this data is quite large and it would not make sense to claim a basis for a parametric costing model as a function of procurement rate, however it does support the concept that procurement rate is very important in considering life cycle cost of these engines. Based on interviews of previous RL-10 program managers and public statements in news articles it seems uncertainty in procurement rates drives up the price of the technology. It also creates a disincentive from making manufacturing improvements since it is difficult for managers to know if capital investments will be amortized in a reasonable time frame.

KEY POINTS

- *Driven by industry related events, the procurement rate of the RL-10 engine has often been highly volatile.*
- *Stockpile surplus and low procurement rate are correlated to engine price spikes.*

2.4 CASE STUDY DISCUSSION AND IMPLICATIONS FOR SYSTEM ARCHITECTING

The RL-10 liquid hydrogen engine is a piece of technology with a uniquely rich development and procurement history over a long period of time. It is also one of the most relevant pieces of technology when considering the future space exploration transportation system beyond LEO. Delving into this level of detail in a case study helps to identify some of the driving issues that appear when the government has to procure a piece of costly technology with uncertain purchasing behavior. One of the overall themes revealed in this analysis is the importance of considering the industrial base issues that end up driving the price to the government customer. There are two overall ways to deal with these supply chain risks. At the outset of large-scale system design there can be metrics that encourage designers to select subsystems that are less likely to have run-away prices (due to low demand) over their lifecycle. This method requires that specific aspects of analysis are integrated into systems architecting methodology. The other option is to design flexible procurement strategies that help alleviate some of the burden fluctuating procurement rate places on a manufacturer.

2.4.1 SELECTING AFFORDABLE TECHNOLOGIES

The data presented in Figure 2-14 indicates the potential for very low procurement rates to significantly impact procurement prices. The most likely explanation for this is that the contracting organization must cover some fixed recurring costs with any number of engines procured. When the expected procurement rate begins to drop very low, these fixed recurring costs begin to dominate the price of the engine. The importance of meeting some minimal production rate to support the industrial capability of a given technology quickly becomes apparent. As a result it makes sense that volatility and uncertainty in the demand for a low-procurement system becomes a significant cost risk. If this in fact is a significant driver of price, we can integrate a measure of procurement rate into the metrics used in architecture selection to encourage affordable, sustainable architecture. We want to create a preference for systems where procurement of various components does not frequently fall to zero. Rather, we would like to preference the inclusion of system elements that provide incentive for manufacturers to make improvements to their technology and encourage elements that will fly frequently to avoid the issue of pressuring a single government customer to (directly or indirectly) assume significant fixed recurring costs.

In the framework to be laid out in Chapter 3 of this thesis, a technology life cycle cost (LCC) proxy metric is introduced. Two factors influence this proxy metric, one of which is related to the readiness and development effort required to enable the technology. The other part of the proxy metric is defined by the potential for other customers to take advantage of the technology element in question. In this thesis the coarse cost proxy metric is the only place to take into consideration these important industrial base issues.

2.4.2 MANAGING TECHNOLOGY PRICE

One of the observations from this case study is that in the presence of very low procurement, the firm-fixed price contracting mechanism did not control the price to the government. The contract type may often be an important factor in controlling the price of technology elements, but it is not necessarily applicable in all procurement situations. In this case study the government was forced to accept a higher price that was most likely covering fixed costs which were integrated into firm-fixed price contracts. Issues related to the implementation of various contract types are covered in other literature such as . While it is worthwhile to consider what sort of projects can benefit from specific contracting mechanisms and will strongly influence life cycle cost, it is outside the scope of long term system architecture planning and will not be addressed in this thesis.

In situations where a technology element is critical to the government but will necessarily have highly volatile or consistently low procurement volume, it is possible a flexible procurement scheme could help to mitigate the resulting price spikes that could otherwise occur. An example of this long term procurement plan could be to guarantee a certain procurement rate until a reasonable stockpile is achieved. Then if the stockpile is not used, a guaranteed minimum amount of funding will be allocated to maintenance, testing, and retirement of the stockpile. This funding level may be significantly less than the development and procurement funding, but would have to be sufficient to keep a minimum of facilities and employees that specialize in the given technology. Then after some amount of time the decision can be made to refill the stockpile and have another procurement batch, or to entirely decommission the technology element from the government's portfolio.

KEY POINTS

- *The potential for a technology's use by non-NASA customers represents a potential increase in demand for the technology element.*
- *Increasing demand reduces the procurement price and Life Cycle Cost of a technology element. As a result this factor is integrated into the technology Life Cycle Cost proxy developed in Chapter 3 of this thesis.*

3 PROBLEM FORMULATION

3.1 CHAPTER OVERVIEW

The transportation system for human space exploration beyond Earth orbit is complex, necessitating a series of steps in order to perform the analysis presented throughout this thesis. This chapter provides a clear definition of the problem at hand and lays out an approach for modeling. Chapter 4 will then provide a framework for the relevant analysis that will support the accompanying recommendations. This chapter is explicitly dedicated to the relevant problem formulation and tradespace exploration methodology since results are sensitive to the embedded assumptions required throughout. The three major aspects to the analysis in this thesis (and to any architecture analysis) are problem formulation, tradespace exploration, and sense-making or the extraction of information from the analysis. The first two of these aspects will be broken down in detail in this chapter and the approach to sense-making will be covered in Chapter 4.

Figure 3-1 Major tasks in understanding architecture anaylsis

Note that at this high-level view of the methodology in question there are no specific tasks related to technologies. Throughout each subsection technology-specific architecting methodologies will be highlighted, however the overall methodology is intended to capture the dynamics relevant to understanding the impact of any arbitrary aspects of system architecture definition.

3.2 DEFINING TECHNOLOGY

In system architecture design, a technology has several defining aspects that make it a distinct alternative for inclusion in the system. Individual technologies can be specific products, processes, or techniques used to fulfill functional requirements in architecture. For the purposes of this work, there is no particular restricting definition of what a technology can be. However, to do useful analysis that allows a system architect to compare different technologies, there are some properties that a technology must have.

- Technologies must have an expected performance relevant to the definition of the system or they must change the performance of other system elements. For example different propulsion types will have different specific impulses (a variable that influences performance). A counter-example would be a technology that improves imaging capability. While important to consider for future exploration missions, this technology will have no relevant influence on the overall transportation infrastructure definition being considered. More precisely, technologies must influence the metrics by which architecture is evaluated.

- Technologies must have some measurable cost or resources required to include them in architecture. It is hard to imagine a performance-enhancing technology consisting of elements and/or processes that have no cost to implementation. Costs will be related both to development work that may be required to increase the readiness of the technology as well as operational costs associated with the operation of the system in the future.

- Other considerations for technologies may include various constraints that come with specific architectural features or other technologies. For example a technology that influences liquid hydrogen only, will be incompatible with propulsion systems that do not use liquid hydrogen.

When defining the parameters of technologies in consideration, it is important to understand the uncertainty that is associated with technology development. Some technologies considered have significant flight history and their performance can be predicted with extremely precise parametrics or other modeling techniques. Meanwhile other technologies have only been tested in simulated environments or have only ever existed as a theoretical design. The realized performance and cost of these early stage systems will be far more uncertain than existing technology capabilities and may deviate from expected values as they are developed over several years. From a decision-making perspective methods for optimizing development effort in the face of this uncertainty is a field that has been considered heavily in the literature described in Section 1.2.3. For the purposes of this thesis performance values are taken to be static and uncertainty of cost and performance variables is not considered. This simplification of technology performance is sufficient to understand the overall impacts of technologies at the system architecture level; it does not provide the capability for system optimization where much more detailed understanding of the subsystems would be required.

3.3 PROBLEM FORMULATION

3.3.1 OVERVIEW

By defining all the relevant sub-problems related to the system at hand, the first major task from Figure 3-1 is fulfilled. This is shown conceptually in Figure 3-2 below. The output of the problem formulation step is the formal definition of all architectures. This defines the possible enumerated tradespace or domain of the problem.

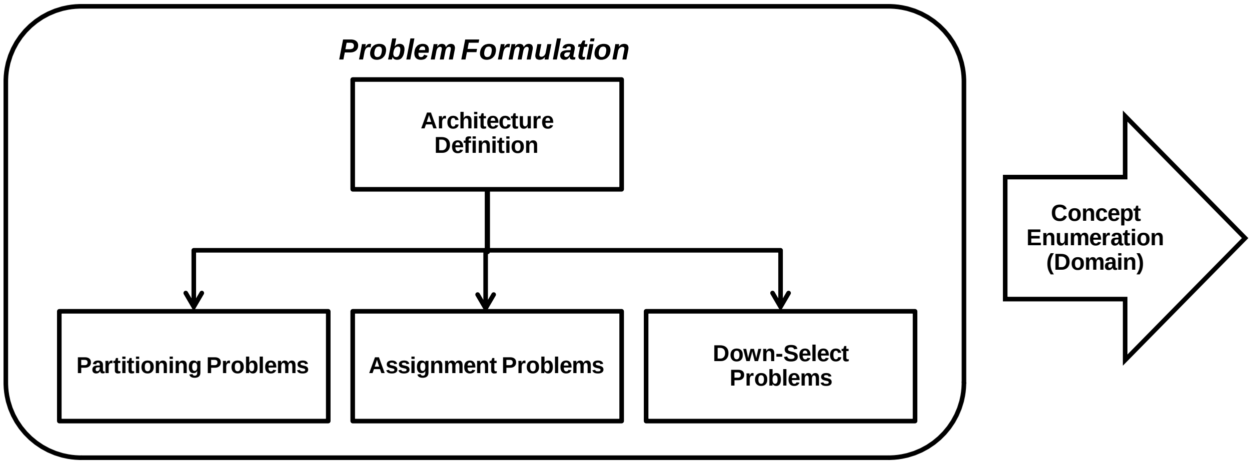


Figure 3-2 Overview of problem formulation with System Architecture Problem (SAP) classes applied in this thesis

The scope of the system considered in this thesis is space transportation for human exploration beyond low Earth orbit. As stated in the first chapter, the driving goal of this thesis is to understand the various interactions between technology development projects and the system architecture for space transportation systems. This means that in addition to exploring the wide tradespace that includes various technologies, the definition of an architecture must distinguish between the different possible habitat configurations and various propulsion staging options that must be defined to accomplish mission goals.

The model developed in this thesis is designed to capture the performance of space transportation systems. Given the complexity of architectures considered, it is useful to set up the problem to any arbitrary destination as an iso-performance analysis as described in . As applied to this thesis, iso-performance means each specific destination has an associated mission profile including crew size, surface duration, and payload capability. Set constant, these parameters fix the science and exploration benefits for all architectures considered. Metrics that are used to determine the influence of various system parameters are then focused on different aspects of the cost or efficiency to achieve the same goal. These metrics are influenced by all the other variables that define system architecture that are considered in the tradespace exploration.

Determining exactly which variables and metrics are required to define the system in consideration to the granularity necessary to distinguish between architectural configurations is a non-trivial problem. In this section the language and notation of Object-Process Methodology (OPM) are used to communicate the functions the system performs and elements that compose the system. OPM is not necessary to define the problem, but a useful tool providing a consistent grammar and framework for describing architecture. The basic OPM symbols that will be used are shown below for reference in Figure 3-3.

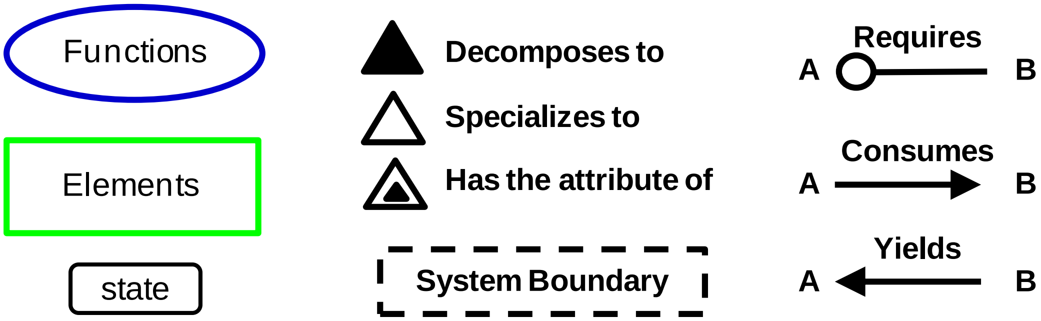


Figure 3-3 Basic OPM Symbols used in the chapter

The overall purpose of the system in consideration is to enable future human space exploration. This exploration system has three primary functions: providing habitation to people, transporting people and cargo, and interacting with the destinations being explored. When these three functions are fulfilled exploration is achieved. The scope of the system under consideration does not include a treatment of the payload or exploration equipment required; it is restricted to considering the system that transports people from Low Earth Orbit (LEO) to other destinations. The goal will be to capture the most important features in the design space of a system that transports people to destinations and is able to keep them alive.

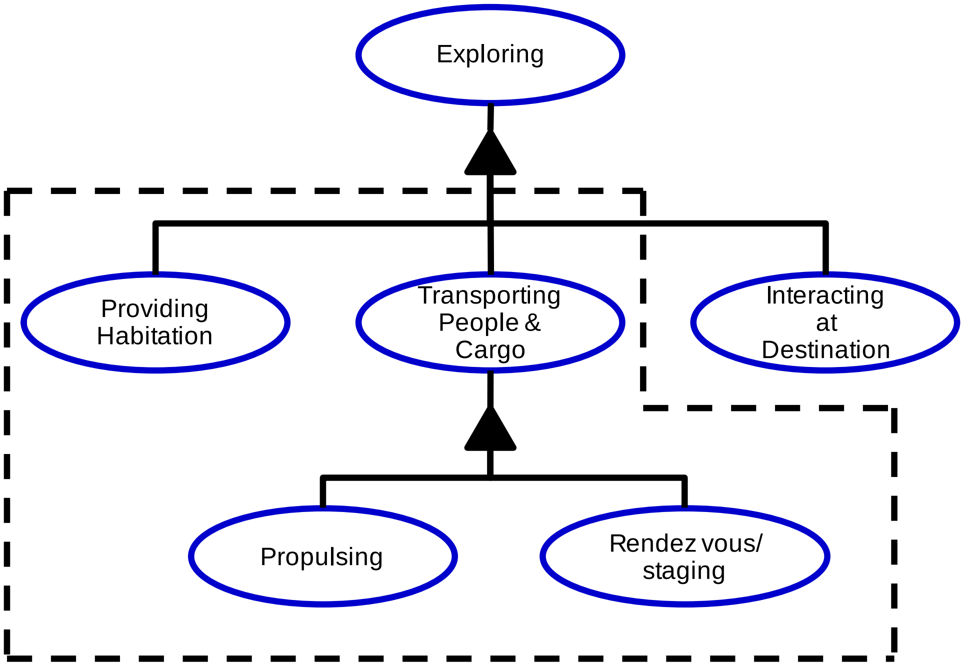


Figure 3-4 Primary functions of the exploration system

Figure 3-4 shows a decomposition of the functions considered in the system. This means each architecture must provide the functions that reside within the dashed system boundary line. At the level of fidelity considered in this thesis providing habitation is not decomposed into more detailed functions (such as various aspects of life-support systems). The transporting function is fulfilled by two sub-functions that come from the actual impulsive propulsion maneuvers and the capability to re-configure elements via rendezvous or staging maneuvers. It is important to note that by leaving the "Interacting at Destination" function out of consideration, architectures where payload and transportation are tightly integrated may not be treated properly. For the Moon and Mars this is most likely not an issue as the deep gravity well at those planets drives a surface system that behaves as a module separate from in-space transportation. For low-gravity bodies (NEAs) architectures such as "hoppers" may use in-space transportation elements for the interaction function. In future work, it may be worth considering details of the surface interaction systems alongside the transportation and habitation systems for these small-body destinations.

To model different architectures these fundamental functions break down into several distinctly different sub-problems that must be combined to define a single architecture. In a taxonomy is proposed to describe different classes of System Architecting Problems (SAP). In this thesis the overall transportation architecture is defined by the combination of several sub-problems that fall into different SAP classes. To capture the various aspects of architecture included in this thesis, the relevant classes of SAP's are:

- ***Partitioning problems*** assign multiple items to a single bin. In the scope of this thesis, a single partitioning aggregates groups of functional requirements to define the requirements specific to each formal element. These partitions define the overall number of elements as well as the requirements that each element of the system must meet. A formal definition and techniques for solving set partitioning problems is treated in .
- ***Assignment problems*** are used to select a single alternative out of several when the choice is exclusive. This is appropriate for decisions where exactly one (and only one) alternative must be selected.
- ***Down-selection problems*** are used to indicate the presence (or lack thereof) of a technology alternative. There is no exclusivity between different technologies (the inclusion of one does not exclude others) so each is its own binary decision with two possible assigned alternatives- on or off. Those technologies selected, or set to "on," define the basket of technologies required for any given architecture.

3.3.2 PARTITIONING PROBLEMS

In Figure 3-4 the two primary sub-functions of the exploration system are providing habitation and transporting people and cargo. These problems have some fundamental characteristics that make them well-suited to a partitioning problem. In the overall exploration transportation system, each of these functions must always exist through a network of destinations and orbits. Every mission will always go through a pre-defined set of points in this network and habitation and transportation will be necessary through each intermediate connecting leg of the journey.

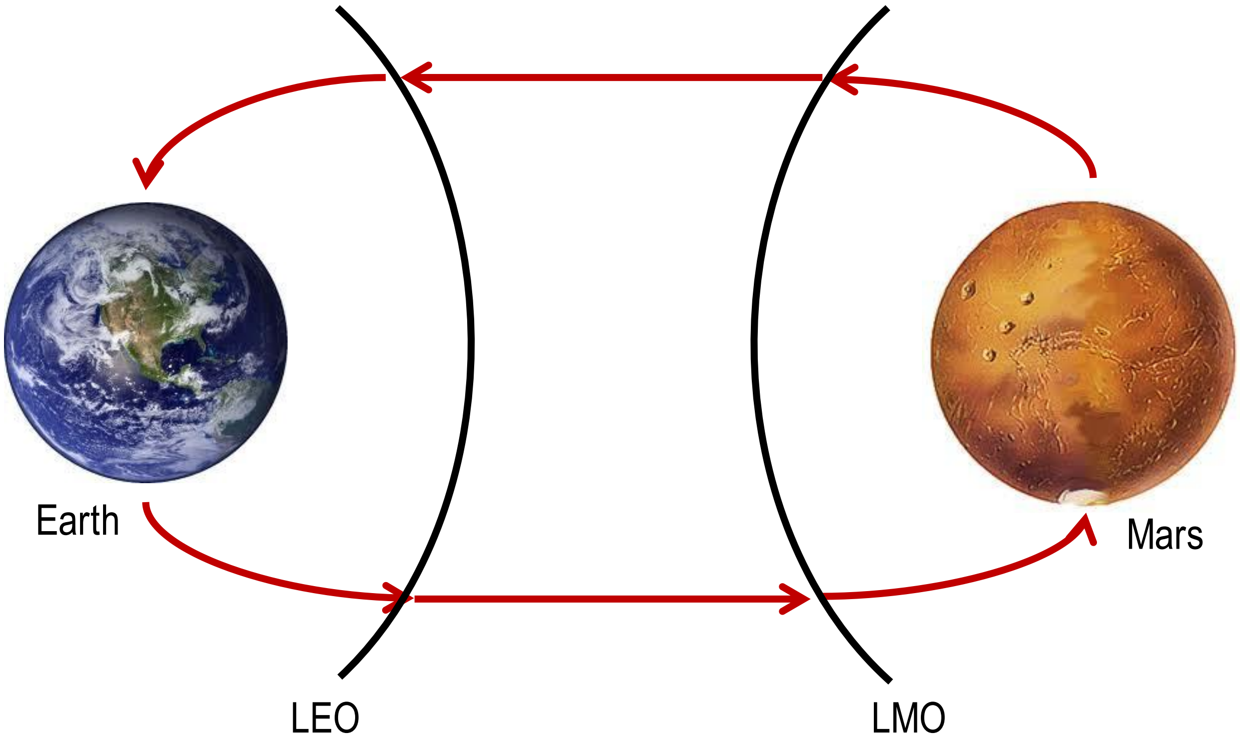


Figure 3-5 Representation of Mars transportation mission segments

An example of the network nodes and edges are shown in Figure 3-5 for Mars above. Each arrow in red represents a leg of the journey that requires a propulsive maneuver. Each location (Earth, LEO, LMO, and Mars) represents a location where stages and payload can be reconfigured.

For sizing the habitat elements of the system it is necessary to define the various environments and conditions that would influence the habitat design. It can be said that the function of providing habitation specializes into seven distinct mission segments that must be accounted for throughout the mission.

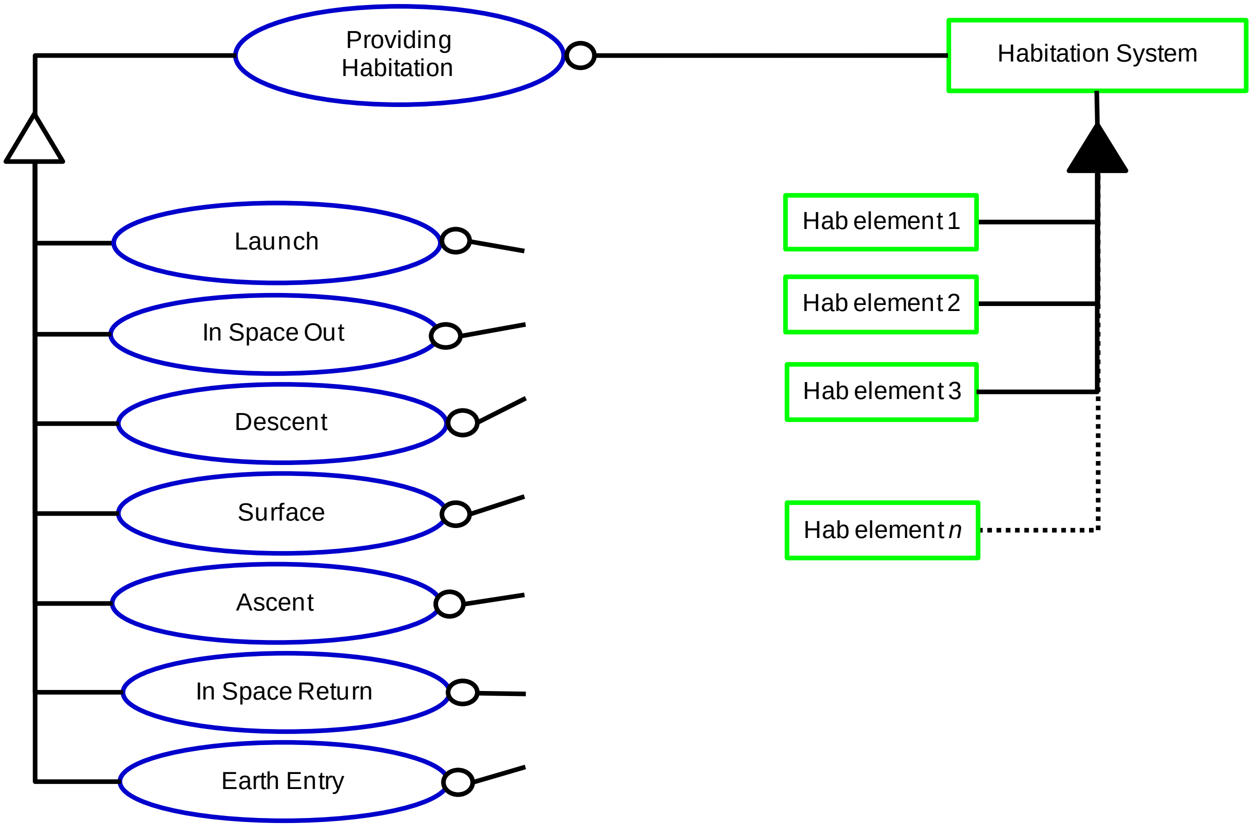


Figure 3-6 Habitation function partitioning problem with unspecified form-function allocation

The list of specialized habitation functions is displayed in Figure 3-6. Here it is shown that the function of "providing habitation" requires the physical elements that constitute the overall habitation system. The physical habitation system decomposes into specific habitat elements. This figure excludes the exact allocation of habitation functions to an arbitrary number of habitation elements. Each of the habitation functions must be fulfilled by a habitat element exactly once. Any given habitat element may perform a single function (mission phase) or multiple habitation functions. The allocation of each specialized habitation function to an element will define the driving design requirements for each of the habitat elements. As previously stated, this is a set partitioning problem since each function must be assigned exactly once.

Similar to the habitation problem, the transportation system specializes into a series of maneuvers that must be performed for every mission. The list of six transportation functions (the major propulsive maneuvers) is shown in Figure 3-7.

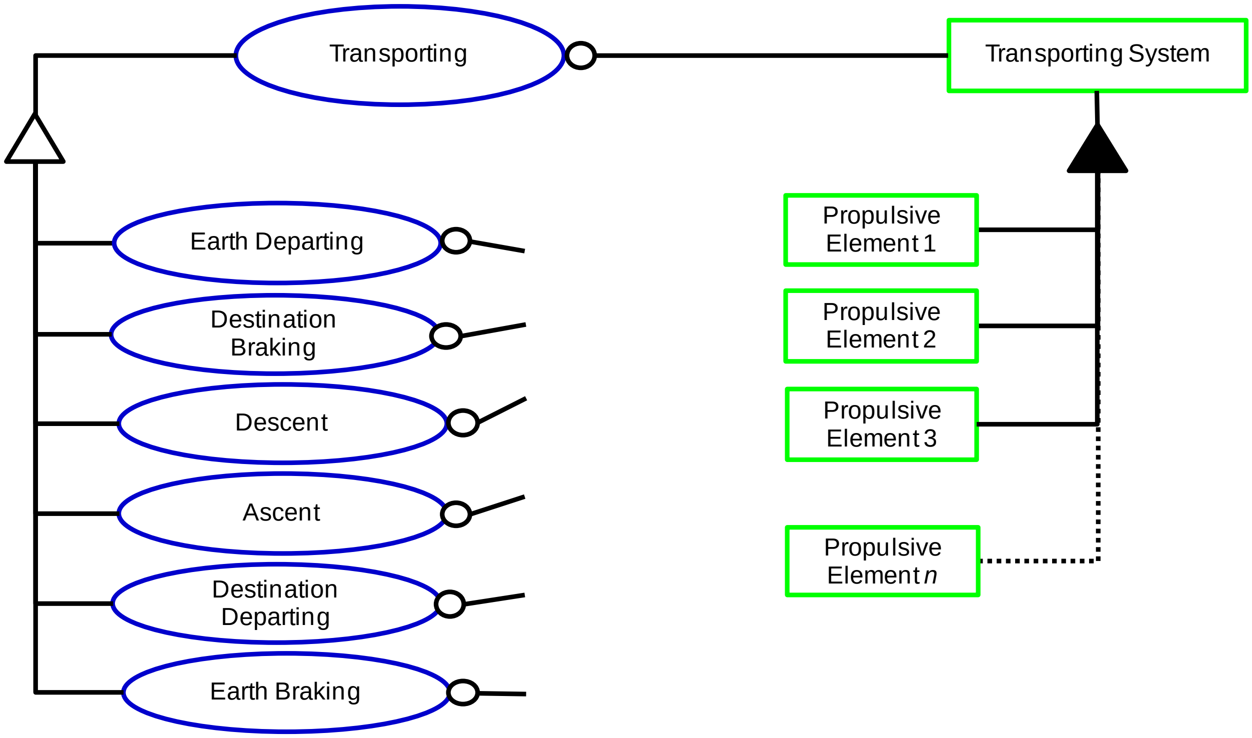


Figure 3-7 Transportation function partitioning problem with unspecified form-function allocation

Just like the habitation function partitioning problem, any given propulsive element (rocket stage) may be required to perform a single delta-v maneuver or multiple maneuvers. The other sub-function to "transporting," re-configuring stages in rendez-vous and separation, is defined inherently once the partitioning of the maneuver functions is complete. This framework allows a single element to perform multiple maneuvers, but does not suggest that multiple elements (stages) will be used for a single impulsive maneuver. While this introduces some inefficiency in the system, this level of optimization is left to future more detailed system design activities.

Defining the form-function partitioning problems for habitation and transportation is the first step in defining a single system architecture for transporting people to the surface of an exploration destination. Now that a list of habitat and transportation elements with functional requirements has been defined, other decisions must be set that define how these functional requirements will be met; that is to say what technologies will be implemented that determine the performance and cost characteristics of each of these elements.

3.3.3 ASSIGNMENT PROBLEMS

Selecting the destination for the transportation system is a good example of a general assignment problem. The question of which rocky body is the ultimate destination for an exploration mission (as defined by the scope of this analysis) is a single selection. There are several possible destinations to choose from and a single mission will be defined to go to exactly one of them. Each mission must have exactly one destination.

In addition to destination selection, all propellant type decisions are assignment problems. In theory, for any given major propulsive maneuver a number of propellants can be selected. For the purposes of this model the selection has been restricted to a few logical alternatives. These alternatives are listed further on in the section in Table 3-5.

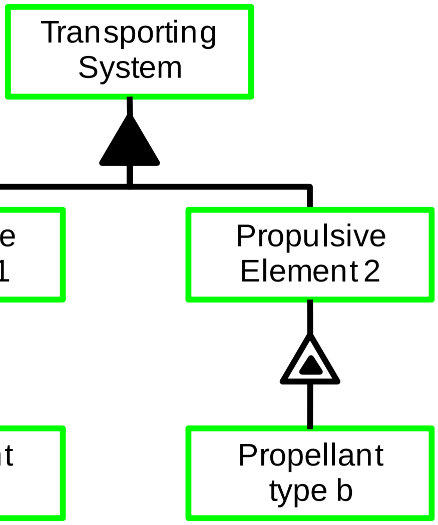


Figure 3-8 Propellant type assignment problems define the attributes associated with propulsive elements

Figure 3-8 shows exactly what is defined by the propellant type assignment decisions. Each unique propulsive element in the system has the attribute of "propellant type." Each propellant type will then have distinct parameters that define the performance of that given propulsive element. The requirements for the element are defined by the partitioning problem already described. This propellant type assignment problem defines exactly how those functional requirements are met.

The first important aspect of assignment problems is that one alternative must be selected- otherwise attributes of the system remain undefined. The second important aspect of selection problems is that the selection is exclusive, meaning no more than one set of attributes can be defined for the associated element.

3.3.4 DOWN-SELECTION PROBLEMS

There are several technologies that can be applied to the system architecture, but are not fundamentally required for the definition of a system. These are non-exclusive technologies that can either be included in the system or not. From a modeling perspective, these technologies assume a binary state- either on or off. In reality, a system architecture utilizing new technologies requires an available stream of funding to develop these capabilities. A given architecture will have an associated basket of the available technologies applied to it. A down-selection must be made ranging from no technologies to the inclusion of all possible technologies. These technology decisions influence architecture in two ways. They may modify the parameters that define certain architectural elements, or they may introduce new functions and elements that must be considered in the architecture.

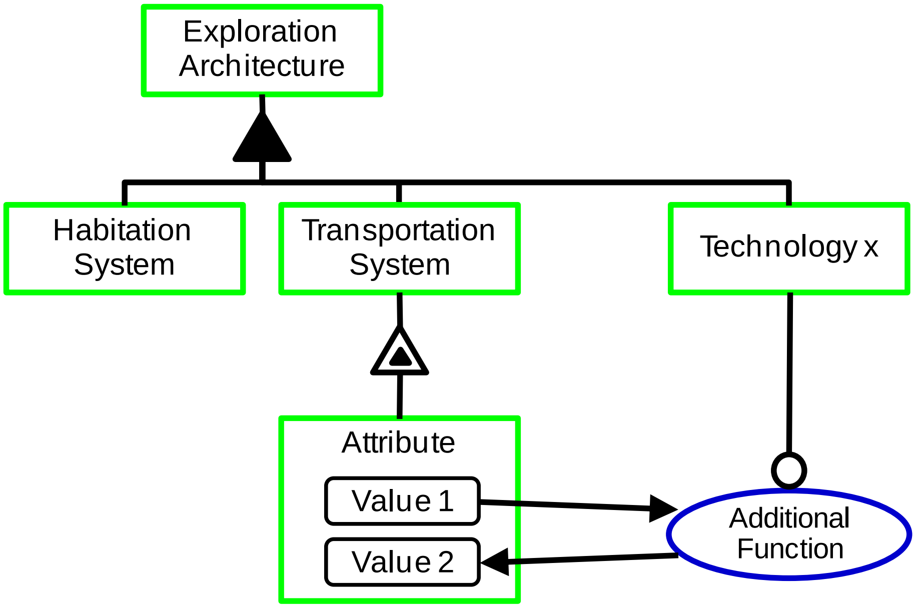


Figure 3-9 Technologies within a down-selection problem modify attributes that influence performance

A typical interaction with a selected technology is shown in Figure 3-9. A technology is introduced to the system architecture that must be accounted for with a new system element. This technology may introduce new additional functions that then change attributes in various aspects of other system elements. The changes in attributes and the additional technology element will all influence the metrics that are used to evaluate the architecture as a whole system.

Technologies in the down-selection problem can be arbitrarily included in an architecture without constraints between each other and so are considered non-exclusive. The specific influences of each binary technology considered are described in more detail in Section 3.5.

3.3.5 SUB PROBLEM SUMMARY

When taken all together, the various partitioning, assignment, and down-selection sub-problems define a single transportation architecture to a single destination. The list of sub-problems can be thought of as a set of decisions, each of which defines different aspects of the mission's architecture. This list is shown in Table 3-1.

Table 3-1 Sub-problems in the definition of an architecture

Architectural Sub-Problem	Problem Type	# of Alternatives
Destination	Assignment	4
Habitat Element Definition	Partitioning	120
Propulsive Stage Definition	Partitioning	776
Trans-Destination Propellant Type	Assignment	3
Descent Propellant Type	Assignment	3
Ascent Propellant Type	Assignment	3
Trans-Earth Propellant Type	Assignment	3
Pre-deployment of cargo	Down-select	2
Boil-off control technology	Down-select	2
ISRU technology	Down-select	2
Aerocapture technology	Down-select	2

Each of these decision sub-problems represents a feature that distinguishes different transportation architectures from each other. Each decision will influence the metrics that are used to evaluate the system. Any system parameter required to define a transportation architecture that is not explicitly covered by the listed decisions must be defined as a fundamental modeling assumption across all architectures.

KEY POINTS

- *Defining the exploration transportation system architecture requires several distinct different sub-problems. Each of these decisions must be defined to describe a single architecture.*

3.4 ASSUMPTIONS REQUIRED FOR EVALUATING ARCHITECTURES

3.4.1 OVERVIEW

In developing a quantitative model to evaluate an arbitrary system architecture as defined by the list of decisions enumerated in the previous section, several fundamental assumptions are set early on that apply throughout the analysis in the following thesis. Systematically cataloging these assumptions is important as they define the scope of the results and recommendations of this thesis. The assumptions listed here are consistently applied across analysis to each destination. Other destination-specific assumptions and constraints are listed in the relevant sections in Chapters 5 and 6.

3.4.2 MISSION TYPE ASSUMPTIONS

Assumption: Destinations must be rocky bodies such as Mars, Moon, and NEAs as opposed to astrodynamically stable orbits such as halo orbits at Earth-Moon Lagrange points or geostationary orbit with no physical surface.

The overall value of an exploration campaign comes from science and exploration needs. Non-physical destinations may provide engineering benefits for exploration preparation in precursor and demonstration missions, but should not drive the overall system architecture definition.

Assumption: There is no consideration of re-use of assets across multiple missions. For the purposes of this analysis, after an element is used and no longer needed it is "discarded."

The analysis presented in this thesis considers the definition of a single mission at a time and the impacts of various technologies on the performance of that mission. It is outside the scope of this thesis to consider a campaign of multiple missions.

Assumption: Solar Electric Propulsion (SEP) is used for pre-deployment of cargo only. All crew must be placed on high thrust impulsive propulsion systems.

It is assumed that SEP systems will be used similarly to most proposals in existing reference design missions. These reference missions usually use SEP to pre-deploy cargo on low-thrust trajectories with times of flight significantly longer than impulsive chemical or nuclear propulsion. It is assumed the increased health risk to humans associated with these significantly longer flight times would be unacceptable for this increased deep-space exposure.

Assumption: The crew must be part of the last "stack" or group of elements to depart low Earth orbit.

Assuming at the level of detail considered all elements are mission-critical it should not be possible for the crew to depart from low Earth orbit and have other elements they rely on fail. This means the propellant for a return stage must be able to be stored for at least the duration of the time-of-flight of the crew (and possibly longer if the element is pre-deployed). If the crew is part of the last "stack" to depart LEO, all other elements will either have been pre-deployed and checked out prior to crew departure, or will be on the same trajectory at the same time.

3.4.3 MODELING IMPLEMENTATION

Habitat Sizing

At the high level of abstraction required, rough habitat sizing is only determined by the relevant environmental functional requirements as defined by the set partitioning problem previously described. A coarse parametric model is built for each relevant mission segment, to each destination, that defines the habitable volume requirements for a given crew and time of flight. This value is then converted to a total habitat mass and volume based on similar data drawn from historical crew-carrying systems and proposed habitat designs from reference missions. Habitats with shorter duration life support systems scale as a function of time of flight and crew size since the life support system capability is a driver for the overall system size. Long duration habitats are driven by a human factors requirement for sufficient habitable volume per crew.

One of the fundamental assumptions embedded in this model is that there is no additional penalty for using a habitat through multiple mission segments. The assumption is that satisfying the most stressing conditions on the habitat will also fulfill the requirements of less significant segments of the mission. There are additional mass considerations for spare parts reserve and daily crew provisions and logistics.

Table 3-2 Habitat parametric sizing drivers

Life Support System Duration	Parametric Inputs	Parametric Outputs
Less than 6 months	Crew size, duration	mass, volume
6 months or greater	Crew size	mass, volume

Table 3-3 Habitat parametric sizing data sources

Type of Habitat	Parametric Data Sources
Short duration/ascent/descent	Mercury capsule, Gemini capsule, Apollo Command Module, Apollo Lunar Module
Long duration- deep space	ISS modules, Skylab
Lunar Surface	Apollo Lunar Module, Constellation Altair
Mars Surface	NASA DRA 5.0, non-NASA reference:

Rocket Stage Sizing

The size of any rocket stage is governed by the Tsiolkovsky rocket equation. The assumption of the rocket equation is that a change in velocity occurs with an impulsive expenditure of propellant from a rocket. We assume that the structural mass of the rocket stage will scale as a ratio of the propellant mass and is characteristic for each propulsion type. Specific impulse is similarly defined as an attribute for each propellant.

Equation 3-1 Tsiolkovsky rocket equation

$$\Delta v = g \times I_{sp} \times \ln \frac{m_{pay} + m_s + m_{prop}}{m_{pay} + m_s}$$

Equation 3-2 Definition of structural mass ratio

$$\xi = \frac{m_s}{m_s + m_{prop}}$$

Equation 3-3 Propellant lost to boil-off

$$m_{loss} = m_{prop} \times (1 - e^{-rt})$$

Table 3-4 Propellant stage sizing variables

Symbol	Description	Units
Δv	change in velocity	m/s
g	gravitational constant	m/s^2
I_{sp}	specific impulse	s
m_{pay}	payload mass	kg
m_s	structure mass	kg
m_{prop}	propellant mass	kg
m_{loss}	propellant mass lost to boil-off	kg
ξ	structural mass fraction	-
r	boil-off rate	%/day
t	time	days

When a rocket stage must perform multiple maneuvers with different payloads, the rocket equation does not provide an explicit solution for propellant mass. There is an additional complexity of accounting for boil-off of cryogenic propellants. An iterative solver is implemented that treats excess propellant and dry mass as payload until the stage size converges. This solver is shown schematically in Figure 3-10.

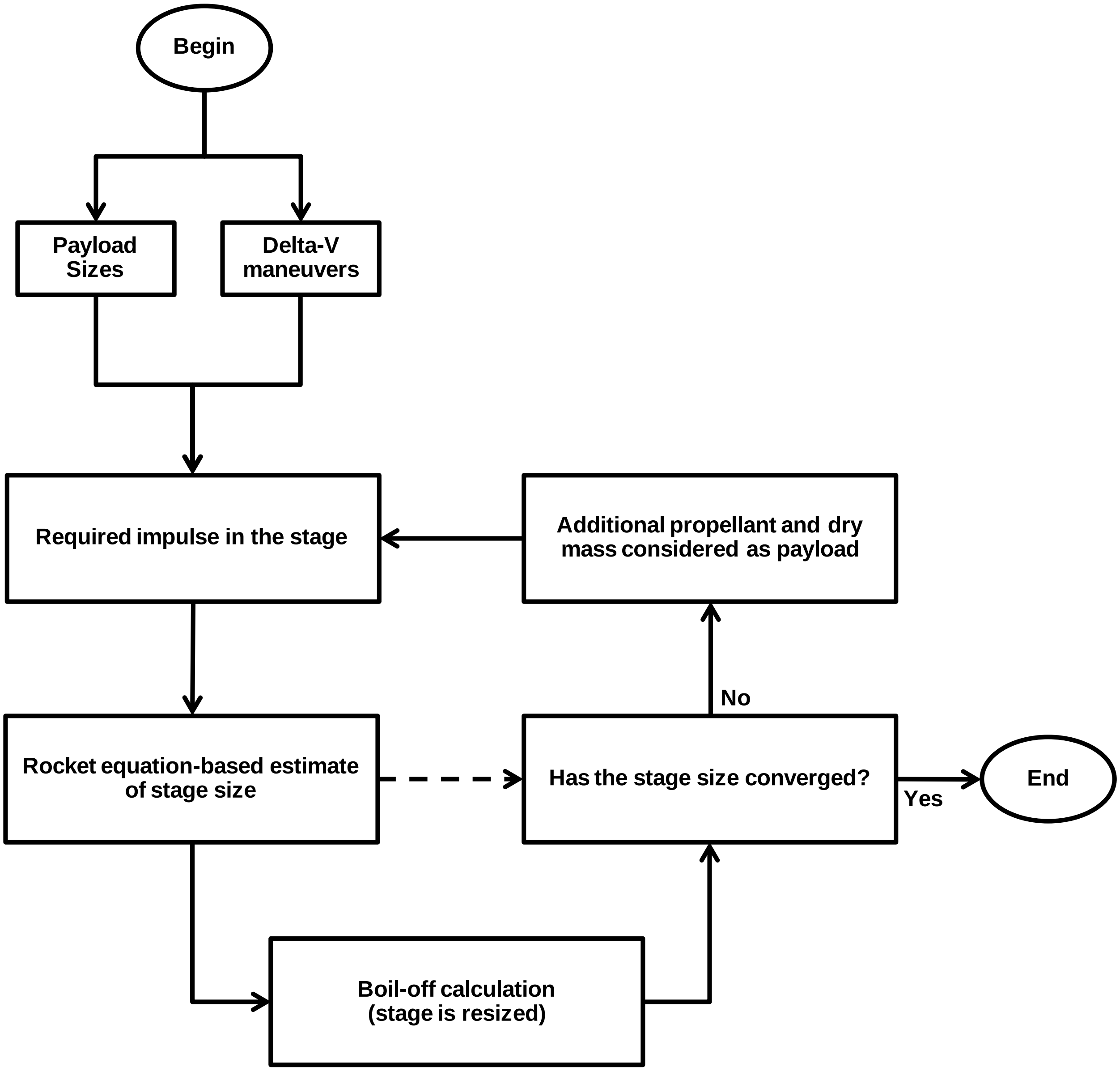


Figure 3-10 Iterative solver for rocket stage sizing

The delta-v requirements for various impulsive maneuvers are aggregated from multiple sources including , , and .

3.5 TECHNOLOGY ALTERNATIVES

Several technologies are included in the tradespace. They all have various performance parameters and influences on the system architecture. It is important to understand how to include the most simple definition of these technologies in the modeling environment so that they are simple enough to capture important behavior, but do not require detailed subsystem modeling that greatly increases the cost of architecture evaluation (in terms of computational complexity). Each technology has been reduced to the basic characteristic interactions that encode the essential complexity information of the system, while being modeled fairly easily. These interactions are documented in the following section.

3.5.1 PROPULSION TECHNOLOGIES

Some constraints are placed on the availability of propulsion technologies for individual maneuvers. For example it is clear that a low thrust propulsion system will not be capable of descent and ascent maneuvers where thrust to weight ratio must be greater than one. The propulsion alternatives for each major mission segment are shown in Table 3-5 below.

Table 3-5 Propulsion alternatives for each major mission segment

Trans-Destination Maneuvers	Descent	Ascent	Trans-Earth Maneuvers
LOX-LH2	LOX-LH2	LOX-LH2	LOX-LH2
LOX-CH4	LOX-CH4	LOX-CH4	LOX-CH4
NTR	Storable Hypergol	Storable Hypergol	NTR
SEP (Cargo Only)			

Cryogenic propellants are viable possibilities for all major mission segments. It is assumed the low thrust SEP system would only be used for pre-deploying cargo as the long time of flights result in unacceptable human health risks due to radiation exposure. It is assumed that storable hypergolic propellants will have unacceptably low performance for the high impulse in-space maneuvers and are only considered for descent and ascent. Details on each propulsion type are given in Table 3-6 below.

Table 3-6 Propulsion type parameters

Storable Hypergol: NTO/MMH	
Specific Impulse (I_{sp})	324 s
Dry mass ratio (ξ)	0.1
Constraints	Only available for descent and ascent
Readiness	Significant flight history
Chemical: LOX-LH2	
Specific Impulse (I_{sp})	465 s
Dry mass ratio (ξ)	0.153
Constraints	None
Readiness	Significant flight history for in-space stages, detailed design of lunar descent stage for Constellation Program
Chemical: LOX-CH4	
Specific Impulse (I_{sp})	369 s
Dry mass ratio (ξ)	0.13
Constraints	None
Readiness	Demonstrated in-space engine
Nuclear Thermal Rockets (NTR)	
Specific Impulse (I_{sp})	950 s
Dry mass ratio (ξ)	0.23
Power plant mass	41.7 metric tons
Constraints	Only available for in-space stages
Readiness	Some development, nothing recent
Solar Electric Propulsion (SEP)	
Specific Impulse (I_{sp})	2000 s
Payload mass/power ratio (β)	.0394 (kg/W)
Electric Efficiency (η)	0.99
Constraints	Only available for pre-deploying cargo
Readiness	Significant flight history with lower power systems

3.5.2 AEROCAPTURE

Technology influence: Mass penalty is incurred by carrying a heat shield and there is a delta-v reduction in the orbit insertion or braking maneuvers at Mars and Earth.

Constraints: Aerocapture is used for Mars and Earth (planets with atmosphere).

Existing systems that use the Mars atmosphere to decelerate payloads have been implemented for terminal landing of robotic assets up to hundreds of kilograms. The assets considered in a human transportation system that must brake into a low-Mars orbit or perform terminal descent can be several metric tons. The most reliable sizing information for such a large aero-thermal deceleration system comes from detailed parametric sizing studies that have been developed specifically for large payloads at Mars. The performance and sizing of a rigid aeroshell system using Phenolic Impregnated Carbon Ablator (PICA) material comes from the relevant parametrics defined in and . Elements were constrained to be within the limits associated with this parametric analysis of around 300 m^3 and a total system mass of 110 metric tons.

3.5.3 PRE-DEPLOYMENT

Technology influence: Propulsive stages, habitats, and other cargo that are not required for the human transportation system out to the destination are pre-deployed on a more efficient SEP system.

Constraints: Crew can not be sent on the low thrust system. For Mars the time of flight of the trajectory must be within one Mars-Earth synodic period.

While the magnitude of impulsive delta-v maneuvers have been analyzed in several sources, the impulsive assumption that the rocket thrust duration is much shorter than the orbital period around a central body does not hold true for the long duration, low thrust trajectories associated with SEP. While detailed trajectory analysis for low thrust systems requires a numerical integration model, some simplifying assumptions can produce a simple model that is computationally trivial to evaluate while providing sufficient precision for the architectural analysis presented in this thesis. It is assumed the power and thruster systems can be scaled to match the required thrust to weight ratio of the thruster system. For sizing stages, the energy expenditure of a SEP system can be estimated and aggregated into a delta-v that would represent the equivalent stage size given a specific impulse. The low thrust SEP trajectory is assumed to be a 2-dimensional (planar) circular spiral with the thruster always pointed tangential to the circle of the current radius. This extremely simplified model captures the major orbital radius changes required for in-space maneuvering with the delta-v described by Equation 3-4.

Equation 3-4 SEP delta-v associated with orbital radius change

$$\Delta v_{SEP\ rad} = \sqrt{\frac{\mu}{r_0} - \frac{\mu}{r_f}}$$

As long as the acceleration due to thrust, a, is much lower than the acceleration due to gravity these circular approximations hold true. The ratio of these values, a non-dimensional term ε, is a measure of the relative strength of gravity at a given radius.

Equation 3-5 Relation of thrust to gravitational acceleration

$$\varepsilon = \frac{a}{\mu / {r_0}^2}$$

The assumption that ε remains small breaks down far from the central body being considered. To extend the model to define the energy required for escape trajectories, an estimate of delta-v to escape must be defined when ε is larger. By calculating the energy numerically for a few points the delta-v as a function of ε can be computed as a parametric. The data points evaluated at various orders of magnitude of ε strongly suggest a dependency on its logarithm as shown on the semi-log plot in Figure 3-11.

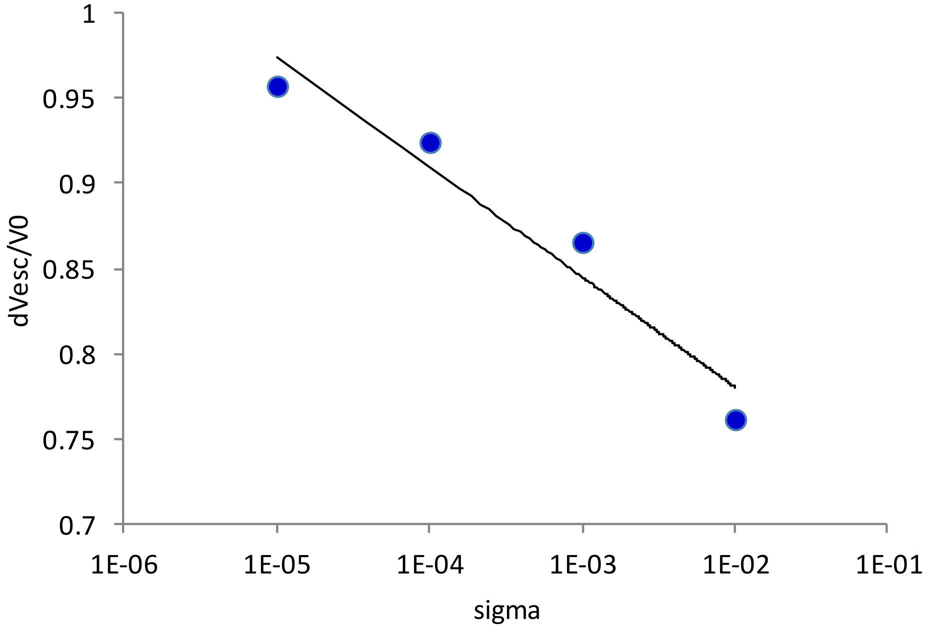


Figure 3-11 Parametric for low thrust escape delta-v

The equation of the fit curve is given by Equation 3-6.

Equation 3-6 SEP delta-v associated with escape maneuvers

$$\Delta v_{SEP\ esc} = v_0(-.028 \ln \varepsilon + .651)$$

The final delta-v's for evaluating the various missions consist of sums of radius-increasing maneuvers and escape maneuvers. The final delta-v values were validated against reference design missions such as .

Table 3-7 Parameters used in delta-v estimates for SEP

Symbol	Description	Units
μ	standard gravitational parameter	m^3/s^2
r_0	initial orbital radius	m
r_f	final orbital radius	m
ε	gravitational strength parameter	-
a	thruster acceleration	m/s^2
v_0	initial orbital velocity	m/s

3.5.4 IN-SITU RESOURCE UTILIZATION (ISRU)

Technology influence: Resource extraction plant and power plant dry masses must be descended to the surface. The ability to manufacture propellant for the ascent stage is gained.

Constraints: ISRU is only used for the ascent and stages combined with ascent. It is not available for the hypergolic propellants.

The desire to reduce the mass that must be launched from Earth drives designers to incorporate resource utilization at the mission destination into architecture definition. Use of destination resources for the creation of structural elements, extraction of water and air for life support systems, as well as the manufacturing of propellant have been considered. With the current focus on the transportation system, the only use of resources modeled and discussed in this thesis is for propellant production. The reactions and design of the power and production plants are covered in and .

Table 3-8 ISRU benefits

Ascent Propulsion Type	Available Resource	Manufactured % of Propellant
LOX-LH2	LOX from atmosphere	80%
LOX-CH4	LOX, CH4 from atmosphere and carried LH2	94%
Hypergolic Propellants	-	0%

3.5.5 BOIL-OFF CONTROL

Technology influence: Resulting increase in dry mass fraction, boil-off rate is reduced.

Constraints: None

There are both passive and active systems that can reduce the rate of cryogenic propellant boil-off. Since the requirements for in-space cryogenic propellant storage to date have been measured in hours rather than months, the design and performance of these systems remains highly uncertain. However in all designs there is some structural mass increase in the rocket stage to achieve lower boil-off rates. Specific structural mass penalties and performance are taken from and .

Table 3-9 Expected boil-off control performance

Propulsion Type	Boil-off Rate r [%/day] (no control)	Boil-off Rate r [%/day] (with control)
LOX-LH2	.314	.00301
LOX-CH4	.248	0
NTO/MMH	0	0
NTR	.621	.0178
SEP	0	0

3.6 TRADESPACE EXPLORATION

3.6.1 OVERVIEW

Once the architecture problem under consideration has been defined, and a model has been built that allows for evaluation of architectures, there must be an intelligent search process that populates a set of architectures worth considering. While ideally a full enumeration with all conceivable formulation of architectures would be used, the size of typical tradespaces and computational complexity of evaluation models rarely allows for full enumeration. A general overview of the tradespace exploration methodology applied in this thesis is shown in Figure 3-12.

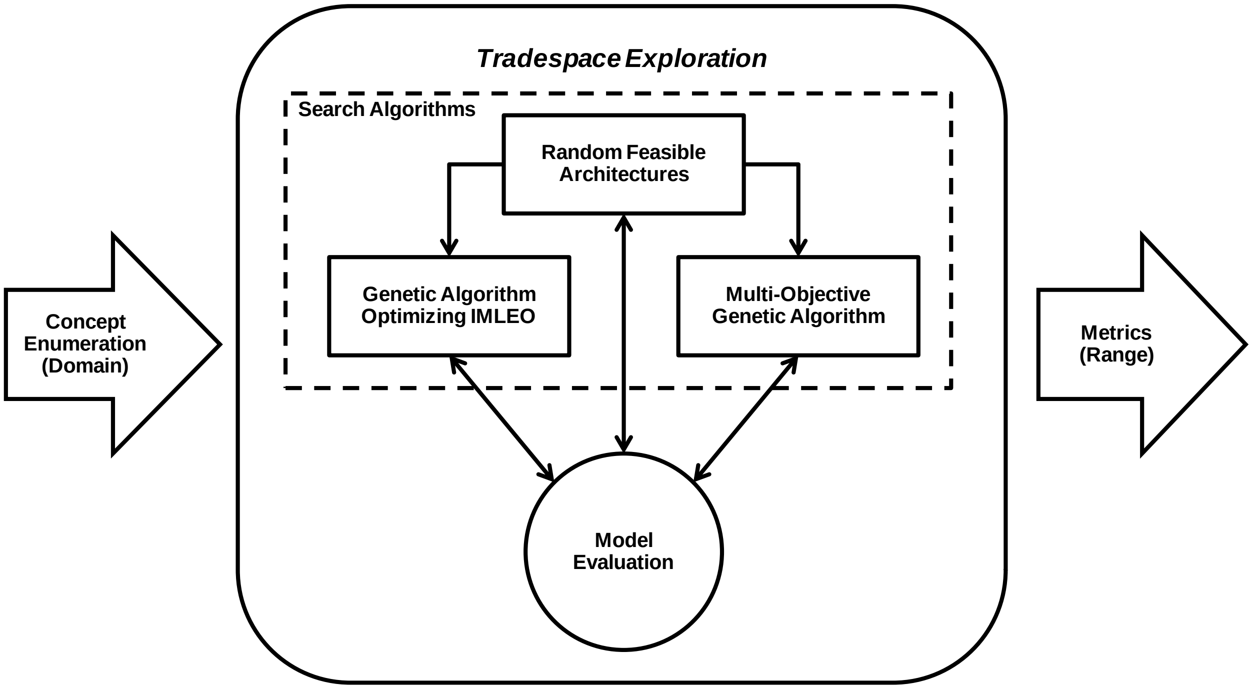


Figure 3-12 Overview of Tradespace Exploration with search algorithms applied in this thesis

Note that there are four distinct components to tradespace exploration.

1. The input to the process or the set of defined architectures, i.e. the domain of the problem
2. An architecture evaluation model, which is fundamentally required for tradespace exploration
3. A search algorithm (even if the search is as simple as full enumeration or completely random)
4. The population of architectures which is produced by the search algorithms or the output of tradespace exploration. This population has been evaluated with associated metrics and defines the range of figures of merit the architectures can achieve.

3.6.2 DEFINING METRICS

After understanding that the breadth of the domain, (design decisions) is covered it is necessary to consider the range that the tradespace covers. As previously discussed every system architecture is iso-performance. That is to say that they all deliver the same benefit of a crew of 4 to the surface of each given destination for a set amount of time. It is not useful then to discriminate architectures on the benefit they deliver but rather the cost or measure of resources it takes to achieve that performance. There are two simple metrics considered that capture different aspects of cost.

Initial mass in low earth orbit (IMLEO) is a proxy metric for recurring operational cost. Since all architectures deliver the same size crew for any given surface mission, this metric also relates to the efficiency with which this benefit is gained. IMLEO is the sum of the mass of everything required to complete the mission except the Earth launch vehicles. Equation 3-7 and Table 3-10 break down the masses considered.

Equation 3-7 IMLEO metric

$$IMLEO = M_{expl} + M_{hab} + M_{log} + M_{trans}$$

Table 3-10 IMLEO metric variables

Variable	Description
$\boldsymbol{IMLEO}$	Initial Mass in Low Earth Orbit (kg)
$\boldsymbol{M_{expl}}$	Mass of exploration equipment (including crew)
$\boldsymbol{M_{hab}}$	Mass of all habitats
$\boldsymbol{M_{log}}$	Mass of supporting logistics (spare parts, food, water, etc)
$\boldsymbol{M_{trans}}$	Mass of all propulsive stages (propellant and dry mass)

While minimizing IMLEO is a very simple objective function and does not capture anything about the relative complexity of the mission, it drives architectures that should be more affordable simply by the high-level concept that larger systems are more expensive.

The other metric considered for this high level architecture evaluation is a technology Life Cycle Cost (LCC) proxy (N_{tech}). It is an accounting system for the technology portfolio that must be developed to fulfill the requirements of a given architecture. N_{tech} is designed to account for both the development and operation of technology projects that does not rely on specific (and highly uncertain) Cost Estimating Relationships (CER). The fundamental assumption embedded in this coarse metric is that while uncertain, the cost of developing and maintaining a technology capability is driven by two factors: the readiness or availability of the technology which influences development costs, and the demand for the technology which influences the price at which the technology will be procured. The justification for this assumption is explained fully in Chapter 2. While N_{tech} does not provide any indication of absolute cost, the idea is to effectively create an ordinal ranking of different architectures considering the relative differences in resources it will take to realize and operate the technologies included in the system. This metric is calculated with Equation 3-8 and Table 3-11 below.

Equation 3-8 Technology Life Cycle Cost (LCC) proxy

$$N_{tech} = \sum_{i} C_i T_i$$

Table 3-11 Technology Life Cycle Cost (LCC) proxy variables

Variable	Description
N_{tech}	Technology LCC proxy
i	Index for each possible technology in the system
C_i	Cost coefficient (see Table 3-12)
T_i	Technology presence coefficient- 0 if the technology is not in the architecture, 1 if it is included

The values for the technology presence coefficients (T_i) are binary, assuming a 1 if a given technology is used in the architecture, and a 0 if it is not. The cost coefficients (C_i) are assigned based on the readiness of the technology and the potential for other users (a measure of demand) for the capability according to Table 3-12 below.

Table 3-12 Cost coefficients

	Technology has other users?	
	NO	**YES**
Low Readiness	1	.5
Relevant Demonstration	0.667	0.333
Existing Capability	0.333	0.167

As explained in Chapter 2 the technology LCC coefficients are driven by a measure of readiness and demand for the technology. In this simple cost proxy accounting system, both factors produce a linear influence on the system. The readiness variable is an extremely simplified version of the NASA TRL described in Section 1.2.3, considering only three categories of technologies- low readiness, demonstrated, and existing. Recalling the previously defined sub-problems, the list of technologies available for the system is derived from both the down-selection of technology decisions and the propellant type assignment decisions. The following table lists the available technological capabilities that can be included in the tradespace to any of the enumerated destinations. The justification for the resulting cost coefficients is based on Table 3-12 above.

Table 3-13 Technological capabilities and cost coefficients

	Description	Readiness	Other Users?	C_i
In-Space Propulsion	NTR	Low	No	1.0
	LOX-LH2	Exists	Yes	0.167
	LOX-CH4	Low	Yes	0.5
	SEP	Demoed	Yes	0.333
Descent engines and stage	LOX-LH2	Low	No	1.0
	LOX-CH4	Low	No	1.0
	Hypergol	Exists	Yes	0.167
Ascent engines and stage	LOX-LH2	Low	No	1.0
	LOX-CH4	Low	No	1.0
	Hypergol	Demoed	No	0.667
	Boil-Off Control	Low	Yes	.5
	ISRU	Low	No	1.0
	Aerocapture	Demoed	Yes	0.333

To find architectures that are relatively efficient with respect to both defined objective functions, the operational cost proxy (IMLEO) and technology LCC proxy (N_{tech}), it is necessary to capture both relevant influences in a search algorithm that uses all relevant objective functions. Assuming a tradeoff exists between the two objective functions, a search algorithm that only minimizes one metric will almost certainly produce architectures that perform poorly by the other metric.

3.6.3 TRADESPACE SEARCH ALGORITHMS

Considering the combinatorial space of the various sub-problems, each destination in consideration has approximately 120 million logically feasible distinct system architectures. While technically feasible it is wholly impractical (costly in time and/or computing resources) to fully enumerate every single architecture to every single destination. Since the goal of the analysis is to optimize two objective functions, and understand how different variables influence the tradespace, it is not necessary to fully enumerate all architectures provided some intelligently selected heuristic methods are implemented in the tradespace exploration.

The "solution set" that will be used for understanding the influence of various architectural parameters is a combination of three populations of architectures produced with different algorithms. Due to the sensitivity to certain parameters, large parts of the tradespace are completely infeasible. Either certain parameters can not be combined or their performance is so poor the rocket equation-based stage size calculator does not converge to a steady value. Selecting completely random architectures by putting in variables for each sub-problem results in approximately 1 architecture in 10 being feasible. Genetic algorithms do not perform well when large parts of the tradespace are completely infeasible with small pockets of the tradespace with good performance. Since the majority of every population would not have objective functions defined using truly randomly selected variables, it is difficult to mutate or cross-over parameters from one population of architectures and produce more feasible architectures, let alone better performing architectures. While changing the frequency of feasible architectures within the model would require a re-formulation of the problem, simply guaranteeing the heuristic methods begin with a diverse and fully feasible initial population provides much better results that converge with a reasonable population size and number of generations. Thus the first search algorithm used in the tradespace exploration is a completely random search that saves only feasible architectures. A large list of feasible architectures that covers the various alternatives for all variables is then used as input as the initial population for more intelligent population-based heuristic search methods. Without reformulating the problem, this allows an otherwise difficult problem to converge without significant computing resources. A description of all three search methods follows:

Random Search

> As previously described a random search populates a list of feasible architectures. This is necessary to fully cover the domain of the problem and seed the heuristic search algorithms with varied feasible architectures.

Single-Objective Genetic Algorithm

> The first heuristic search is performed as a single-objective genetic algorithm. Taking random samples from the feasible random search dataset as an initial population, this GA seeks to minimize IMLEO. This objective is taken alone since mass reduction is considered to be of high importance when defining exploration architecture. This provides more insurance that a true IMLEO minimization has occurred and allows for understanding how far off mass-optimal the system is when a tradeoff is made for cost and risk in the technologies used in "good" architectures.

Multi-Objective Genetic Algorithm

> The multi-objective GA is run similarly to the single-objective GA, except it considers both cost proxies. In this implementation of GA an "elite" subset of each population is defined as the architectures that must be passed on to the next generation. The property of being "elite" is defined by being on a Pareto frontier defined by minimizing both development and operational cost proxies.

After running all three search algorithms the unique architectures from the integration of all three sets of feasible architectures defines the tradespace to be considered. Running the algorithms multiple times and finding steady answers to both minimum IMLEO and Pareto-optimal architectures suggests the important part of the tradespace is being efficiently explored. In terms of efficiency of this approach as compared to a full enumeration, the final set of architectures represents approximately 0.2% of the full set of feasible architectures. Based on the consistency of results from multiple runs however there is some confidence these architectures are populating the relevant part of the space. It is important to understand that these heuristic methods provide no guarantee of optimality in any (or multiple) objective functions.

3.6.4 VERIFYING COVERAGE OF DOMAIN

While there are random variables introduced with the heuristic search algorithms, it is desirable to know that feasible architectures exist over each alternative for each sub-problem in the domain. If an alternative is entirely infeasible no matter how other variables are set, it should not be considered as a relevant part of the tradespace. Additionally looking at the distribution of frequency of alternatives for the sub-problems from the random search will ensure that the initial populations in the heuristic searches span the domain. Again this provides no guarantee that the optimal region of the tradespace is covered, but helps to ensure it is easily discovered and explored through the heuristic search algorithms.

A simple histogram of the frequency of occurrence of each variable's alternatives in the feasible architectures produced by the random search algorithm provides this information at a glance. It is verified that every alternative has some feasible architectures for each sub-problem to each destination. Considering these histograms will also provide initial insights into drivers of architecture performance as shown in the following examples. Figure 3-13 and Figure 3-14 demonstrate the coverage of the habitation and transportation set partitioning problems respectively. These represent the inclusion of different possible partitions in the initial population of the tradespace exploration after significant model reduction for the transportation system to Mars. By considering some constraints on the Mars habitat (explained in Chapter 5) and infeasible propellant combinations due to the large delta-v's associated with travel to Mars, in the end only 100 habitation partitions and 24 transportation partitions are left in the feasible space.

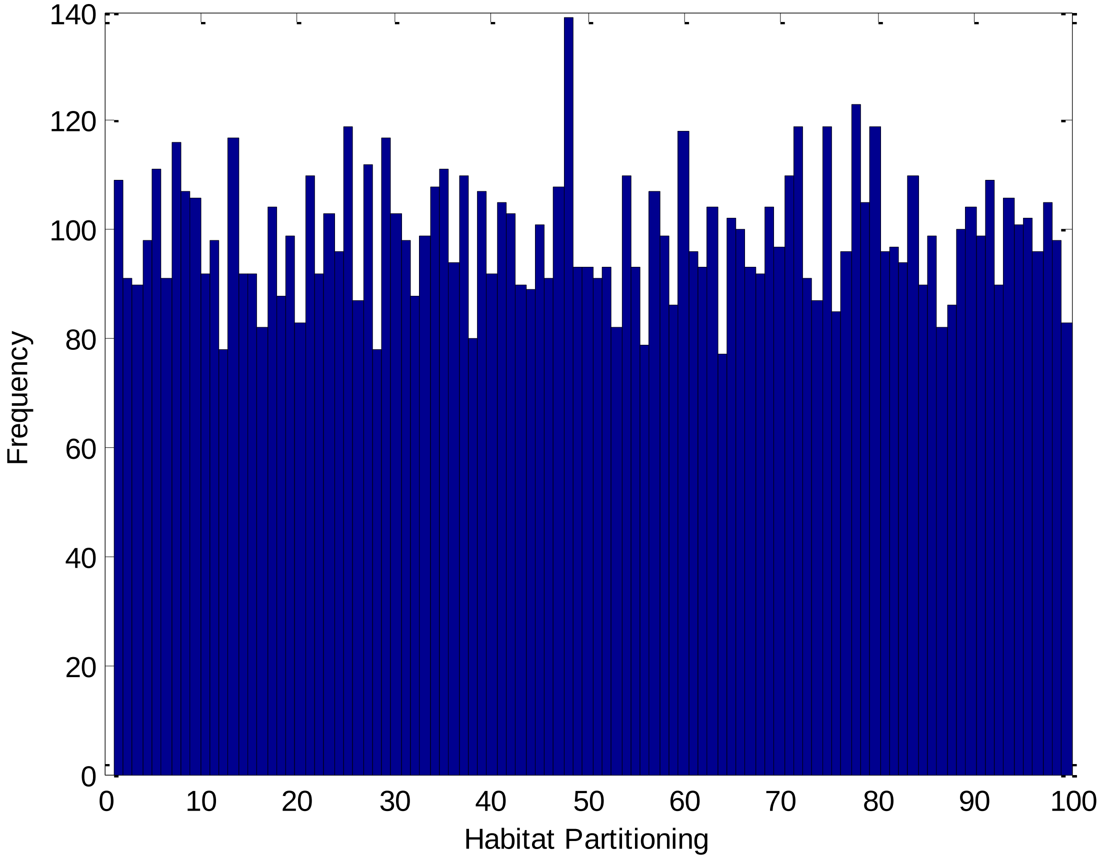


Figure 3-13 Distribution of habitat partitioning problem in random search for the Mars case

In Figure 3-13 above, it is clear that while not evenly distributed, many feasible architectures were produced through random sampling of the habitat function set partitioning problem. Some of the spikes could be from the random nature of the inputs or relate to the frequency with which that habitat allocation results in a feasible architecture. The distribution for transportation function set partitioning tells a significantly different story in Figure 3-14 below.

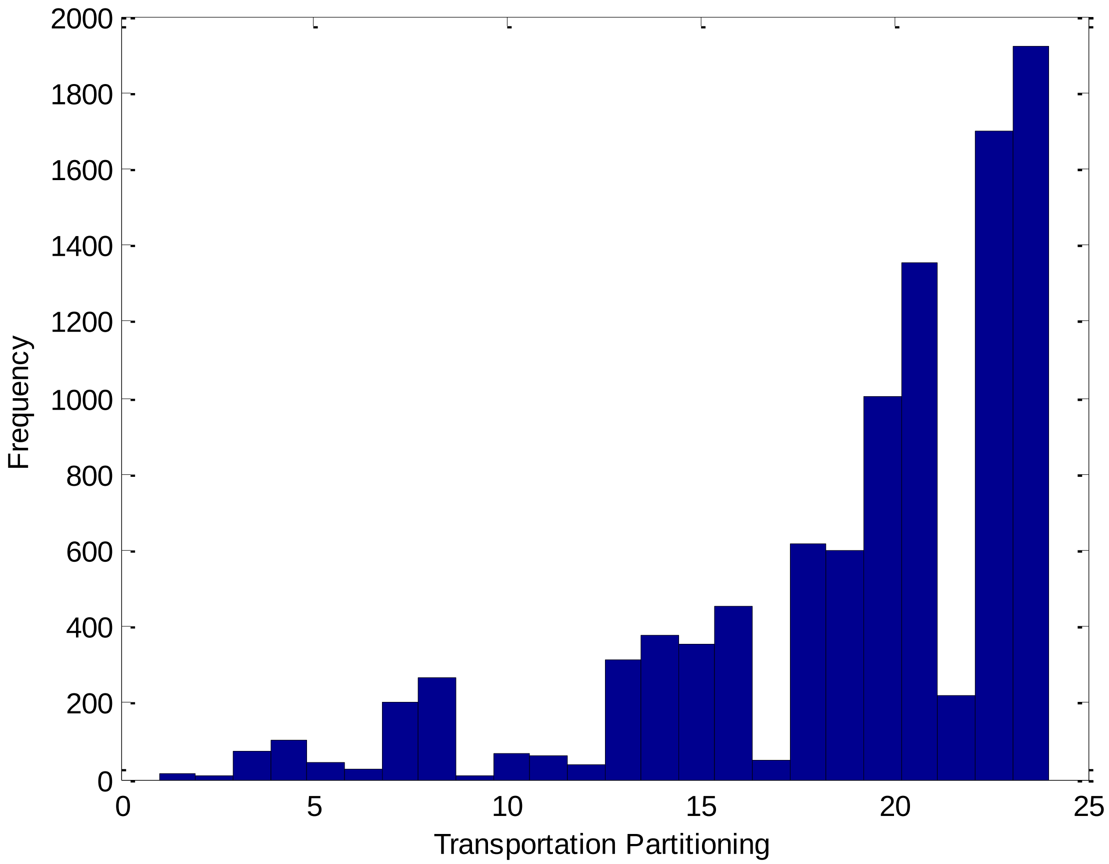


Figure 3-14 Distribution of transportation partitioning problem in random search for the Mars case

The distribution of transportation function allocations for the Mars case is not at all uniform. This indicates there are certain transportation partitions that will result in feasible architectures far more frequently than others. While the initial population for the heuristic algorithms will be skewed towards certain partition decompositions, there are still some feasible architectures provided for all the possible function partitions, meaning some feasible architectures were found for every transportation function allocation. There is clearly a very strong relationship between this sub-problem and feasibility of the entire architecture. The skewed distribution of the initial population is not necessarily a concern as the heuristic methods will continue to mutate these parameters independently of the frequency of feasibility of certain combinations. This histogram tells us both that the problem is fairly well posed as no alternatives are entirely infeasible, and that this sub-problem will have strong influence on the system. It also suggests that certain features within the partitioning problem will be highly coupled to the performance of the overall system. This will be treated in detail in Chapter 5.

3.6.5 IMPROVING SEARCH EFFICIENCY

It was mentioned previously that approximately 90% of the fully enumerated tradespace is infeasible. Not only does this have implications for the search algorithms used as described, but it makes it difficult to reduce the overall computation time for any search algorithm. For every architecture populating the feasible set approximately nine other randomly selected architectures are discarded as infeasible. The problem with infeasible architectures is that they do not have metric values that would indicate the relative performance of that particular architecture definition (beyond being infeasible) and so time is spent evaluating these architectures without informing the ultimate analysis. If the infeasible condition is met because of a hard constraint that is set on the bounds of the domain, there is no significant computational penalty. However an architecture that is logically feasible but fails to find a solution through the iterative calculation of the rocket equation shown in Figure 3-10 may take significantly more time before it is discarded and the next architecture is evaluated.

To try and reduce the percentage of infeasible architectures would require a re-formulation of the sub problems that define a single architecture. While this may be worth pursuing as part of future work, it is not necessary to drastically alter the problem as it has been formulated. However by detecting architectures that are logically feasible but are likely to fail to find a solution before the iterative solver begins, significant time can be saved in evaluating these infeasible architectures.

When the structural dry mass is defined as a percentage of the total propellant mass, the rocket equation develops an asymptote for the gear ratio as a function of delta-v. The location of this asymptote is specific to various combinations of specific impulse and structural mass fraction, but a typical example where I_{sp} = 450 s and ξ = 0.23 is shown below in Figure 3-15.

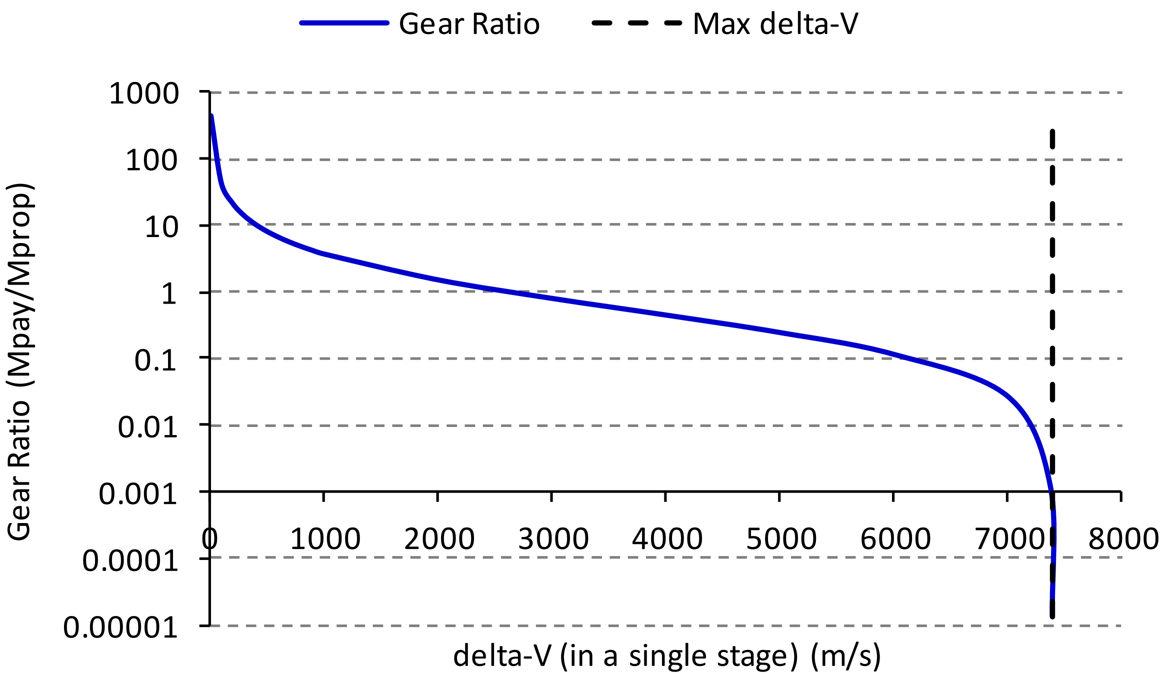


Figure 3-15 Limit of delta-v in a single stage

As the delta-v approaches zero, the gear ratio becomes infinite, and in this case as the delta-v for a single stage approaches approximately 7400 m/s, the gear ratio drops and becomes undefined for further increasing delta-v values. Using this knowledge for every propulsion type, a quick check can be implemented that a single stage with a single payload does not try and aggregate multiple delta-v maneuvers whose sum is greater than the asymptote for that particular propellant type.

KEY POINTS

- *Search algorithms must deal with the large infeasible regions of the tradespace. This can be handled in part by using intelligent heuristic methods, seeding those methods with feasible architectures, and efficiently identifying infeasible architectures.*
- *It is necessary to check the coverage over the domain of the problem to ensure heuristic methods have the chance to uncover "good" regions of the tradespace, and to see that the sub problems are not very poorly formulated.*

4 MAKING SENSE OF THE ARCHITECTURE TRADESPACE

4.1 OVERVIEW

Following the problem formulation and tradespace exploration that were described in Chapter 3, the full range of architectures to be considered have been defined. These architectures then allow for analysis that has three major outputs. The first output is the identification of “good architectures” as defined by the metrics evaluated over the tradespace. There is then the sensitivity of these metrics to technologies and thirdly the coupling that goes on between all technologies or other architectural features. All this information is then turned into the knowledge-base and recommendations that system architects feed to decision makers.

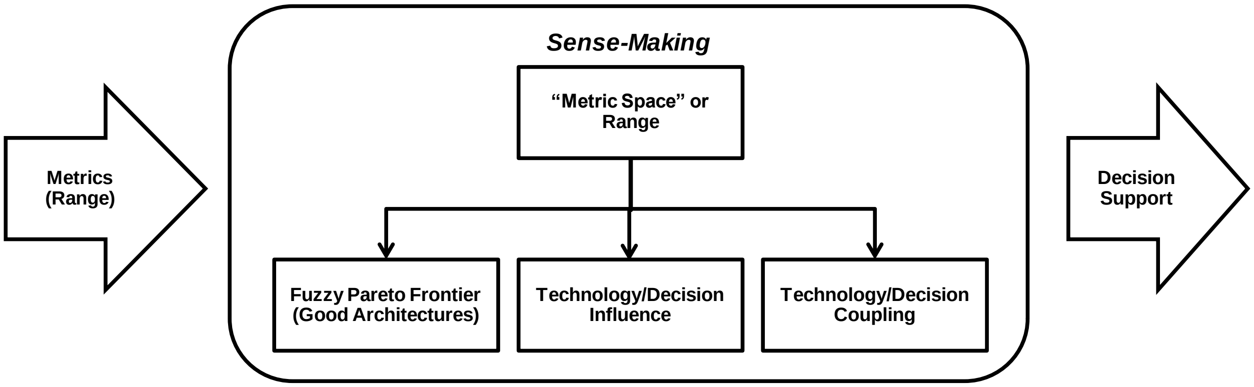


Figure 4-1 Overview of "Sense-Making" task for architecture definition

This chapter provides the methodological contributions required by the analysis presented in Chapters 5 and 6. An extension of the background discussion presented in Section 1.2.4 is provided, giving more details on the motivation and relative contribution of the incorporated methodology. A definition of "good architecture" is provided, defining a set of architectures of interest for further analysis. Finally the approach to measuring the influence of architectural features and the coupling between them is presented. The chapter concludes with a brief discussion of the relevance of these measures.

4.2 ARCHITECTURE ANALYSIS CONTRIBUTIONS

As described in Section 1.2.4, a strong motivator of this work is the sensitivity and connectivity measures of various decisions as defined by Simmons in . In his work, Simmons measured the sensitivity of different variables in the definition of an architecture by measuring the influence of architecture decisions using Property Variable Sensitivity (PVS) of system-wide metrics. He also defined a measure of the "connectivity" of architecture decisions based on the constraints and alternatives in the problem formulation. Simmons put together these two measures of sensitivity and connectivity to provide the "Decision Space View" of an architecture problem. This view organizes the decisions that define architecture into problems that have more or less influence on the system, and problems that have more or less connectivity to the rest of the problem. The purpose of this view of the architecture problem is to provide the system architect with a means to understand some of the prioritization and organization of various aspects of an architecture problem. Following are some specific aspects of Simmons's work that were identified and built upon in this thesis.

4.2.1 ARCHITECTURE MEASURES AND EMERGENCE

In the field of systems architecture multiple definitions have been provided for concepts such as complexity and emergent behavior. While the precise definition of these terms is not central to the concepts presented in this thesis, a general understanding of them is required and drawn from and . Complexity in the definition of systems relates to the multiple interactions between parts of a system. As a result of these numerous interactions, the overall function of complex systems by definition must be more than simply the sum of the functions of the parts when they are separate from each other. The overall function of a large complex system then brings about the concept of emergent behavior. Whether it is desired or undesired, the emergent behavior of a system relates to all the functionality and output of a system when its parts interact with each other. A simple example of desired engineered emergent behavior is the capability for increased communication that comes with widespread adoption of mobile telephones. A relevant example of possibly undesired emergent behavior in mobile telephony is the possibility of an increase in distracted driving accidents.

In the context of this thesis, we are concerned with the interactions of variables that define system architecture and how they interact to influence performance of the system. This means we consider a limited subset of the emergent behaviors that can be measured by the metrics being tracked through tradespace exploration. As previously discussed, any architecture problem will have some (if not several) quantitative metrics, otherwise there is nothing to distinguish how "good" one architecture is in relation to another. While Simmons's "Decision Space View" draws information on sensitivity from the metrics associated with the tradespace (a posteriori knowledge), his definition of connectivity comes from purely a priori knowledge and is dependent of the system modeler's problem formulation.

Providing decision-makers with information that is based on the setup of a model to describe the system architecture in consideration brings about two potential problems in certain architecture design spaces.

The first problem associated with Simmons's definition of connectivity is that problem formulation is subjective. As discussed in there is no one-to-one mapping between system architecture problems and their formulation as an SAP. Reconfiguring problems will introduce different kinds of constraints, and different combinatorial spaces that could drastically change the Simmons definition of decision connectivity.

The second problem associated with Simmons's definition of connectivity is that a priori knowledge may not be available for different parts of an architecture problem. While in the case studies Simmons presented, the connectivity measure provided a distinguishing factor between decisions, applying the framework to the problem of space transportation in this thesis this was part of what motivated the capability to consider coupling between architecture decisions based on a posteriori knowledge. In this case, there were no specific constraints enabled by any sub-problem alternatives that would make the decision coupling metric a distinguishing factor. The lack of constraints may result from a lack of knowledge of the system at hand, but exploring the tradespace would reveal this in the defined metrics that correlate to various architectural parameters.

While Simmons's overall framework is effective it does not necessarily capture the couplings that result from complex system interactions. This means that the output of his "Decision Space View" is based partially on modeled performance and partially on the assumed interactions between architectural decisions. In the realm of system architecting we would like to take advantage of as much knowledge as possible and use a coupling measure that is based on the modeling required for tradespace exploration to begin with. The extent of emergent behavior that can be captured by the metrics is of course limited to the scope of what is being modeled and captured by system wide metrics, although it is an improvement over assuming the problem formulation sufficiently encodes coupling information. The definition of coupling with a measure derived from the evaluated tradespace also provides the capability to capture any non-linear interactions present in the system metrics. Simmons's connectivity measure has coarse granularity and may not capture the relative strength between two architectural decisions. By basing the coupling measure on system metrics, the exact strength of coupling can be determined and distinguished on a continuous scale between any two aspects of the architecture in consideration.

4.2.2 ARCHITECTURE MEASURES AND SAP CLASSES

While Simmons's approach provides an effective framework for considering the influence of decisions and the resulting implications, it is limited in the scope of applicable architecture problems. Simmons has embedded in his work the assumption that all system architecture problems are composed of a set of multiple assignment sub-problems. While from a theoretical standpoint this may be possible, it is not necessarily desirable for partitioning problems that are inherently different from simple assignment. (N.B. While it may not be an effective formulation, a partitioning problem can be framed as an assignment problem by listing the various unique partitions as alternatives to an assignment sub-problem). In this thesis defining the transportation and habitation partitioning problems can not necessarily be treated identically to selection of propellant type or other assignment problems. The metrics of PVS and connectivity begin to lose meaning when considering partitioning problems. An unconstrained partitioning problem with only ten elements has over 100,000 alternatives. In a problem where this is one sub-problem among several others, it is almost certain that there will be significant variability in performance across those alternatives. Taken as a single assignment decision of one out of 100,000 possible partitions makes it difficult to meaningfully measure the influence of different aspects of the sub-problem. Ideally a generic formulation should allow the system architect to consider the influence of an entire partitioning or any arbitrary feature of that sub-problem.

Another major difference from previous work with the following proposed methodology is that in this work, any architectural feature under consideration has defined influence and coupling measures. Any single feature can be described as having a binary state- it is either present in the architecture or not. While certain aspects of the architecture such as technologies in a down-selection problem may already be defined in this way, this allows other prominent features in other problem types to be explored comprehensively. For example taking advantage of an orbit-rendezvous is a specific strategy that is more generally encoded within a set partitioning problem. However it can still be considered despite not being an explicit decision to be made. In this way both the influence and coupling effects are not necessarily tied to the initial problem formulation. The features to be considered can be determined independently of the problem sub-classes and the definition of these measures is based on metrics that do not necessarily require knowledge in the problem formulation.

4.2.3 MEASURING SENSITIVITY VS INFLUENCE

The final major difference between the sensitivity measure, PVS, and the impact measure proposed in this thesis stems from the inability of PVS to specify the direction of the influence on a given metric. PVS is a calculation of the absolute magnitude of the average change in a metric various alternatives create within an assignment decision. When considering the influence of technologies or other features in the system architecture definition we not only want to understand the sensitivity of the feature, but the influence it has on system-wide metrics.

4.2.4 CONTRIBUTION CONCLUSIONS

Compared to the framework presented by Simmons, the approach presented in this thesis provides a tradeoff between an understanding of the system in problem formulation, and precision in the decision measures over the evaluated tradespace. Measuring sensitivity and coupling of metrics based on the evaluated tradespace provides a robust method independent of a priori system knowledge, at the expense of having limited understanding of these issues before complete model development and tradespace exploration. The presented framework also provides a more comprehensive view of pair-wise coupling between all decisions allowing for an overall understanding of decisions that can be treated separately and those that must be taken together.

KEY POINTS

- *The definition of coupling with a measure derived from the evaluated tradespace also provides the capability to capture any non-linear interactions present in the system metrics*
- *The features to be considered can be determined independently of the problem sub-classes and the definition of these measures is based on metrics that do not necessarily require knowledge in the problem formulation*
- *The proposed method is independent of a priori system knowledge.*
- *Comprehensive pair-wise coupling between all technologies or architectural features allows for an overall understanding of decisions that can be treated separately and those that must be taken together.*

4.3 DEFINING "GOOD" ARCHITECTURES

The most direct output of tradespace exploration is to define what are "good" architectures. Seen in this way, tradespace exploration can also be framed as a multi-objective optimization. In terms of an optimization problem, the definition of architecture is the independent variable and the metrics are the objective functions to be minimized. There may be no single minimum in a multi-objective optimization problem, but the architectures that minimize all objective functions define the set of "good" architectures.

By nature of producing random architecture definitions in the tradespace it is not uncommon for a design point in consideration to be logically feasible but impractical in its size. It is unlikely that a successful Mars transportation system will have an IMLEO several orders of magnitude larger than the largest human spaceflight project to date, the International Space Station (ISS). While it is difficult to define exactly what IMLEO represents an infeasible size for an exploration transportation system, values are selected and imposed as a constraint on what defines "good" architectures. Assuming the annual NASA Human Spaceflight budget is not going to drastically increase, using the ISS as a reference point for the scale of projects that can be achieved over a few decades is reasonable.

The following maximum IMLEO constraints are set for defining "good" architecture as shown in Table 4-1.

Table 4-1 IMLEO constraints on "good" architecture by destination

Destination	Max IMLEO (mt)	Number of ISS
Low NEA	225	0.5
High NEA	450	1.0
Moon	450	1.0
Mars	900	2.0

The tradespace exploration problem approached in this thesis has only two metrics, but the methodology is designed to apply to an arbitrary number of metrics over the tradespace. Since there is no single optimal point, a better definition of "good" architectures is provided by the concept of Pareto efficiency. Briefly stated, Pareto efficient points in a tradespace can not improve one metric without losing performance in another metric. The set of Pareto efficient points then form a frontier that represents the efficient allocation of resources to gain some benefits. The Pareto frontier is the set of the most desirable points in a tradespace and inherently spans the tradeoffs that naturally occur in systems with limited resources. A thorough approach to applying the concept of Pareto efficiency to multi-objective optimization problems is provided in .

Continuing with the view that the tradespace exploration can be cast as an optimization problem, the set of each metrics evaluated for a single architecture can be described by a vector $\boldsymbol{J^n}$. Each element of that vector will be the value of the metric associated with the $\boldsymbol{n}^{\text{th}}$ architecture. The Pareto frontier is defined as the set of architectures that optimize all the metrics considered. A more formal definition of the Pareto frontier is the set $\boldsymbol{S}$ of architectures that are non-dominated. An architecture $\boldsymbol{x}$ is dominated if another architecture exists that performs better in every single metric. This is described mathematically below in Equation 4-1 and Table 4-2 below.

Equation 4-1 Definition of Pareto frontier (assuming all metrics are to be minimized)

$$x^* \in S \quad IFF \quad J_i^{x^*} \leq J_i^x$$

$$\forall\, i\,,\ x \notin S$$

Table 4-2 Pareto frontier definition symbols

Symbol	Description
$\boldsymbol{J}$	Vector of objective functions (metrics)
$\boldsymbol{x}$	Individual architecture
$\boldsymbol{x^*}$	Non-dominated architecture
$\boldsymbol{i}$	Index over objective functions (metrics)
$\boldsymbol{S}$	Set of architectures on the Pareto-frontier (non-dominated)

While the methodology presented is a search to find "good" architectures due to the high level abstract nature of the modeling of the problem, there is no guarantee that the Pareto frontier that is uncovered in the tradespace represents the definitive set of non-dominated architectures that should be considered. There are three major issues that drive consideration of a broader set of architectures than just those on the Pareto frontier.

The nature of the space transportation problem treated in this thesis introduces a large amount of often difficult to quantify uncertainty. Modeling simplifications and estimates result in uncertain parameters that are embedded in the assumptions, modeling parameters, and definition of metrics in the problem. While in theory dominated architectures are inferior to the non-dominated set, we can not claim such a high level of precision in the uncertainty of the metrics defined for each architecture.

The second issue is that the non-dominated set of architectures in the tradespace is desirable based only on the two simple metrics considered in this thesis. The scope of the current analysis is limited by the abstraction in the model. Future more detailed analysis will have to include other metrics that relate to figures of merit such as probability of mission success, robustness to political desires, and flexibility in system deployment. Architectures that are entirely dominated in the current cost-related metrics are not likely to ever become strong candidates for good architecture. However architectures that are near the frontier (but not on it) may become extremely desirable once more detailed modeling provides these other dimensions by which the tradespace can be evaluated.

Finally, the heuristic search methods employed provide no strict guarantee of optimality. While unlikely due to population size, it is always possible that points that should be on the Pareto frontier may never be enumerated. Points slightly off of the frontier may represent very similar architectures that are dominated, but more representative of a unique and desirable alternative that did not happen to be enumerated through the population-based search algorithm.

To ensure that the analysis presented is robust to the previously described issues that introduce uncertainties into the definition of Pareto-optimal architectures, we expand the set of "good" architecture to include a fuzzy Pareto-optimal set that is more inclusive. The concept of a fuzzy Pareto set as defined by successive Pareto fronts is described in detail in . This fuzzy Pareto region is defined by finding a Pareto front, removing it from the set of architectures in consideration, and defining a new Pareto frontier. We repeat this process successively until 5% of the feasible architectures have been included. While the architectures included in the fuzzy Pareto front are no longer optimal by the two metrics included in the analysis, we have defined a much more rich set of architectures that are all within a few percentage points of the relevant frontier.

4.4 MEASURING THE INFLUENCE OF ARCHITECTURAL FEATURES

As discussed, it is desired to have a measure of the influence of an arbitrary architectural feature in the tradespace on a system-wide metric. For the purposes of decision making this measure should be based on architectures that could be realistically pursued. Measuring the "impact" in relation to an architecture that is infeasible does not realistically represent the benefits associated with the technology. Using the previous descriptions of a set of good architectures, we can restrict the measure of influence over only these preferred points in the tradespace.

Overall we want to define a measure, the Technology Impact Measure (TIM) that tells us the average influence of a technology or other architectural feature without knowing the specific architecture. We take the average of a metric over architectures within the fuzzy Pareto region that do have the feature and the average of a metric over those architectures in the region that do not have the feature to come up with the average influence on the relevant tradespace. As discussed in section 1.2.4 TIM is taken from main effects analysis in design of experiments literature . The important distinctions are in the sets of architectures (or "experiments") to which the averages are applied.

Equation 4-2 Technology Influence Measure (TIM)

$$TIM_{M,T} = \bar{M}\{T_{on}\} - \bar{M}\{T_{off}\}$$

$$T_{on} \cup T_{off} = S'$$

Table 4-3 TIM variables

Variable	Description
TIM	Technology Influence Measure
M	A specific metric
T	A specific technology or architectural feature
$\overline{M}$	Average metric value for relevant subset of architectures
T_{on}	The set of architectures with the technology or feature included
T_{off}	The set of architectures without the technology or feature included
S'	The fuzzy Pareto set of architectures previously described, the “good” architectures

While the TIM does not tell us the specific interactions of any given architectural feature for a single selected architecture, it gives us a broader view of how specific architectural features will influence the tradespace. TIM looks at a realistic set of architectures and helps us measure the influence on the final system considering we don’t instantaneously choose the system in its entirety. It requires a realistic consideration of all major relevant system architecture decisions. By restricting architectures in the calculation to feasible realistic architectures we couple complex system interactions and decisions to the influence calculation so that the influence includes how the rest of the definition of the system is likely to evolve with that isolated change. TIM provides an understanding of the influence various architectural features have on metrics that is realistic and does not unfairly favor any given architecture in the tradespace.

4.5 MEASURING COUPLING BETWEEN ARCHITECTURAL FEATURES

As previously explained the coupling measure presented in this thesis must be defined by the metrics after evaluating the tradespace and not necessarily dependent on the problem formulation. The coupling Simmons measured summed up all interaction effects into a single value so that each decision had an overall coupling “strength” in context of the entire problem. The proposed measure of Technology Coupling Interaction Effects (TCIE) provides a more rich understanding of the various interaction effects that arise by addressing specific coupling between any two architectural features or technologies.

While the TIM was calculated over the preferred fuzzy Pareto set of architectures, from experience in developing these metrics this subset of the tradespace does not necessarily provide sufficient variety of system architectures to give useful TCIE measures for all interactions. In particular strongly detrimental interaction effects between two features may result in architectures that are heavily dominated and do not appear in the fuzzy Pareto region. For example two technologies may represent different strategies that create architectures on opposite ends of the Pareto front. It may be that these technologies would not both be included in any architectures in the fuzzy Pareto region because they are incompatible. However it is desirable to be able to define a coupling interaction effect for these two technologies to understand the magnitude of decreased performance when the two technologies are combined. For this reason, the TCIE is evaluated over the entire evaluated tradespace. As a result, the magnitude of

TCIE values is only meaningful as a relative measure in comparison with other TCIE. This is in contrast to the TIM that represents a more realistic measure of the actual magnitude of influence that various technologies and architectural features have on the system design.

Equation 4-3 Technology Coupling Interaction Effects (TCIE) Definition

$$TCIE_{M,T^1,T^2} = \bar{M}\{T_{on}^1 \cap T_{on}^2\} - \bar{M}\{T_{on}^1 \cap T_{off}^2\} - \bar{M}\{T_{off}^1 \cap T_{on}^2\} + \bar{M}\{T_{off}^1 \cap T_{off}^2\}$$

$$T^1 \neq T^2$$

$$T_{on}^1 \cup T_{off}^1 = P \qquad T_{on}^1 \cap T_{off}^1 = \emptyset$$

$$T_{on}^2 \cup T_{off}^2 = P \qquad T_{on}^2 \cap T_{off}^2 = \emptyset$$

Table 4-4 Technology Coupling Interaction Effects (TCIE) Variables

Variable	Description
$TCIE$	Technology Coupling Interaction Effect
M	A specific metric
T^n	A specific technology or architectural feature (*n* is an arbitrary index)
$\bar{M}$	Average metric value for relevant subset of architectures
T_{state}^n	The set of architectures with the *n*th technology or feature either on or off (represented by *state)*
$\{T_{on}^1 \cap T_{on}^2\}$	The set of architectures that have both technology 1 on and technology 2 on (provided as an example)
P	The full set of evaluated architectures across the tradespace

TCIE is a measure of the influence that one technology has on another technology’s influence. Just as with TIM, TCIE is derived from the design of experiments literature borrowing the concept of interaction effects . That is to say TCIE measures the influence of one technology on the TIM of another technology. Assuming metrics are designed to be minimized, a large positive TCIE value means the technologies or architectural features do not go well together, while a large negative value indicates there is a strong beneficial coupling that greatly reduces the metric in consideration when the two technologies or features are combined. A relatively small TCIE in either direction means the presence of one technology does not strongly influence the other.

With an explicit definition of coupling effects, a rigorous evaluation of couplings can be done between all technologies and architectural features. A simple way to organize this information is using an n^2 diagram that contains the TCIE between every combination of technologies. We call this aggregated view of the coupling information the Technology Coupling Interaction Matrix (TCIM). Each technology or feature in consideration is listed across the columns and rows of the matrix, and each cell contains the TCIE for the associated variables in consideration. The TCIM will have diagonal symmetry.

4.6 RELEVANCE OF INFLUENCE AND COUPLING

The definition of "good" architecture and measures of the tradespace that have been defined all support the goal of turning architecture tradespace exploration into useful decision support. The TIM provides a sense of the importance and prioritization of variables in the architecture. In terms of technology investment strategy this can help to identify prioritization for near term funding. The coupling information embedded in the TCIE can help to inform what groups of technologies are worth considering together and those that represent different approaches to architecture design. It also can help to provide a sense of major design issues that can be considered in parallel and those that must be combined into a single trade study since they are so highly dependent on each other. More details of the application of TIM and TCIE and how they provide decision support are provided in the relevant sections of Chapters 5 and 6.

KEY POINTS

- *Good architectures are defined by an IMLEO constraint and a fuzzy Pareto frontier.*
- *Descriptions of architectural features that are defined by the metrics in the tradespace rather than a priori system definition can capture more of the emergent properties related to complex system interactions that have not necessarily been predicted by the architect during problem formulation.*
- *There is a need to apply metrics of system architecture features to arbitrary architecture definition, not just assignment class SAPs.*
- *Technology Influence Measure (TIM), like main effects analysis, provides a measure that describes the average influence a technology or architectural feature has on the tradespace.*
- *Coupling effects, TCIE, allow for rigorous treatment of the interactions between any two technologies or architectural features.*

5 TECHNOLOGY DEVELOPMENT PROJECTS FOR TRANSPORTATION TO MARS

5.1 OVERVIEW

In this chapter the technologies and system architecture for transportation systems to Mars are considered through an abstracted system architecture model. Some fundamental assumptions and methods for exploring the tradespace are provided. By populating a set with favorable architectures, performance benefits are measured for various technologies across these different architectures. Then specific interaction effects between system decisions are highlighted. This information is used to structure information about the various decisions that define the transportation system and favorable subsets of technologies promising to provide high value to a Mars exploration program in the long term.

5.2 MARS MISSION ASSUMPTIONS

To evaluate the influence of different technologies, a single model is required that allows for variation in the definition of habitats and transportation stages and the various technologies that are then applied to this system. The model must have a consistent set of assumptions for other mission parameters that are not being explicitly included in the tradespace. The fundamental objective of this section is to understand what transportation architectures will efficiently deliver astronauts to the surface of Mars in a sustainable long-term operational scheme. The relevant assumptions are derived from this approach.

To perform a fair comparison across all architectures it is assumed that the propulsive requirements stemming from astrodynamics considerations remain constant across all missions. For this tradespace only “long-stay” conjunction class missions are being considered since they are most likely to be selected for a long term presence at Mars. An explicit trade study considering the costs and benefits associated with a "short-stay" opposition-class mission and the "long-stay" conjunction class mission are considered in section 6.2 of NASA's Mars Design Reference Architecture 5.0 .

Furthermore the delta-v requirements for conjunction class missions varies from one flight opportunity to another. For the purposes of comparing the differences in system architecture already described, it is assumed these delta-v requirements remain constant. While many studies use values for particularly favorable mission opportunities, delta-v values for an average mission opportunity are used. This is done with the assumption that the transportation architecture must remain favorable in an infrastructure where Mars missions occur relatively frequently in relation to the mission opportunities provided by the synodic period between Earth and Mars. The delta-v requirements of the major maneuvers are compiled from , , and .

The values associated with these majors assumptions are shown in Table 5-1.

Table 5-1 Mars mission assumptions

Mission class	Conjunction class
Crew size	4
Surface duration	500 days
Total crew mission duration	860 days
Total mission delta-v	17.9 km/s

In addition to the general modeling assumptions presented in Chapter 3 and the trajectory assumptions just discussed, there is an additional assumption that manifests itself as a constraint on the habitats used for the Mars transportation system. It is assumed that a single monolithic habitat could not perform the long duration in-space outbound, return and surface segments of the mission. This constraint was implemented after discussion with experts and comes from an understanding of the habitat development risk and mission risk that is not otherwise directly captured in the level of fidelity of the modeling presented in this thesis.

KEY POINTS

- *Tradespace analysis is iso-performance. All evaluated architectures provide the same mission performance with varying objective function costs associated with various architectures.*
- *Mission parameters are based on a Mars long-stay "conjunction-class" mission.*

5.3 MARS TRANSPORTATION ARCHITECTURE TRADESPACE

As described in Chapter 3, it is impractical to fully enumerate the entire tradespace of these Mars transportation architectures. Using the heuristic population-based search algorithms, architectures are evaluated to span the domain of possible architectural decisions. It is necessary to broadly sample the domain (even if not exhaustively) to understand the influence that different factors have not on any one single architecture, but rather over a set of good candidate architectures.

The population of evaluated architectures produced can be viewed in Figure 5-1 which shows a plot of the two high level metrics considered. For definitions and discussion of IMLEO and technology Life Cycle Cost (LCC) proxy see Section 3.6.2. As previously discussed a feasibility constraint is imposed that architectures must have an IMLEO less than two ISS masses. Since all of these architectures deliver a crew of 4 people to the surface of Mars for 500 days, the ideal or "utopia point" in the tradespace would be at zero cost, or the bottom left corner of the plot. Viewing the output of tradespace evaluation in this way provides some immediate information about the cost proxy metrics. There is a tradeoff between IMLEO and the technology LCC proxy creating the convex space bounding the utopia point. Architectures that are non-dominated define a Pareto frontier (marked in red) where no architecture does better in both metrics at the same time. Circled in black are points within the "fuzzy" Pareto front region defined in Chapter 4. This set of fuzzy Pareto architectures defines the architectures of interest that are later used to evaluate the influence of different technologies. Selected architectures are labeled that will be discussed in more detail.

Finally it is worth noting that after a value of about 5 in the technology LCC proxy, there are no architectures in the fuzzy Pareto frontier region. This means that even if technology costs were not considered, it would still not be desirable to apply all possible technologies to the transportation system, as adding more technologies would not necessarily provide incremental benefit.

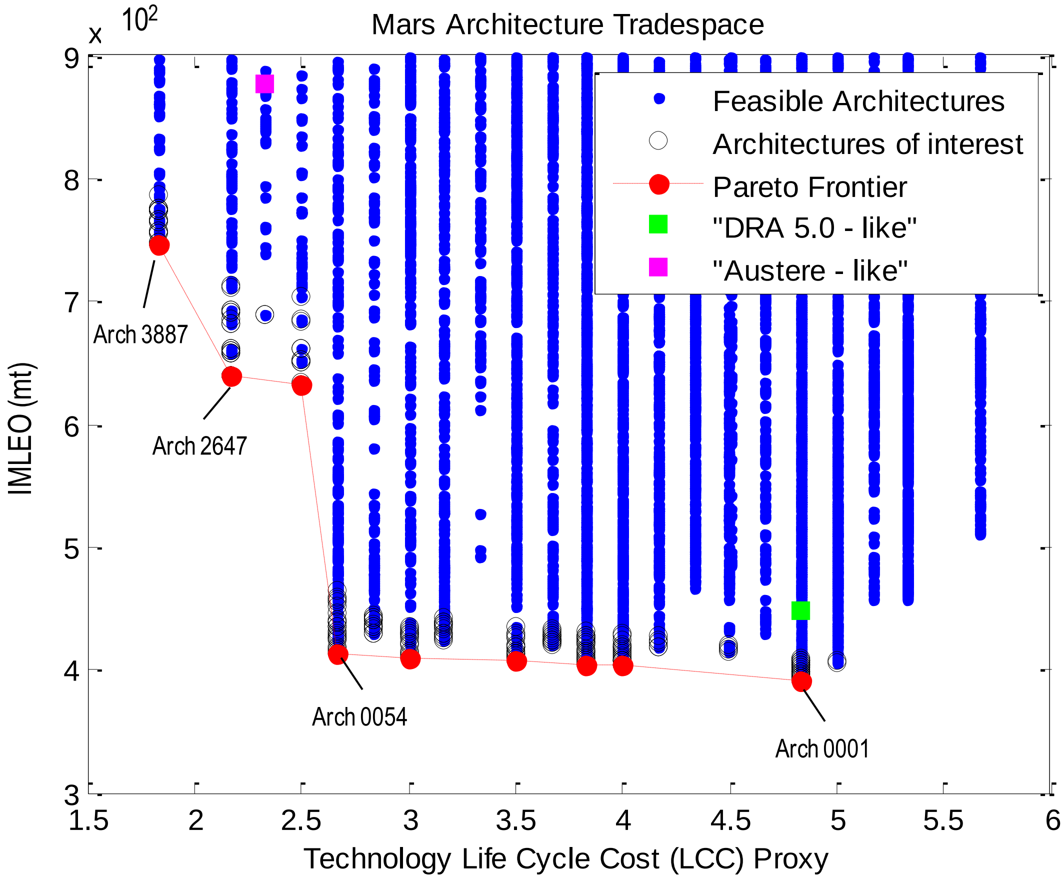


Figure 5-1 Mars architecture tradespace viewed by metrics

Two reference points are included in the tradespace. The green square in Figure 5-1 marks an architecture that is similar to the NASA Mars DRA 5.0 while the magenta square denotes an architecture similar to the JPL Austere reference mission . It is important to note that the actual IMLEO derived from these separate studies is not directly comparable to the data points evaluated in this architectural tradespace as there are some fundamentally different assumptions in each reference architecture as to the mission objectives, requirements, and modeling approach. For example, the DRA 5.0 assumes a specific mission opportunity with significantly lower delta-v and also provides significantly more payload to the surface (that would not necessarily be delivered in the operational transportation scenario considered here). Note that by changing the assumptions used in architecture evaluation we were able to use these data points to validate the model to within 5 percent of the reference designs. While the sizing assumptions are different, the fundamental architecture defined by the habitation and transportation partitioning problems and the technologies applied are analogous between the references and their corresponding data points represented in the tradespace. When converted into similar architectures in the current tradespace these two reference points do represent fundamentally different approaches to the transportation infrastructure for delivering people to Mars. Capturing the differences between the architectures in their definition and then measuring the resulting differences in the associated metrics is a good validation that the fundamental design philosophies for each respective study are appropriately captured in the model presented. The DRA 5.0 mission relies on a relatively large technology portfolio requiring significant development and is well suited to a robust surface exploration campaign with a lot of mass required to be descended to the Martian surface. In contrast the Austere mission represents an architecture with a higher overall mass for the same exploration capability but requires a measurably smaller set of technologies to be available. The Austere mission represents a more minimalistic approach and is well suited to a mission that has less surface capability.

The nine architectures that are on the Pareto frontier are shown in Table 5-2. These architectures do not represent all available alternatives but highlight some efficient transportation infrastructure schemes. The four architectures highlighted in yellow are described in more detail and labeled in Figure 5-1.

Table 5-2 Mars Architectures on the Pareto frontier (highlighted architectures are described in more detail below)

Index	IMLEO (mt)	Tech LCC Proxy	Habitats	Transportation Stages
0001	392	4.833	Mars Orbit rendezvous-like	Mars Orbit rendezvous-like
0014	403	4.0	Mars Orbit rendezvous-like	Mars Orbit rendezvous-like
0017	404	3.833	Mars Orbit rendezvous-like	Mars Orbit rendezvous-like
0030	408	3.5	Mars Orbit rendezvous-like	Mars Orbit rendezvous-like
0034	409	3.0	Mars Orbit rendezvous-like	Mars Orbit rendezvous-like
0054	413	2.667	Mars Orbit rendezvous-like	Mars Orbit rendezvous-like
2552	632	2.50	Mars Orbit rendezvous-like	Serial Stages
2647	639	2.167	Mars Orbit rendezvous-like	Serial Stages
3887	746	1.833	Mars Orbit rendezvous-like	Serial Stages

Index	EDS Prop Type	Descent Prop Type	Ascent Prop Type	TEI Prop Type	Predeployment	Boil-Off Control	ISRU	Aerocapture
0001	NTR	LH2	LH2	NTR	No	Yes	Yes	Yes
0014	NTR	Hypergol	LH2	NTR	No	Yes	Yes	Yes
0017	NTR	LH2	LH2	NTR	No	Yes	No	Yes
0030	NTR	LH2	Hypergol	NTR	No	Yes	No	Yes
0034	NTR	Hypergol	LH2	NTR	No	Yes	No	Yes
0054	NTR	Hypergol	Hypergol	NTR	No	Yes	No	Yes
2552	LH2	Hypergol	LH2	LH2	Yes	Yes	No	Yes
2647	LH2	Hypergol	Hypergol	LH2	Yes	Yes	No	Yes
3887	LH2	Hypergol	Hypergol	LH2	No	Yes	No	Yes

By looking at a few different architectures on the Pareto frontier we get an initial understanding of some of the different types of architectures that come out of the tradespace exploration. We also begin to get a sense for the inherent tradeoffs between systems that are more mass-efficient but rely on multiple technologies and those that require a smaller set of available technologies. Architectures along the frontier vary from completely mass-optimized to completely technology LCC optimized.

Mars architecture 0001 is the most optimized for minimal mass. It takes advantage of a "Mars-orbit-rendezvous" scheme for both habitats and transportation elements. A large nuclear earth departure stage pushes the entire stack out to Mars and drops those large tanks. On the surface an ISRU system replenishes a LOX/LH2 stage to be re-used for ascent. After ascent, the same NTR engine is used on a second tank stage to return the in-space habitat that was left in low Mars orbit. Finally, the vehicle brakes into Earth orbit so the crew can descend in a small capsule. Boil-off control is implemented on the LH2 that is used in all the propulsion systems and aerocapture is used in the braking maneuvers at both Earth and Mars. A schematic representation of Mars architecture 0001 is shown in Figure 5-2.

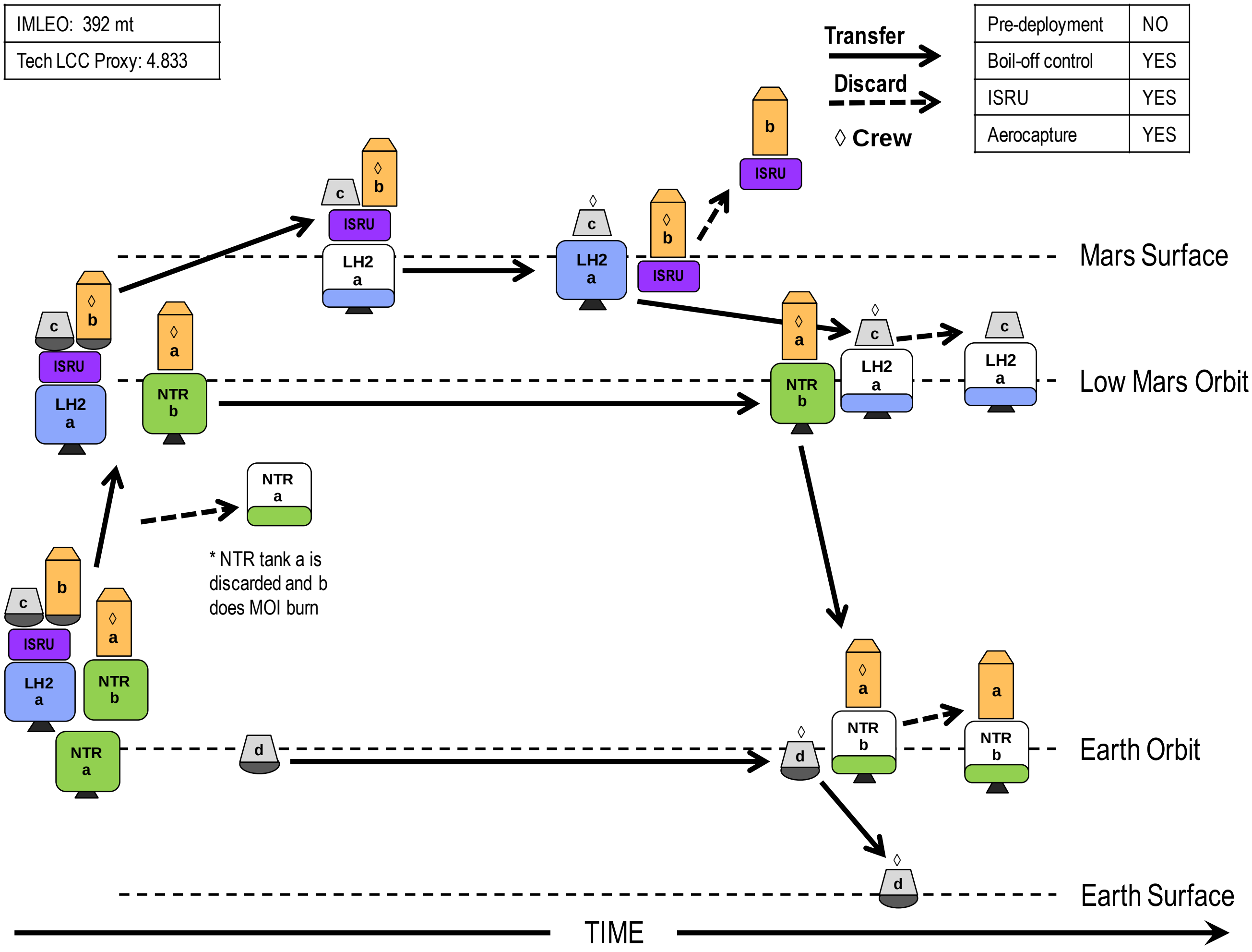


Figure 5-2 Mars architecture 0001 from the Pareto frontier

Architecture 0054 is similar to architecture 0001. The main differences between the two architectures are in the ascent and descent stages to and from the Martian surface. Rather than a combined LH2 stage that is filled with ascent propellant from an ISRU facility, architecture 0054 uses hypergolic propellants in separate stages for ascent and descent and does not rely on ISRU at all. The schematic of architecture 0054 is presented in Figure 5-3.

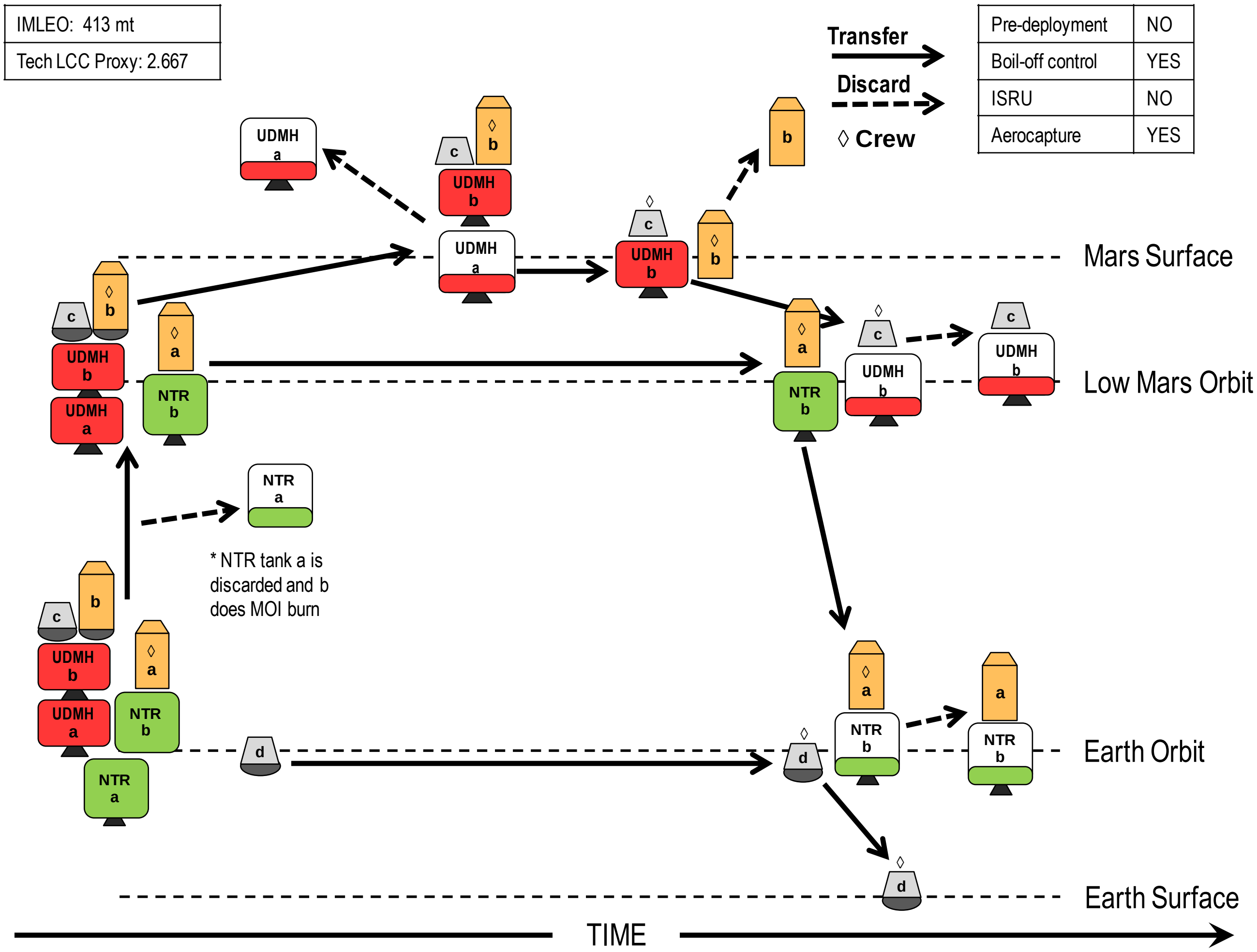
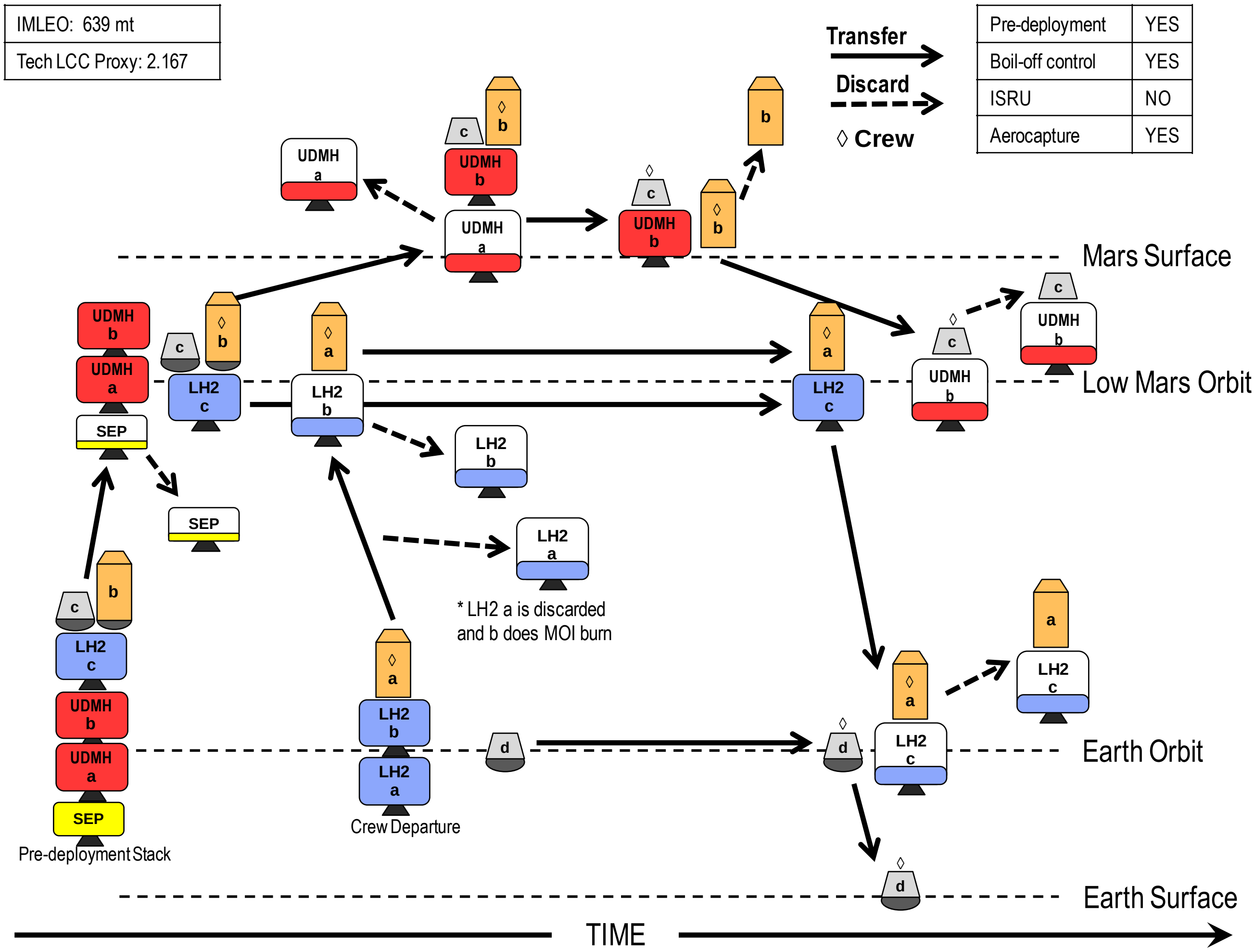


Figure 5-3 Mars architecture 0054 from the Pareto frontier

Between architecture 0001 and architecture 0054 a tradeoff is made between the simplicity of existing propulsion systems and the efficiency of advanced technologies for the descent and ascent maneuvers to and from the Martian surface. This tradeoff is captured by the two metrics being considered with a 5% increase in IMLEO and reduction of the technology LCC proxy of approximately 45%. Moving from architecture 0001 to 0054 has a fairly small IMLEO penalty for a significant improvement in the technology LCC proxy.

Mars architecture 2647 is significantly different from both architecture 0001 and architecture 0054. Since pre-deployment is used, there are two separate "stacks" sent that represent two groups of elements that depart Earth in separate synodic periods. SEP is used to pre-deploy descent, surface, and ascent habitats and stages on a more efficient but longer time of flight trajectory. Hydrogen is used for in-space propulsion of all crewed elements, and each major maneuver has a separate stage. The benefits associated with pre-deployment with SEP are significant when the Mars Orbit Insertion (MOI) and Trans-Earth Injection (TEI) maneuvers are performed by separate stages since the TEI stage is a large element that can be pre-deployed. Finally the descent and ascent stages use storable hypergolic propellant. While requiring the development of high power SEP capability, this architecture takes advantage of this efficient propulsion technology with a system decomposition that allows for pre-deployment of elements that are not time sensitive and at the same time uses other propellants with lower specific impulse but less development risk.



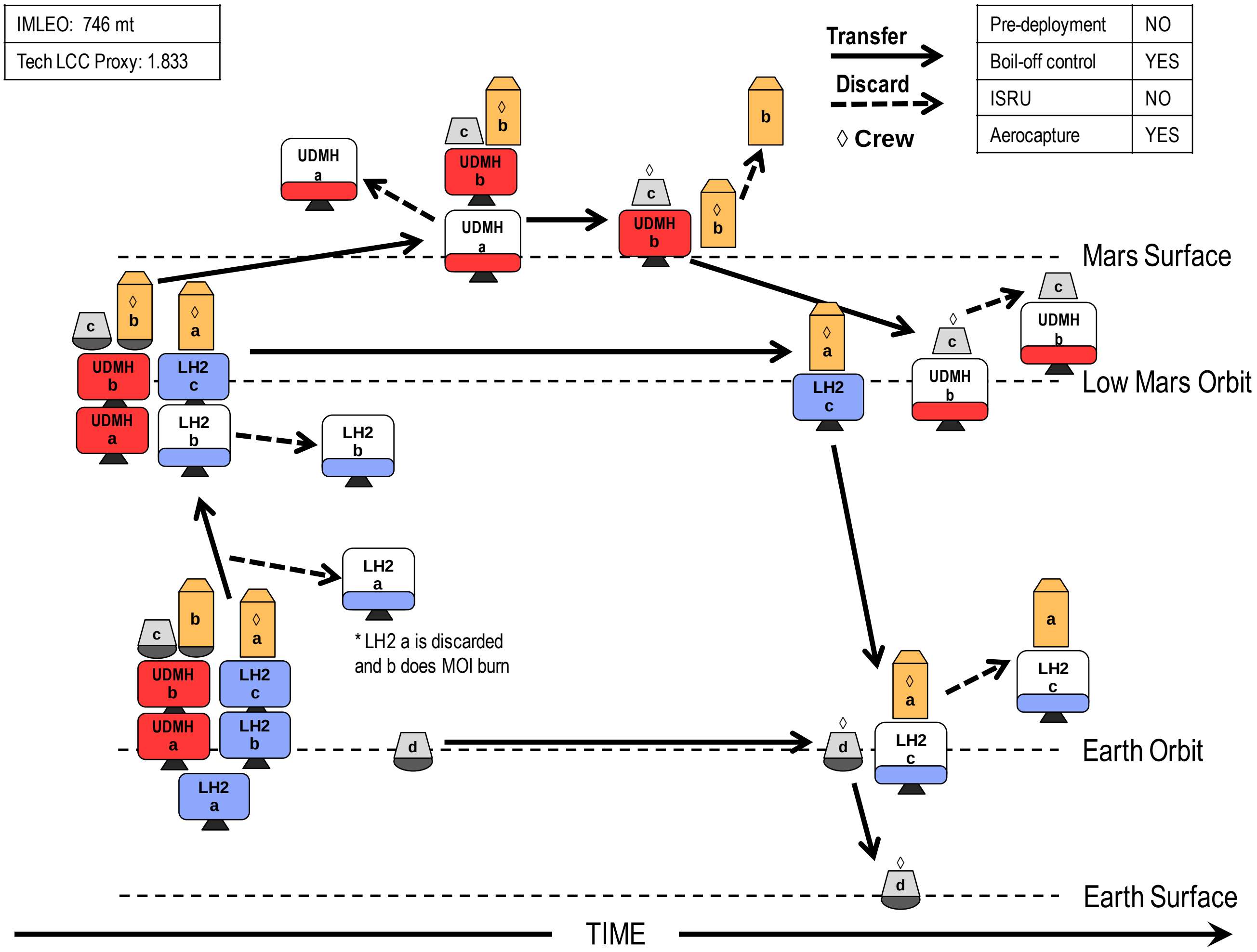
IMLEO: 639 mt	
Tech LCC Proxy: 2.167	

Pre-deployment	YES
Boil-off control	YES
ISRU	NO
Aerocapture	YES

Figure 5-4 Mars Architecture 2647 from the Pareto frontier

Compared to architecture 0001, architecture 2647 represents a larger incremental tradeoff between technology LCC and IMLEO. Architecture 2647 has a 63% higher IMLEO than architecture 0001 but a 55% lower technology LCC proxy.

Finally, architecture 3887 is the most technology LCC optimized architecture on the Pareto frontier. Boil-off control and aerocapture are the only major capabilities that would need to be developed for this architecture. Individual liquid oxygen-liquid hydrogen stages are used for each major in-space maneuver and storable hypergols are used for ascent and descent at Mars. After each major propulsive maneuver the corresponding stage is discarded. The schematic of architecture 3887 is presented in Figure 5-5.


IMLEO: 746 mt
Tech LCC Proxy: 1.833

Pre-deployment	NO
Boil-off control	YES
ISRU	NO
Aerocapture	YES

Figure 5-5 Mars architecture 3887 from the Pareto frontier

From a technology development and mission operations perspective architecture 3887 is a low-risk and low-complexity architecture. The cost of the simplicity of this architecture is that it is no longer mass-optimized and sits on the opposite side of the spectrum from architecture 0001. Comparing these two architectures on opposite ends of the Pareto frontier, the most LCC-optimized architecture has 90% increase in mass and 62% decrease in technology LCC proxy from the most IMLEO-optimized architecture.

The benefits from implementing specific technologies vary according to other architectural decisions. While it is interesting to consider the short list of architectures on the Pareto frontier, the exact influence of different technologies and the reasons that certain architectures are on the frontier are not necessarily clear. In the following sections we will explicitly measure the influence of these technologies and the coupling to other architectural decisions to have a more comprehensive view of the implications of developing any given technology.

KEY POINTS

- *2 metrics of IMLEO and technology LCC proxy capture fundamentally different design philosophies.*
- *Multi-objective tradespace exploration results in a variety of system architectures and a variety of technologies on the Pareto frontier.*

5.4 MEASURING THE INFLUENCE OF TECHNOLOGIES

The goal of this section is to understand how various technologies influence the system architecture for transporting people to Mars. To begin, it is useful to look at two different individual architectures from the previously described Pareto frontier. As previously described architectures 0001 and 2647 (Figure 5-2 and Figure 5-4 respectively) represent two very different approaches to the Mars transportation infrastructure. We would like to understand the overall influence of certain technologies on the transportation system to Mars. However we do not yet know the overall system architecture that will be used. To begin to understand how any technology can influence the entire tradespace, we start by measuring the change in metrics for a given architecture when a technology is or is not applied to the architecture. This can be considered a technology "switch." Holding all other variables constant, the objective functions are evaluated with and without the technology. Some of the technology switches are evaluated in Table 5-3 for the two previously selected architectures. The values indicate the influence in IMLEO by turning the technology on. A large negative number indicates that the technology provides more benefit while a large positive number indicates that the technology increases the IMLEO when applied to that architecture.

Table 5-3 Influence of technology "switches" on selected architectures

Architecture ID (all units mt)	Δ IMLEO NTR	Δ IMLEO SEP	Δ IMLEO ISRU	Δ IMLEO Aerocapture
0001	-324	+70	-35	n/a*
2647	-35	-107	-14	-3,120

(*This architecture is infeasible within the modeling capability of the evaluation software without aerocapture).

From these two examples it becomes clear different technologies can have varied influence depending on the other system architecture decisions. For example NTR is a huge factor in the performance of architecture 0001 while an order of magnitude less significant for architecture 2647. SEP is significant for 2647 and actually increases IMLEO for 0001. Meanwhile ISRU and aerocapture provide benefit to both architectures while the benefit is smaller for ISRU and very significant for aerocapture.

5.4.1 TECHNOLOGY-SWITCH IMPACT RANGE

While it is relatively trivial to evaluate these technology "switches" for an arbitrary set of architectures, the resulting data produced is cumbersome to navigate. A given switch may drastically alter one architecture while contributing only marginally to another. We are interested in the question "What are the performance improvements across the tradespace from any given technology?" as opposed to looking at one or two architectures at a time. To treat these influences systematically, we can look at the subset of architectures within the "architectures of interest" or "fuzzy Pareto" region described in section 5.3. For each of these architectures the technology switch is evaluated to understand the range of influence a technology can have in that part of the tradespace. The resulting distribution of the influence of the technology for all feasible architectures gives a good understanding of the overall range of impacts a technology can have without unfairly giving preference to a certain architecture. It would be misleading to claim the influence of a technology is that associated with only a single reference design when ambiguity in those other system parameters remains. Plotting a histogram of this influence can give a sense of the magnitude of impact. It will also give a sense if the derived performance benefits are consistent across all architectures or rather highly dependent upon other architectural decisions.

An example of this range is shown in Figure 5-6 for the influence on IMLEO of NTR across the architectures of interest in the fuzzy Pareto region..

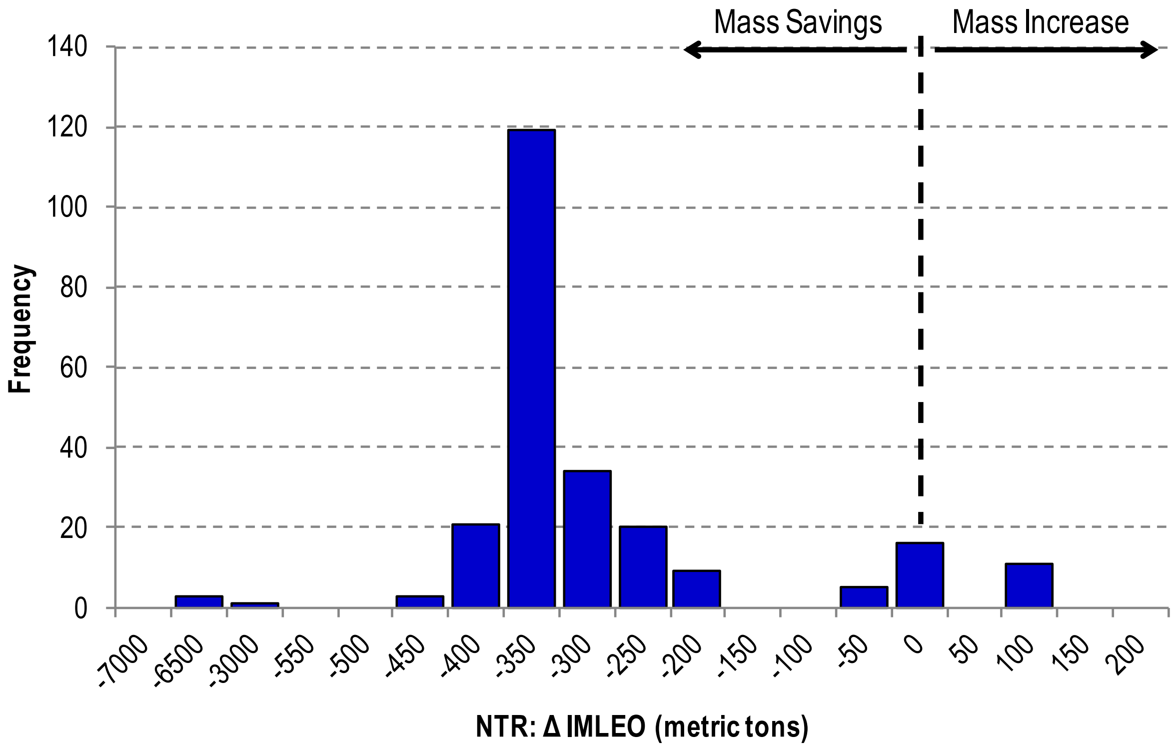
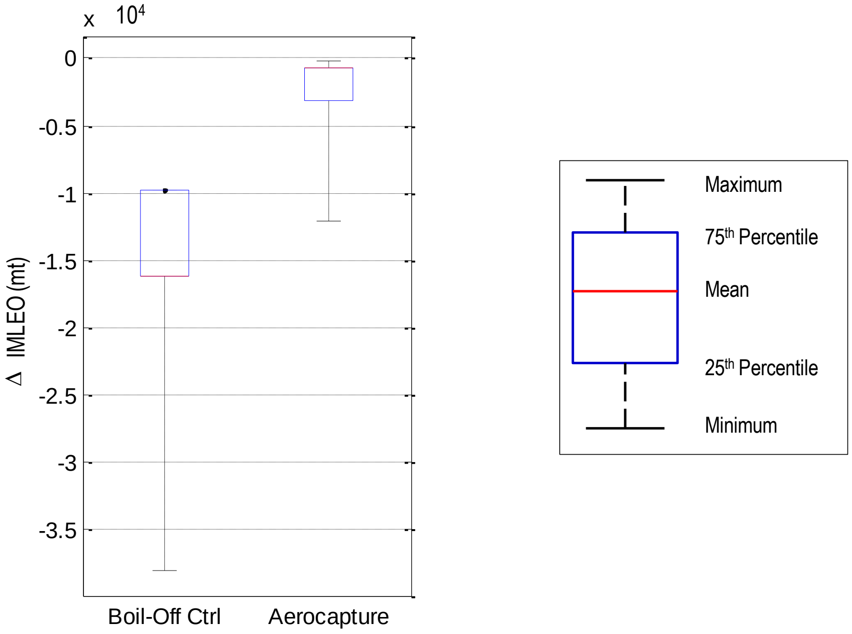


Figure 5-6 Histogram of Technology-Switch Impact Range for NTR

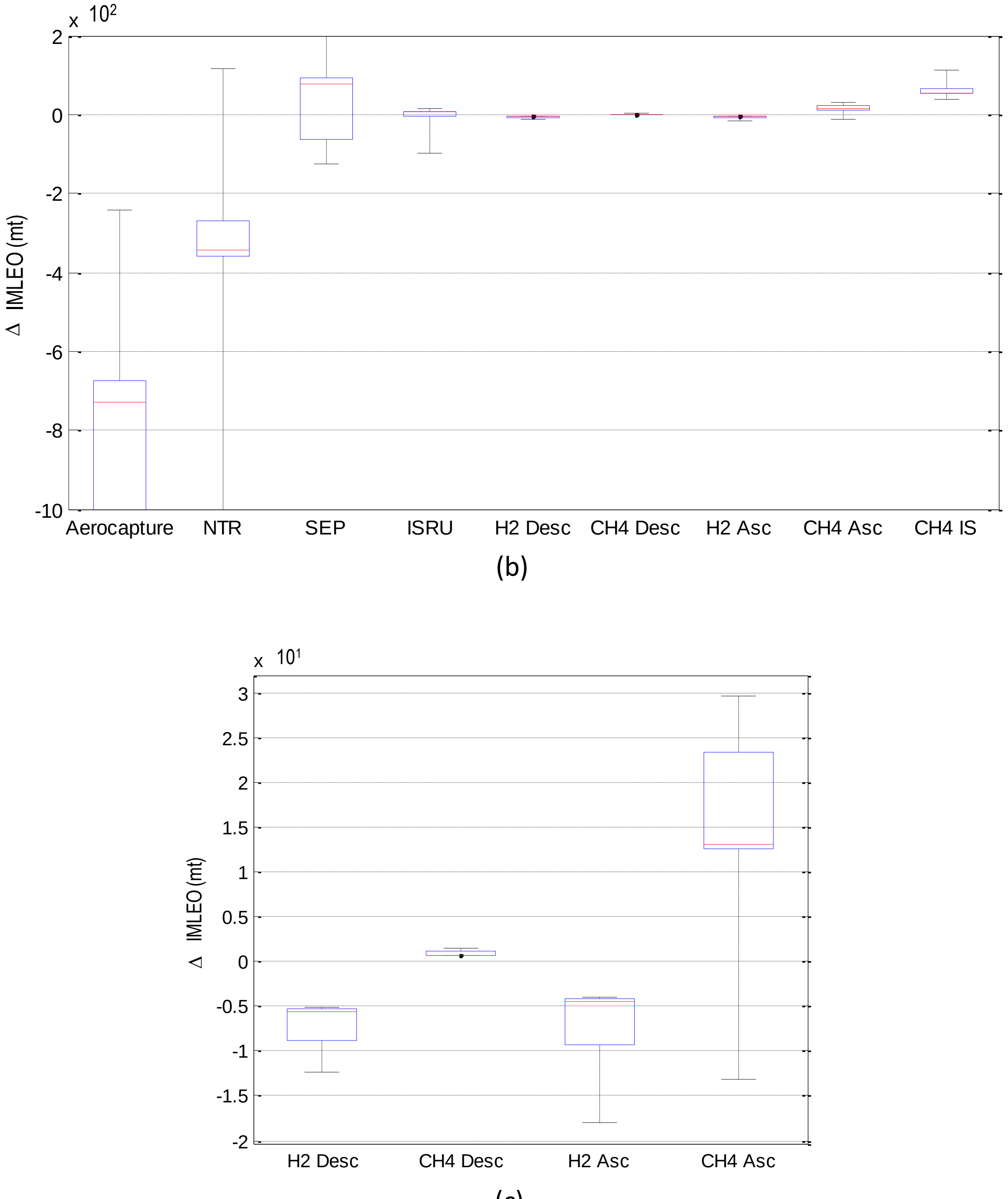
Traditional wisdom would indicate that NTR will provide significant performance benefit to the system by reducing IMLEO compared to a chemical in-space propulsion alternative. Looking across the architectures of interest this is often, but not always the case. The benefit of switching between NTR and chemical propulsion can range from an IMLEO reduction of thousands of metric tons all the way to an increase in mass of hundreds of metric tons. This means a significant number of good architectures are so well suited to chemical propulsion that they perform less efficiently with the added large dry mass of the NTR power plant, despite benefits from improved specific impulse. The mean influence is a reduction in IMLEO of about 350 metric tons, but it is now clear how this value alone does not explain the overall impact of NTR.

Each technology available in the system design space will have an associated distribution of influence across the architectures of interest. The most important relevant information can be captured in a simplified figure that allows comparison across multiple technologies. Figure 5-7 shows the various technology switch impact ranges for all major technologies on the system architecture tradespace. For each box-and-whisker plot the whiskers denote the minimum and maximum impact for all architectures of interest, the boxes denote the 25th and 75th percentile impact ranges, and the red bar indicates the mean impact.



(a)

(Figure 5-7 (b) and (c) follow on the next page)



(b)

(c)

Figure 5-7 Box & Whisker plots of technology-switch impact range (organized by order of magnitude): boil-off control and aerocapture (a), all technologies except boil-off control (b), and cryogenic descent and ascent propulsion stages (c)

In Figure 5-7 (a) the impact from boil-off control is two orders of magnitude larger than most of the other technologies and no architectures are feasible without this technology. That is to say when otherwise good architectures have the "switch" of boil-off control turned off, they all become infeasible. This indicates that some amount of boil-off control will be necessary in the overall architecture; the transportation system simply becomes infeasible without it. The technology tradeoffs between various cryogenic propellants for ascent/descent stages and hypergolic propellants are an order of magnitude smaller than the other technologies being considered. The highly variable impact of a methane ascent stage (as compared to the other descent/ascent stages) is due to coupling effects with ISRU. Some architectures leverage the benefits of ISRU while others do not and as a result this is a technology that can provide either a significant performance increase or decrease. The overall impact of a methane descent stage is near 0, indicating a very even tradeoff (on mass alone) with storable hypergols. NTR, SEP, and ISRU all have impact ranges that significantly span positive and negative regions. These wide impact ranges indicate the potential for associated benefits are highly coupled to other decisions and can't be arbitrarily assumed to be good or bad. They depend on other aspects of the definition of the architecture. ISRU has a mean impact resulting in mass growth but can have as much beneficial influence as SEP (depending on the architecture).

These results show large variability in flipping the "switch" for any given technology however it does not necessarily represent the actual magnitude of influence on system wide metrics. Since the calculation of technology switch impact is performed on an architecture with and without a technology, it does not fairly represent the complex set of decisions that are tied to the inclusion of any given technology. If a technology is planned to be included in an architecture but development of the technology fails, it is unlikely that all other aspects of the architecture will remain constant. Every technology decision is tied to a series of logical other decisions within the architecture that may change if one variable is adjusted.

The calculation of the technology switch impact frequently includes heavily dominated architectures that would never be pursued. The reason these architectures are unrealistic is best described with an example. There could be an architecture that is highly reliant on the high specific impulse of NTR where several large delta-v maneuvers are aggregated into a small number of stages. If the development of NTR fails and this technology is no longer available it would not necessarily be directly replaced with massive chemical stages. Rather, other adjustments to other parts of the system would be made, either employing other technologies, or at a minimum, reconfiguring the rocket stages to a scheme that is more optimized for chemical rockets. Due to the sensitivity to certain parameters, the magnitude of change in performance of an architecture when a single technology is flipped on or off may be significant. However since this inferior architecture would never be pursued, the resulting change does not provide a good measure of the overall influence of the technology.

It is desirable to use another measure of technology influence that considers the variation in all system architecture parameters but only considers feasible, preferred architectures in determining the overall influence.

KEY POINTS

- *Evaluating technology switches for only one or two architectures can obscure the overall impact of a technology considering the ambiguity in other system parameters.*
- *Technology switches cause a wide range of changes in metric values depending on the specific architecture being considered and the other decisions to which any given technology is coupled.*
- *The distribution of technology switch impacts does not necessarily provide a realistic view of the magnitude of a technology's overall influence since changing a technology may result in changes to other architectural variables.*

5.4.2 TECHNOLOGY INFLUENCE MEASURE (TIM)

As described in section 4.2 the Technology Influence Measure (TIM) (see Equation 4-2) captures more complex information than the technology switches from the previous section. Rather than isolating the technology and considering the distribution of influences a technology has, TIM provides an abstracted measure of average influence considering the complex interactions that exist between architecture decisions and tradeoffs that occur between metrics. Assuming all the architectures in the fuzzy Pareto region are realistic architectures, TIM provides the overall influence in mass savings (or growth) and technology LCC savings (or growth) that come as result of implementing a new technology. In Figure 5-8 the TIM of IMLEO is shown for each technology considered in the design space.

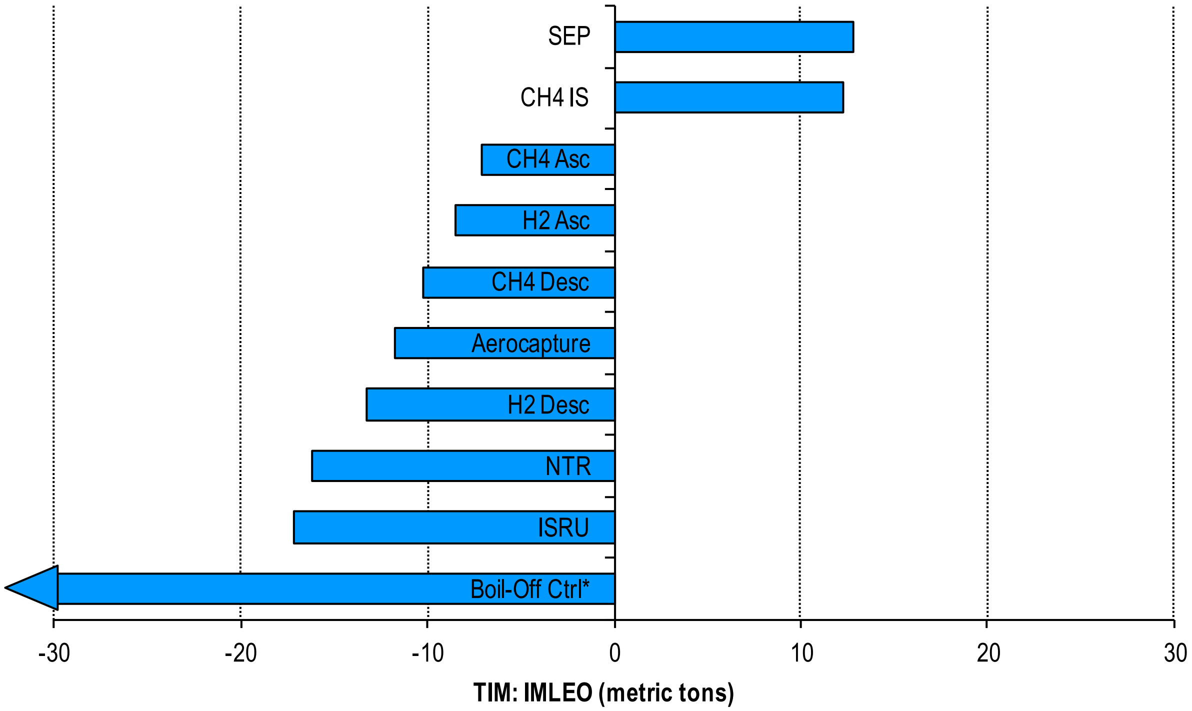


Figure 5-8 Technology Impact Measure for IMLEO for Mars transportation architectures

***Note that $\mathrm{TIM}_{\mathrm{IMLEO}}$ is negatively infinite for boil-off control because every feasible architecture has the technology included.**

As compared to Figure 5-7, the disparities between the magnitude of influence of different technologies is much smaller in Figure 5-8. This indicates that the fuzzy Pareto region being considered has a range of architectures that all respond significantly to changes in technology and architectural decisions. The exception to this is the influence of boil-off control which is arbitrarily large for IMLEO because all feasible architectures require that boil-off control is implemented (within the fidelity of the evaluation model that was used). While each technology (other than boil-off control) has an influence in the same order of magnitude, SEP and CH4 in-space propulsion have positive TIM values rather than negative TIM values. This indicates that the average influence of these technologies in the region of preferred architectures is an increase in IMLEO. While increasing IMLEO may not seem desirable, this is the influence within a region that is already considered to be of high performance.

Each technology influences the overall system in very different ways for both the IMLEO and technology LCC metrics. These different influences are made clear when each technology is plotted on axes corresponding to each of these influence measures in Figure 5-9.

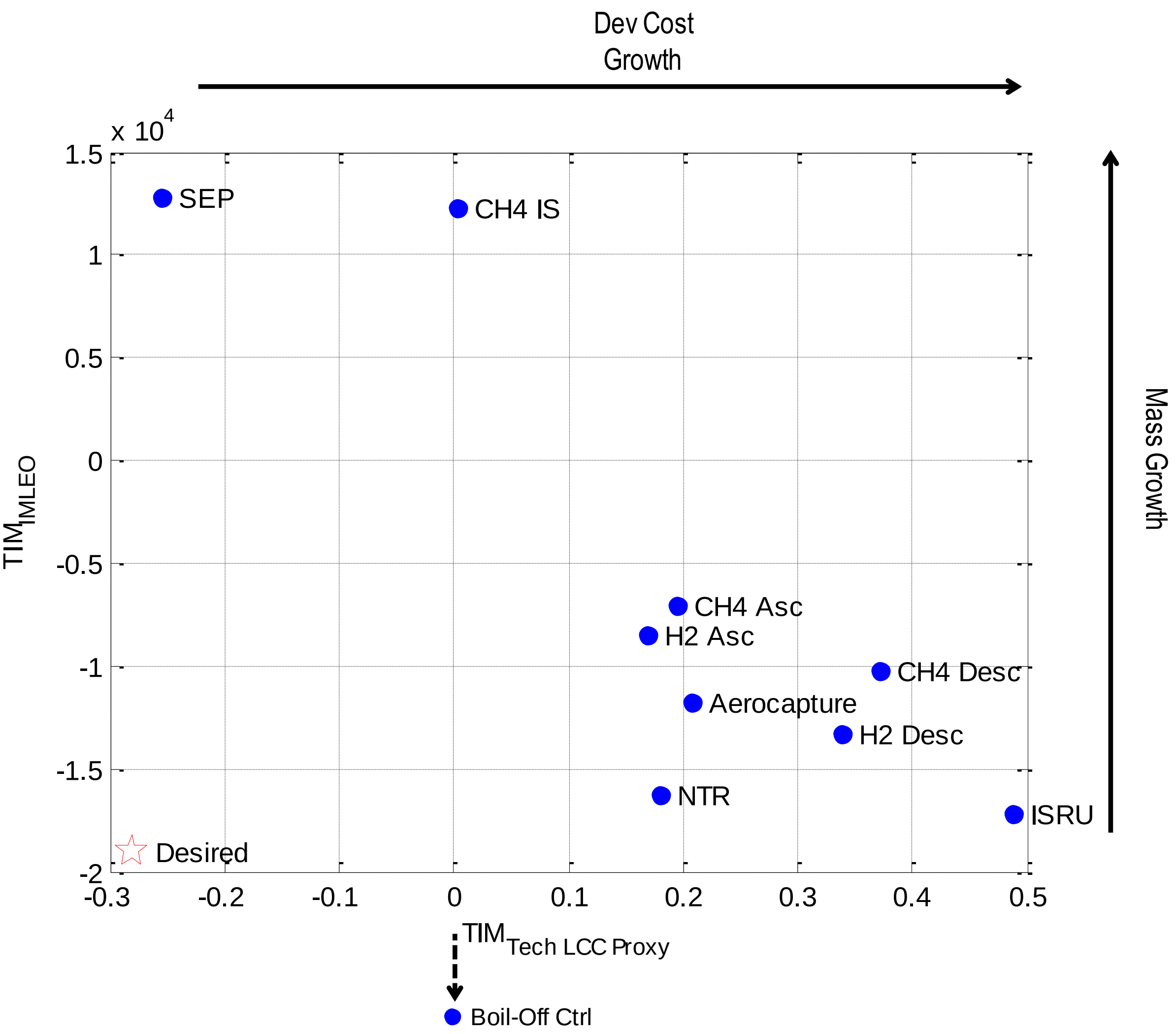


Figure 5-9 Technology Impact Measure (TIM): IMLEO vs. technology LCC proxy for Mars transportation technologies

An inherent tension between influencing IMLEO and influencing technology LCC proxy is seen as the clustering of technologies in opposing corners of Figure 5-9. It is expected (and observed) that the implementation of most technologies results in a mass savings and an increase in the technology LCC proxy. For both the in-space CH4 stage and use of SEP these correlations are reversed. Both these technologies result in an architecture that is on the higher end of the acceptable IMLEO range while having some technology LCC savings. This effect is particularly strong and unique to implementing Solar Electric Propulsion (SEP) for pre-deployment of cargo. The favorable SEP architectures tend to be more fractionated and slightly less efficient in terms of mass, however they allow for significant amounts of pre-deployed cargo on more efficient trajectories and do not require many other major technologies to create a fairly efficient transportation system. The methane stage results in a relative increase in IMLEO across the tradespace and virtually no impact on technology LCC. The increase in IMLEO is in comparison to other non-dominated architectures relying on higher specific impulse propellants. However, this stage can be implemented without significant technology LCC impact. When sensitivity to the performance of boil-off control is considered over its development, the alternative of methane stages (which are significantly less sensitive to boil-off of propellant) will become more valuable. At this high level of abstraction we do not capture these other benefits from using methane due to its insensitivity to boil-off control; however this is a subtlety of coupling between technologies that will be treated in the next section.

The ideal desired technology would sit in the lower left hand corner of Figure 5-9. That region of the plot represents a technology that provides reduction in both IMLEO and technology LCC proxy. Considering that this ideal most likely does not exist, the inherent differences between NTR and SEP are immediately clear. NTR is a high-cost, high-performance technology. SEP is a technology that can reduce overall cost but will not provide the same mass-efficiency in performance. Recalling architectures 0001 and 2647 from Table 5-2, these two points in the tradespace take advantage of these different system influences. Architecture 2647 has a higher IMLEO but lower technology LCC and architecture 0001 is the lowest IMLEO point in the space but has the highest technology LCC of any point on the Pareto front.

KEY POINTS

- *Applying the Technology Impact Measure (TIM) on the fuzzy Pareto region abstracts complex interactions between system architecture decisions to show a realistic view of the influences of each technology given a wide architectural tradespace.*
- *Most technologies reduce IMLEO and increase development cost, but Solar Electric Propulsion (SEP) has the opposite interaction on the system.*
- *Boil-off control is required to realize a feasible architecture to Mars.*
- *Boil-off control, SEP, NTR, and aerocapture are all highly beneficial technologies in the Mars transportation tradespace.*

5.5 FORM-FUNCTION ASSIGNMENT DECISIONS IN THE TRADESPACE

This thesis is focused on the technologies within the tradespace, but clearly the functional decomposition of transportation stages and habitats is important. (For more detail on how functional decomposition defines an architecture see Section 3.3). Architectures 0001 and 2647 demonstrate intuitively some of the differences. Architecture 2647 realizes benefits from pre-deploying separate stages on low energy trajectories while architecture 0001 aggregates more delta-v into the large, high-specific impulse nuclear stage. The alternative system decompositions for habitats and transportation stages are numerous, but reduce down to some repeating patterns in the good architectures. Since the allocation can be described as a series of binary combinations, we can consider the frequency with which certain function-form combinations occur in the previously defined “fuzzy Pareto” architecture set in order to analyze what decomposition factors make it into the non-dominated region, and specifically which combinations of habitats and propulsive maneuvers result in good architectures.

An n-squared diagram enumerates possible combinations of each habitat or transportation function together in Table 5-4 and Table 5-5. The value in each cell is the frequency with which those two habitat or transportation functions are combined into the same element (or stage) among the preferred architectures in the fuzzy Pareto region.

Table 5-4 Frequency of function combinations for habitat elements

	Launch	IS Out	Descent	Surface	Ascent	IS Return	Re-Entry
Launch		43%	9%	9%	0%	33%	17%
IS Out			35%	35%	0%	65%	7%
Descent				75%	7%	0%	0%
Surface					0%	0%	0%
Ascent						0%	0%
IS Return							10%
Re-Entry							

Table 5-5 Frequency of function combinations for transportation stages

	E Dep	M Arriv	Desc	Asc	M Dep	E Arriv
E Dep		0%	0%	0%	0%	0%
M Arriv			0%	0%	74%	65%
Desc				14%	0%	0%
Asc					0%	0%
M Dep						82%
E Arriv						

The highlighted values in each of Table 5-4 and Table 5-5 represent the most frequent features that appear in the preferred tradespace. No function combinations are completely dominant and occur in every architecture. However, several potential combinations never occur in this preferred set of architectures. In the following sections the distinctive features that appear frequently in good architectures, (highlighted in yellow), will be considered in how they couple to various technologies in the tradespace.

5.6 COUPLING BETWEEN TECHNOLOGIES AND OTHER ARCHITECTURAL FEATURES

Section 5.4 provided a framework to understand and quantify the influence of each technology on the architectural tradespace. In the distributions plotted in Figure 5-7 the wide variability of influences indicates there are significant couplings to other technologies and architectural features that can significantly change the influence of any given technology. Evaluating the TIM in Figure 5-9 removes the information of the variability of the influence. However by considering the specific coupling or interaction effects that occur, we can define not just the variability of influence with a single variable but the other specific features with which it must be combined to achieve the best performance (or those features with which it should not be combined to avoid performance losses). In addition to evaluating the overall impact considering all preferred architectures, it is important to identify the strong couplings amongst the architectural decisions that influence the performance gains and losses associated with different technologies.

5.6.1 METHANE AND BOIL-OFF CONTROL: A MOTIVATING EXAMPLE

As described in Section 3.5.5 all the cryogenic propellants have associated boil-off rates. Implementing boil-off control technology is modeled as a system dry mass penalty and a reduction in the rate of propellant loss over time. However the boil-off rates for methane propellant are significantly lower than that of the liquid hydrogen associated with the other in-space propellant alternatives of nuclear thermal rockets and LOX-LH2 chemical propulsion. It is then expected that there may be some important couplings between the various methane propulsion stages and the implementation of boil-off control technology.

To evaluate the coupling that may (or may not) exist between implementing methane in the various major propulsive stages and boil-off control we can look at the previously defined TIM to the methane technology decision. To understand the differences that occur with boil-off control on and off, we can evaluate the TIM (influence measure) of the major methane stages for two different subsets through the architecture tradespace- those architectures with boil-off control and those architectures with no boil-off control.

In Section 5.4.2 the TIM was defined over the set of preferred architectures in the fuzzy Pareto region. However it has already been established that boil-off control is always on for the architectures below the feasible IMLEO constraint. To be able to evaluate the various couplings that occur with boil-off control more precisely, it is necessary to consider the couplings through the entire tradespace, including architectures that otherwise violate this mass constraint. As a result the values associated with technology coupling measures are only useful in relation to other couplings in the same tradespace. They do not represent the actual magnitude of impact on the tradespace since the evaluation considers architectures that are otherwise infeasible. While they do not necessarily indicate absolute influence, the relative magnitudes from one coupling measure to another do provide a good understanding of the coupled influences throughout the tradespace.

The TIM for implementing methane stages across the four major propulsion segments are shown in Figure 5-10, evaluated for architectures both with and without boil-off control respectively. Recalling the definition of TIM (Section 4.4), the lower the value in the figure, the greater the relevant benefits derived by implementing the associated technology.

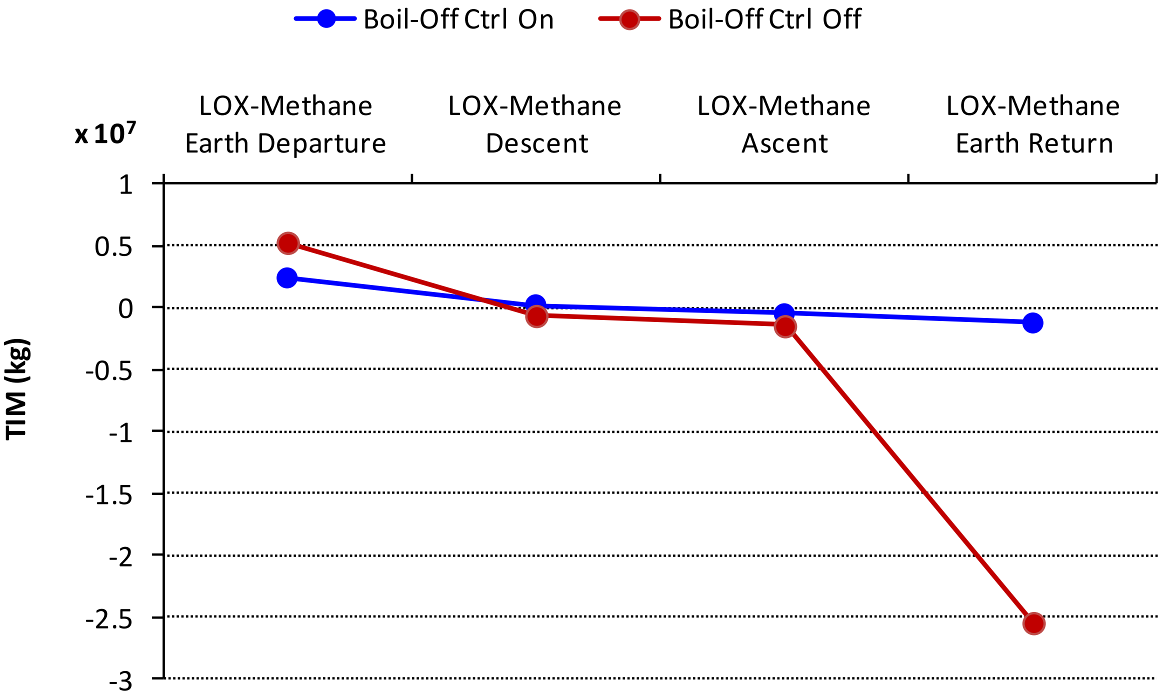


Figure 5-10 Interaction effects between methane propulsion technology and boil-off control

The overall magnitude of influence from methane with boil-off control is smaller than the influence of methane without boil-off control as demonstrated by the blue line in the figure remaining closer to the 0 (no influence) line. This makes intuitive sense as the primary benefit from implementing methane is a reduction in boil-off rate. At a high level the flattening of this (blue) curve indicates that boil-off control reduces sensitivity to these decisions of implementing methane in each stage. By reducing the overall influence of the technology, boil-off control makes the tradeoff between methane and other propellants more even.

Looking in detail one maneuver at a time, a methane Earth departure stage creates a positive change in mass, indicating it is not a preferred technology compared to the alternative choices. The influence of methane and relative difference with or without boil-off control for the descent and ascent stages is quite a bit smaller than the influences for the large in-space stages. Finally, for the return stage, there is a very significant difference in the benefits of methane with and without boil-off control. Most of the benefits of methane go away on the return stage when boil-off control is implemented. It is necessary to understand how boil-off control can reduce the benefits of methane.

Relative performance of these stages depends primarily on the impulse requirement for the stage and also the time that passes before the stage is expended- that is how much propellant there is to dissipate (boil-off) and the time it has to do so. It becomes clear in the return stage the advantage of methane is the low boil-off rate for a stage that has to remain in space for years before being used. When boil-off control is implemented other propellants no longer have a much higher boil-off rate than methane, and the relative benefits of methane become less significant. This does not necessarily indicate methane is or is not an overall good choice for the Earth return stage. It does say however that the answer to this question is highly coupled to the implementation of boil-off control in that stage.

In this example of technology coupling, the decisions for propellant types for each stage do not necessarily happen all instantaneously. The implementation timeline for the Mars transportation system will certainly be measured in decades, and advances in various technologies through that time are highly uncertain. Most likely an Earth departure stage will be developed first as a capability for demonstration and precursor missions. This will almost certainly take place long before design and development of the descent, ascent, and possibly in-space return stages are completed (or even well-defined). Understanding that boil-off control is able to reduce the sensitivity to a later propellant type decision is very valuable. It is possible that the Earth departure stage can be defined and operated while development on boil-off control continues. As time passes and the uncertainty on the performance of boil-off control is resolved, the later stages (especially the in-space return stage) can be re-evaluated based on a better understanding of the performance of boil-off control and the availability of the various exotic in-space propulsion systems. This is a significant opportunity for flexibility in the development of the entire system architecture that comes from boil-off control's interaction effects with propellant decisions.

KEY POINTS

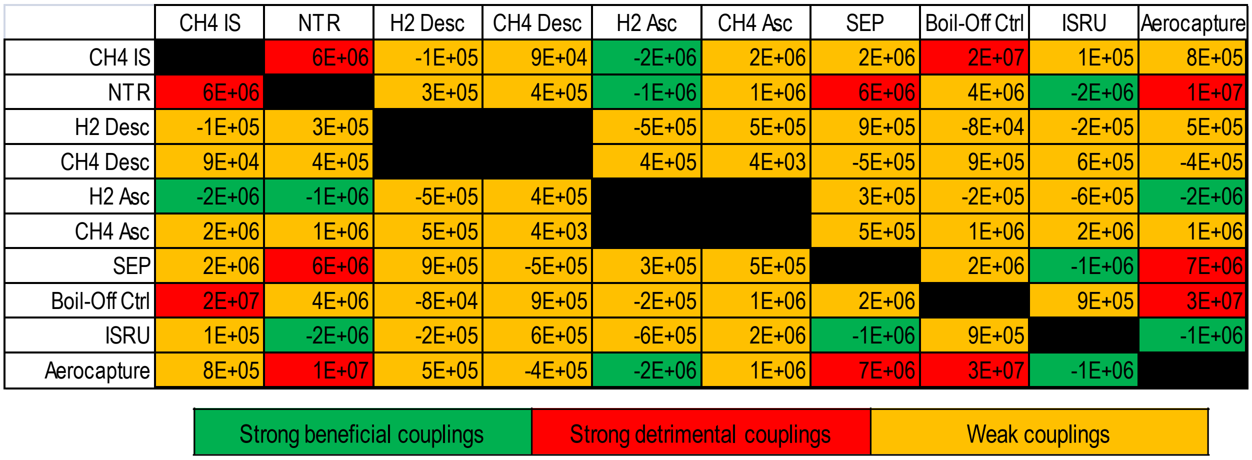
- *Implementing boil-off control can reduce the sensitivity to propellant type decisions.*
- *Interaction effects or coupling among system architecture technology decisions provides relevant information to decision makers.*
- *Reducing Technology Impact Measure (TIM) or sensitivity of a technology indicates possible opportunities for flexibility in the development process of different segments of the architecture.*

5.6.2 TECHNOLOGY COUPLING INTERACTION EFFECTS (TCIE)

In the previous section a specific coupling is selected and analyzed in detail. However looking through a complex tradespace with many possible technologies to consider, it is desirable to have a thorough method for searching for strong interaction effects between technologies and other architectural features. In particular it is important to be able to detect those couplings that were not predicted a priori. These interaction effects are a result of constraints and interfaces that get implemented in modeling but are not necessarily apparent to the designer due to the complexity of system interactions.

We have now motivated that we want a comprehensive understanding of the interaction effects of technologies within the tradespace. A single metric will not necessarily indicate the complexity of analysis from the previous section, however it can help sort through a large combinatorial space of couplings, where it is worth considering interaction effects in more detail. For any two technologies the Technology Coupling Interaction Effect (TCIE) is evaluated according to the equation in Section 4.5 (see Equation 4-3). These values are essentially the change in TIM for a technology caused by the presence or absence of another technology. These values are then organized in an n-squared matrix that encompasses the interactions between all technologies in consideration. This matrix is the Technology Coupling Interaction Matrix (TCIM) shown below in Table 5-6.

Table 5-6 Technology Coupling Interaction Matrix (TCIM) for Mars transportation technologies



	CH4 IS	NTR	H2 Desc	CH4 Desc	H2 Asc	CH4 Asc	SEP	Boil-Off Ctrl	ISRU	Aerocapture
CH4 IS		6E+06	-1E+05	9E+04	-2E+06	2E+06	2E+06	2E+07	1E+05	8E+05
NTR	6E+06		3E+05	4E+05	-1E+06	1E+06	6E+06	4E+06	-2E+06	1E+07
H2 Desc	-1E+05	3E+05			-5E+05	5E+05	9E+05	-8E+04	-2E+05	5E+05
CH4 Desc	9E+04	4E+05			4E+05	4E+03	-5E+05	9E+05	6E+05	-4E+05
H2 Asc	-2E+06	-1E+06	-5E+05	4E+05			3E+05	-2E+05	-6E+05	-2E+06
CH4 Asc	2E+06	1E+06	5E+05	4E+03			5E+05	1E+06	2E+06	1E+06
SEP	2E+06	6E+06	9E+05	-5E+05	3E+05	5E+05		2E+06	-1E+06	7E+06
Boil-Off Ctrl	2E+07	4E+06	-8E+04	9E+05	-2E+05	1E+06	2E+06		9E+05	3E+07
ISRU	1E+05	-2E+06	-2E+05	6E+05	-6E+05	2E+06	-1E+06	9E+05		-1E+06
Aerocapture	8E+05	1E+07	5E+05	-4E+05	-2E+06	1E+06	7E+06	3E+07	-1E+06	

🟩 Strong beneficial couplings
🟥 Strong detrimental couplings
🟨 Weak couplings

In the TCIM certain values have been blacked out because they represent the undefined interaction effects between mutually exclusive technologies such as a methane and liquid hydrogen descent stage, only one of which can be present in a single architecture at a time. Cells highlighted in green represent the top 10% strong beneficial interaction effects, indicating the IMLEO is greatly reduced when those two technologies are combined. Cells highlighted in red represent the top 10% strong detrimental interaction effects, meaning the IMLEO generally increases when two technologies are combined together.

The highlighted interaction effects in Table 5-6 provide insight into important couplings. The strong interaction effects between boil-off control and an in-space methane return stage have already been discussed in the previous section. We can now quickly identify what technologies strongly influence each other and those that are more weakly coupled. For example one of the strongest interactions occurs between NTR and Aerocapture. To see in a little more detail how this coupling manifests itself, we plot the average mass of four subspaces within the architectural tradespace- the architectures with and without NTR, and the architectures with and without aerocapture. Figure 5-11 plots these subspaces.

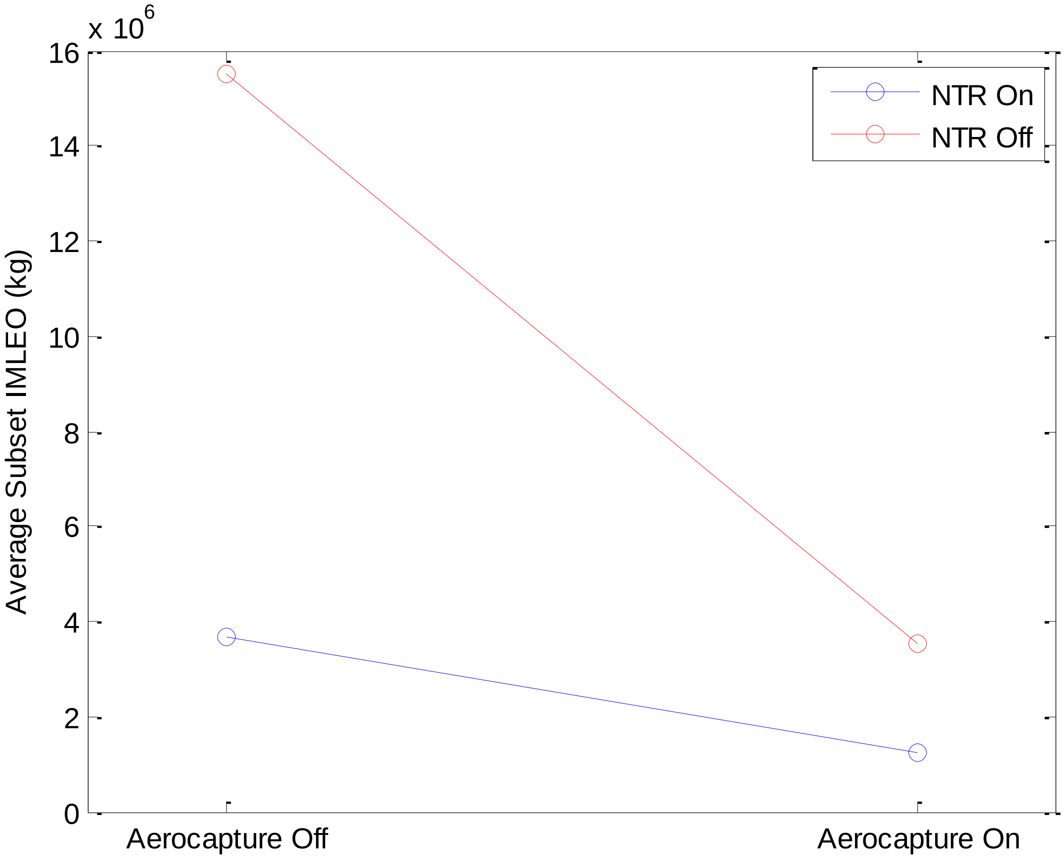


Figure 5-11 Strong interaction effects between NTR and aerocapture

Looking back at the TIM displayed in Figure 5-8 and Figure 5-9, the impacts of aerocapture and NTR are quite similar. What is not clear from those figures alone are the benefits derived when both technologies are applied and how they influence each other. Looking at the subsets of NTR and aerocapture here, we see the influence of aerocapture is small once NTR has already been applied to the system. Moreover the magnitude of influence of aerocapture without NTR is nearly the same as the influence of NTR without aerocapture. There is a highly positive TCIE value between these technologies indicating one reduces the benefits of the other. This powerful result indicates there can be a tradeoff between the two, and it is not necessarily worth pursuing both as major development projects.

Another strong interaction effect occurs between SEP and NTR. While both provide benefit on average, the presence of one reduces the influence of the other as shown in Figure 5-12.

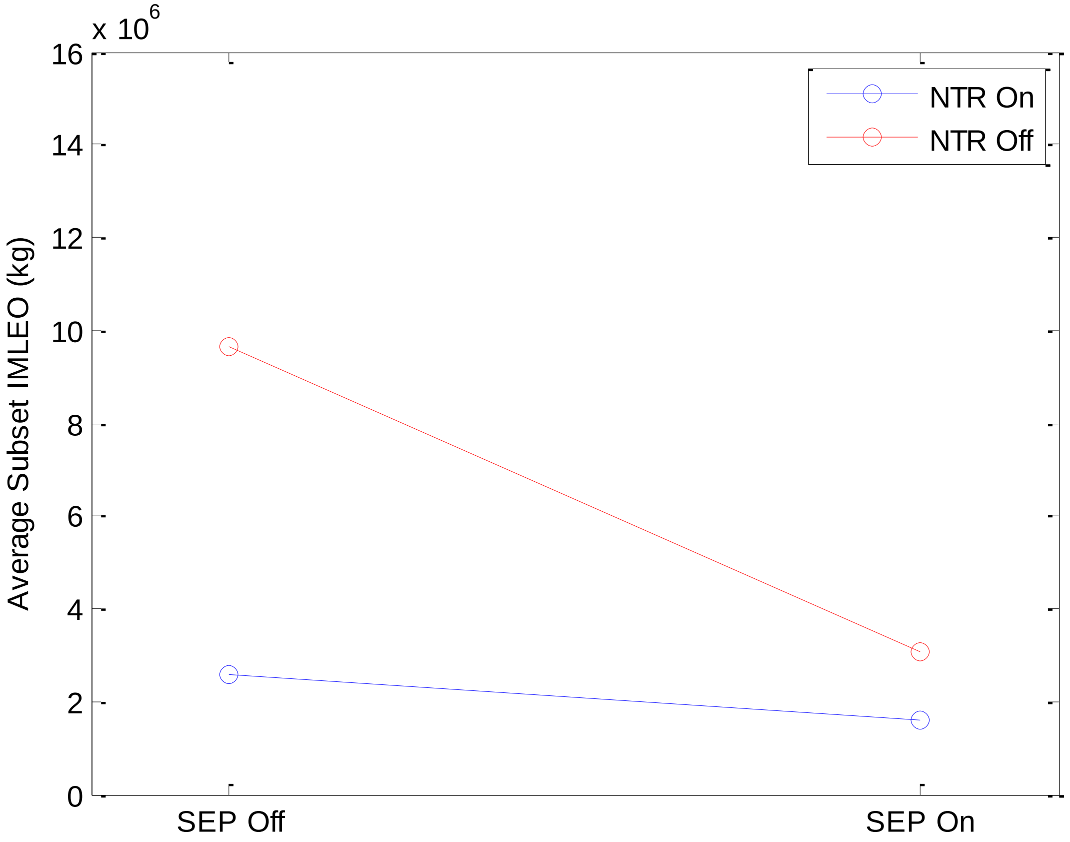


Figure 5-12 Strong interaction effects between NTR and SEP

SEP's benefits are derived when there is significant non-crewed mass that can be pre-deployed on a more efficient trajectory than with other propulsion types. In contrast when NTR is implemented the large powerplant required is usually used for both in-space segments of the journey. As a result, there is significantly less mass that SEP can pre-deploy as compared to architectures that may have larger Mars departure stages. Again this strong interaction demonstrates that both SEP and NTR can have strong influence on the architecture, but they do not complement each other well.

In contrast to a strong coupling it is worth looking at two technologies that interact weakly. The technologies of a liquid methane ascent stage and SEP for example have a fairly weak coupling as shown in Figure 5-13.

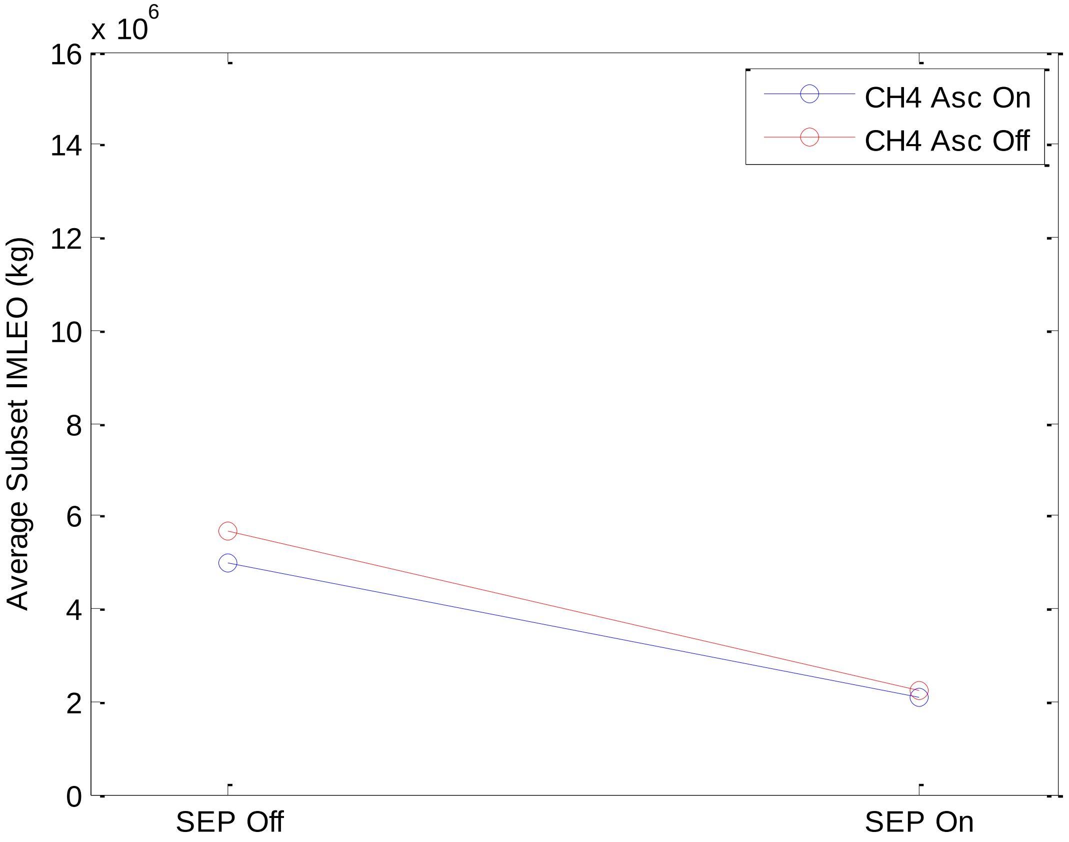


Figure 5-13 Weak interaction effects between SEP and LOX-CH4 ascent stage

The weak coupling is seen as nearly parallel lines on this chart with much lower slope than subsets from other interaction plots. While the influence of SEP and a liquid methane ascent stage have different overall influences on the system, the presence of one does not strongly change the influence of another.

When looking through all the couplings in the tradespace it is clear certain types of interaction effects frequently occur. While nothing inherently restricts the types of interaction effects that may occur between architectural features, archetypical interactions arise for the Mars transportation case being considered in this chapter as shown in Figure 5-14.

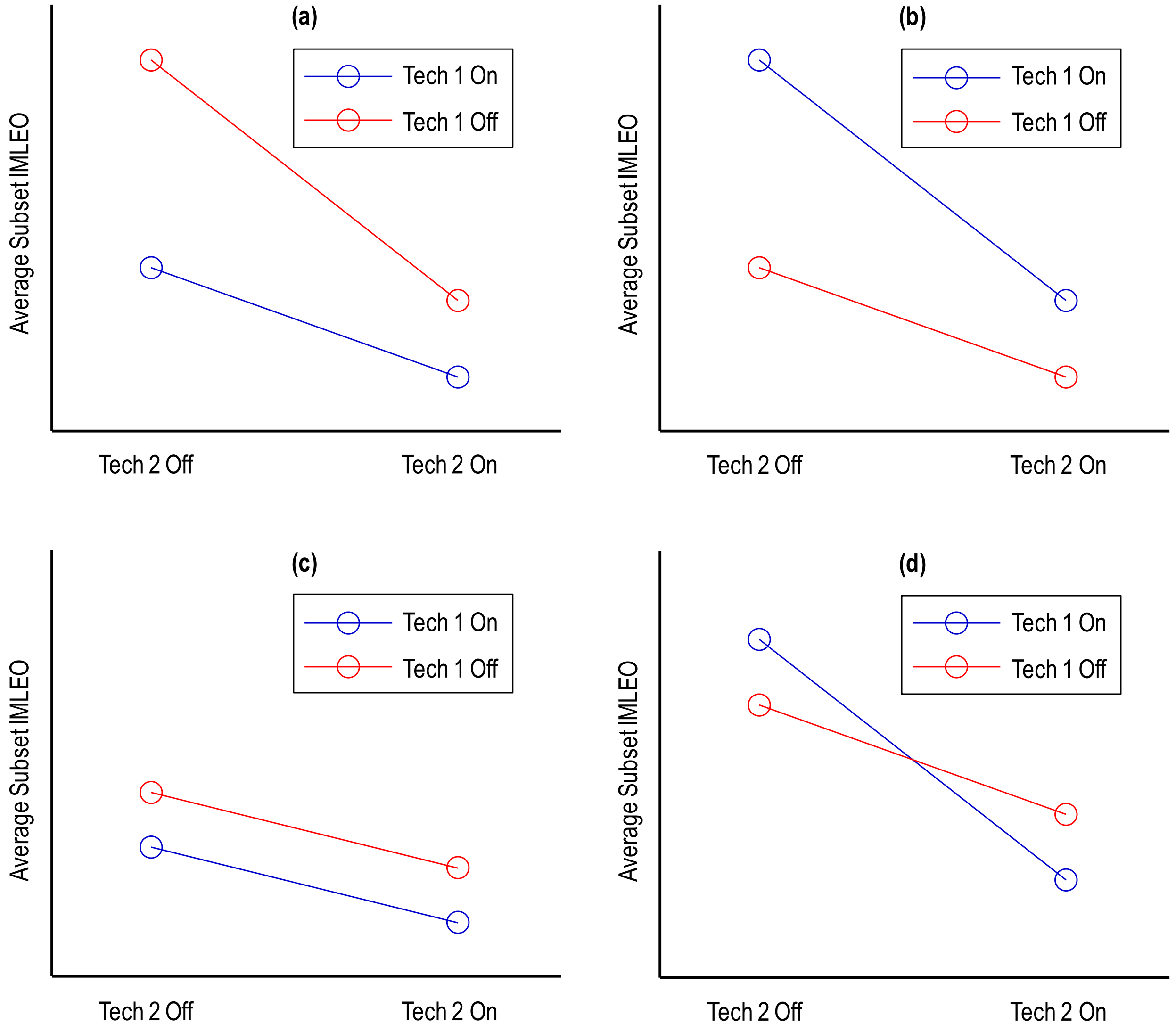


Figure 5-14 Cartoons of characteristic couplings throughout the tradespace

Figure 5-14 (a) demonstrates a typical coupling where two technologies both have strong influence on the system. However the presence of one technology reduces the overall influence of the second technology. This type of tradeoff occurs frequently in the tradespace being explored because of the inherent dynamics of the rocket equation that significantly drives the IMLEO of the system. Take for example a simple system of a rocket with two serial stages. Holding all other design parameters constant, a given reduction in total system mass can be created in several ways. Reducing the payload will linearly decrease the propellant load for both stages. Improving the performance of the second stage will decrease the second stage mass, and the resulting decrease in second stage mass will roll back to a reduction in first stage mass. Finally, improving the performance of the first stage will decrease its mass without any other effects. Due to these inherent strong coupling effects the benefits of technologies that provide small benefits to later stages or the payload of the system often provide a tradeoff with technologies that improve the performance of initial propulsive maneuvers. The NTR-aerocapture and NTR-SEP couplings already discussed fall into this category with large positive TCIE values.

Figure 5-14 (b) is similar to Figure 5-14 (a) except that in this case technology 1 is not beneficial (on average) for the system. Now both technologies have a strong influence on the system but the presence of technology 2 improves the performance of technology 1. An example of this type of coupling exists between SEP and ISRU. Averaging across the tradespace, the large descended dry mass penalty associated with ISRU makes this technology undesirable. However SEP greatly reduces this negative impact because it can pre-deploy the large mass on an efficient trajectory. More simply stated, SEP increases the desirability of ISRU. These beneficial interactions are characterized by a large negative TCIE.

Figure 5-14 (c) represents a variety of interactions with minimal coupling. Usually low interaction effects come from two technologies that do not influence each other's performance. In this case both lines will be parallel. The overall influence of the first technology will determine the spacing between the lines and the overall influence of technology two will determine the slope of the lines.

Finally, Figure 5-14 (d) represents two technologies that interact in such a way that the presence of one changes the overall preference for the other technology. These interactions can be of smaller or larger magnitude and will be more or less important as a result. An example of this sort of interaction is between ISRU and a LOX-CH4 ascent stage.

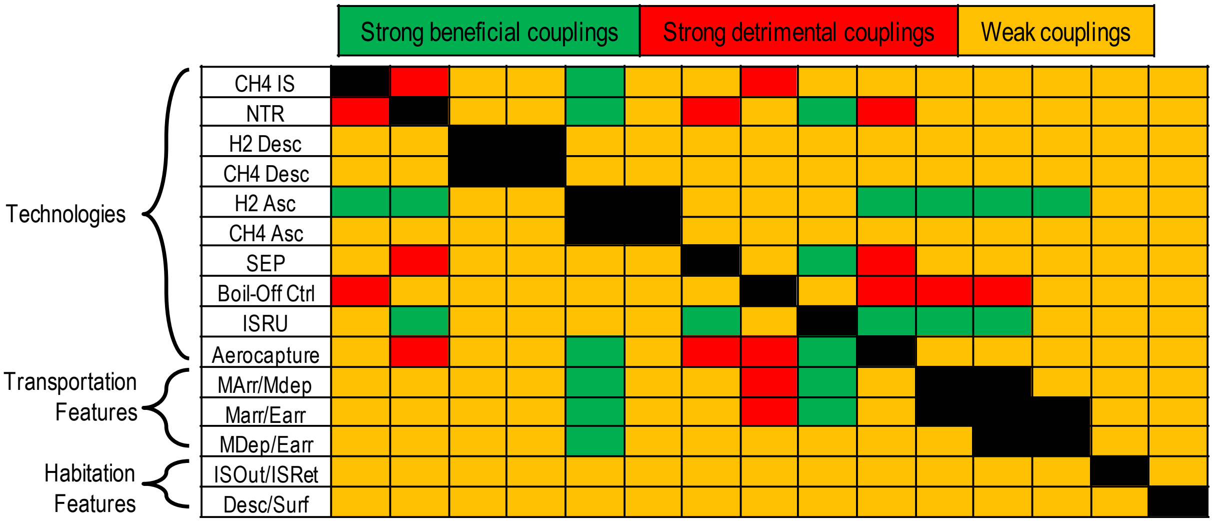
KEY POINTS

- *TCIM provides a comprehensive view of interaction effects- both strong and weak.*
- *Strong interaction effects change the value proposition of one technology in the presence of another.*

5.7 ORGANIZING THE DECISIONS THAT DEFINE ARCHITECTURE

While the influence and coupling analysis has been focused on the technology-related decisions that define architecture, the transportation and habitat element definition is also an important factor. These aspects that define system architecture can be difficult to treat in the same way as other decisions due to the nature of set partitioning problems (see Section 3.3.2). Nonetheless it is important to understand the coupling between the technologies and important architectural features that are defined by these partitioning problems. This helps to identify the non-technology features of architecture that are required to reap the benefits of different technologies. We already identified the habitat and transportation form-function allocation features that appear frequently among the preferred set of architectures in Table 5-4 and Table 5-5. Features such as the combination of the Mars arrival (MOI) and Mars departure (TEI) burns in a single stage are part of the defining aspects of reference design missions in literature; in this case defining a "Mars-Orbit Rendezvous" scheme. We can add the features that are prominent in the preferred architectures as a binary variable to the space of technologies we are considering. The binary variable is whether or not any two habitation or transportation functions are combined into a single element (1 or 0 respectively). Since we have now reduced these features of the partitioning problems of the architecture tradespace into a select number of binary decisions, we can define the same kind of interaction effects alongside the technologies being considered. Moreover we can expand the TCIM to include the 5 propulsion and habitat allocation features highlighted in Table 5-4 and Table 5-5. The expanded TCIM, including both technologies and architectural features, is shown below in Table 5-7 (with values removed for readability).

Table 5-7 Expanded TCIM including technologies and other architectural features



🟩 Strong beneficial couplings
🟥 Strong detrimental couplings
🟨 Weak couplings

Technologies	CH4 IS	⬛	🟥	🟨	🟨	🟩	🟨	🟨	🟥	🟨	🟨	🟨	🟨	🟨	🟨	🟨
	NTR	🟥	⬛	🟨	🟨	🟩	🟨	🟥	🟨	🟩	🟥	🟨	🟨	🟨	🟨	🟨
	H2 Desc	🟨	🟨	⬛	⬛	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
	CH4 Desc	🟨	🟨	⬛	⬛	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
	H2 Asc	🟩	🟩	🟨	🟨	⬛	⬛	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟨	🟨
	CH4 Asc	🟨	🟨	🟨	🟨	⬛	⬛	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
	SEP	🟨	🟥	🟨	🟨	🟨	🟨	⬛	🟨	🟩	🟥	🟨	🟨	🟨	🟨	🟨
	Boil-Off Ctrl	🟥	🟨	🟨	🟨	🟨	🟨	🟨	⬛	🟨	🟥	🟥	🟥	🟨	🟨	🟨
	ISRU	🟨	🟩	🟨	🟨	🟨	🟨	🟩	🟨	⬛	🟩	🟩	🟩	🟨	🟨	🟨
	Aerocapture	🟨	🟥	🟨	🟨	🟩	🟨	🟥	🟥	🟩	⬛	🟨	🟨	🟨	🟨	🟨
Transportation Features	MArr/Mdep	🟨	🟨	🟨	🟨	🟩	🟨	🟨	🟥	🟩	🟨	⬛	⬛	🟨	🟨	🟨
	Marr/Earr	🟨	🟨	🟨	🟨	🟩	🟨	🟨	🟥	🟩	🟨	⬛	⬛	⬛	🟨	🟨
	MDep/Earr	🟨	🟨	🟨	🟨	🟩	🟨	🟨	🟨	🟨	🟨	🟨	⬛	⬛	🟨	🟨
Habitation Features	ISOut/ISRet	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	⬛	🟨
	Desc/Surf	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	⬛

An example of the technology-architecture interaction effects is shown in the relationship between pre-deployment with SEP and the combination of the Mars Orbit Insertion (MOI) and Trans-Earth Injection (TEI) stages is shown in Figure 5-15.

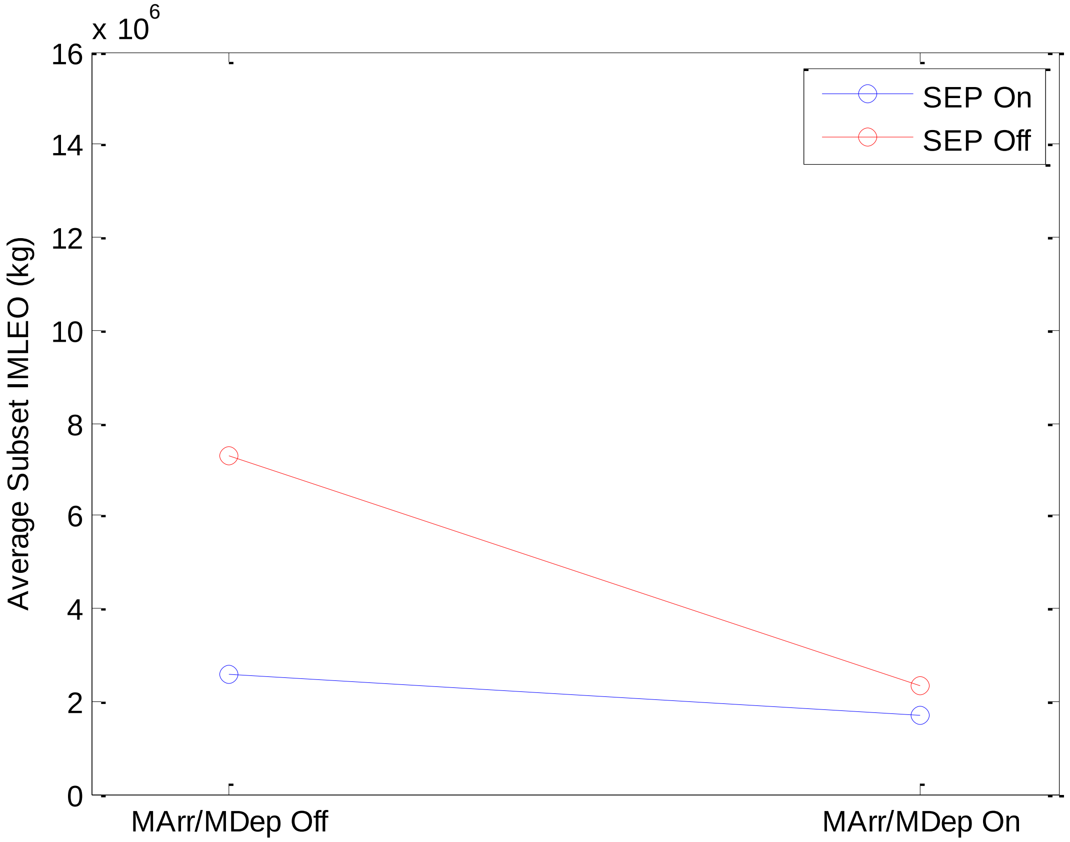


Figure 5-15 Interaction effects between SEP and MOI/TEI stage combination

This coupling is important because in order to benefit from SEP we want to pre-deploy as much mass as possible. There is much less benefit from SEP when the later return stages are combined with those required for initial MOI, meaning SEP effectively pre-deploys a much smaller percentage of the overall system. These features are seen together in architectures that employ a pre-deployment strategy on the Pareto frontier in section 5.3.

Another good example of technology-architecture coupling is the relationship between boil-off control and the combination of the MOI and TEI maneuvers into a single stage shown in Figure 5-16.

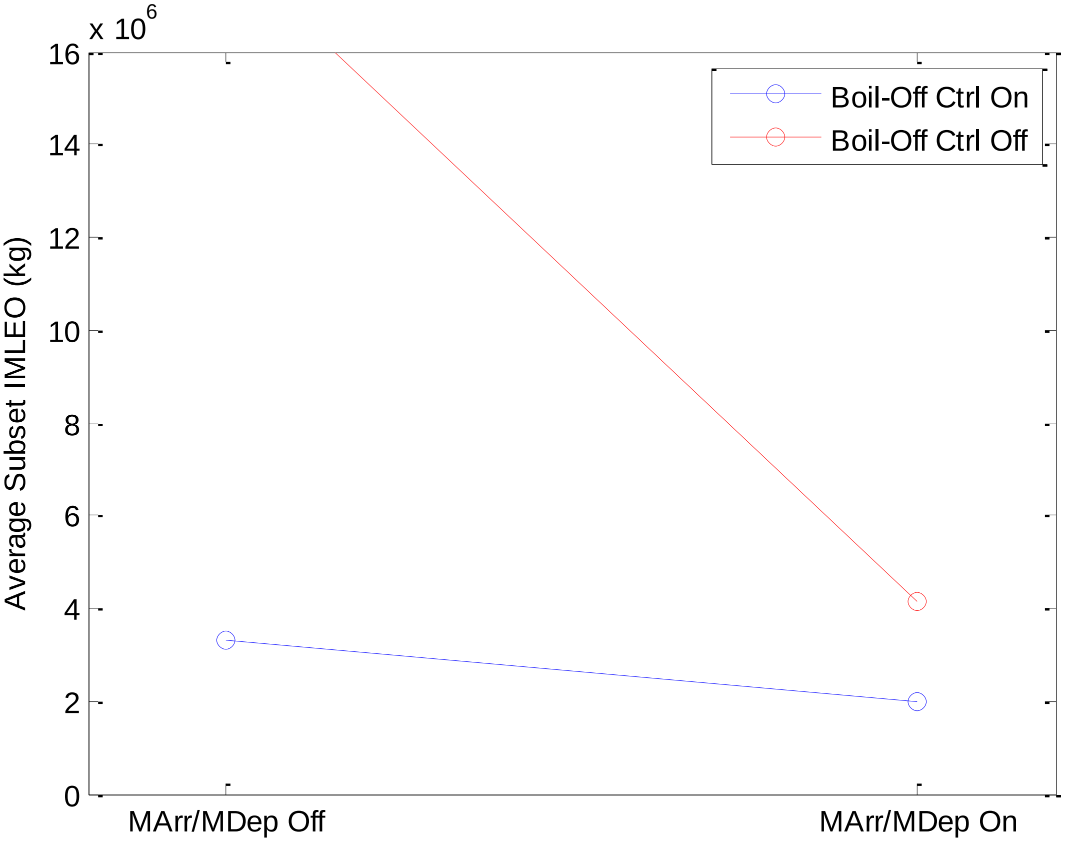


Figure 5-16 Interaction effects between boil-off control and MOI/TEI stage combination

While it has already been established that some amount of boil-off control is necessary for a feasible system, the negative coupling identified between this architecture suggests a strategy if progress in boil-off control is less than expected or the technology is not realized at all. When boil-off control is not implemented and the "Mars-orbit rendezvous like" stage allocation is used, there is a very large monolithic propellant stage that must remain in space for a long time. With a high rate of propellant loss for cryogenic propellants this produces very poor performance. However if boil-off control is unavailable and large maneuvers are performed in separate stages, higher specific impulse propellants with higher rates of boil-off can be used for early stages such as TMI and MOI maneuvers while a more storable propellant such as LOX-CH4 can be used for later stages.

Now that we have a comprehensive understanding of all the first-order influences these decision variables have (TIM) and all the couplings that go on in between variables (TCIM), we can consider how to pursue more detailed analysis by prioritizing and grouping decisions. In large, long term projects, there will be multiple rounds of analysis at increasing levels of fidelity. The sort of analysis here is highly abstracted so that generation and evaluation of architectures is highly automated. This is the kind of high-level broad scope, low fidelity analysis that happens early in the life-cycle process in phase 0 (pre-phase A) conceptual studies. As the requirement for higher fidelity trade studies and detailed reference mission designs come it becomes infeasible to evaluate thousands of architectures and understand all the influences that should theoretically be considered between interacting variables. However if the broad high level analysis performed here can inform those studies with a thorough treatment of the relevant decision variables, organizationally we can improve the ability for analysts to capture the interaction effects that are important and ignore those that are not.

We would like to group the major decisions that define the architecture on the whole to create potential analysis teams that interact when they need to but can efficiently work in parallel when possible with just some shared assumptions. Weakly coupled decisions should be treated in parallel because there is a high cost associated with waiting for one piece analysis to begin before pursuing another. Likewise it is necessary to combine decisions that are highly coupled in a single study so that the relevant coupling interaction effects are considered and a thorough tradeoff on all relevant figures of merit can be performed.

To find a “good” organization of the decisions we consider three major desires in organizing architecture trade studies:

1. Prioritize high-influence decisions early on
2. Minimize the dependency between groups of decisions (low magnitude coupling interaction effects)
3. Maximize the interdependency within groups of decisions (large magnitude coupling interaction effects)

By trying to meet these criteria, we can come up with a structure that represents an idealized process flow for architectural trade studies. To do so a heuristic clustering algorithm is implemented that tries to satisfy the previous three criteria. There is no guarantee of an “optimal” organization to these decisions; however the most consistent results can be taken as guidance for a relatively “good” solution. One of these “good” solutions is shown in Figure 5-17.

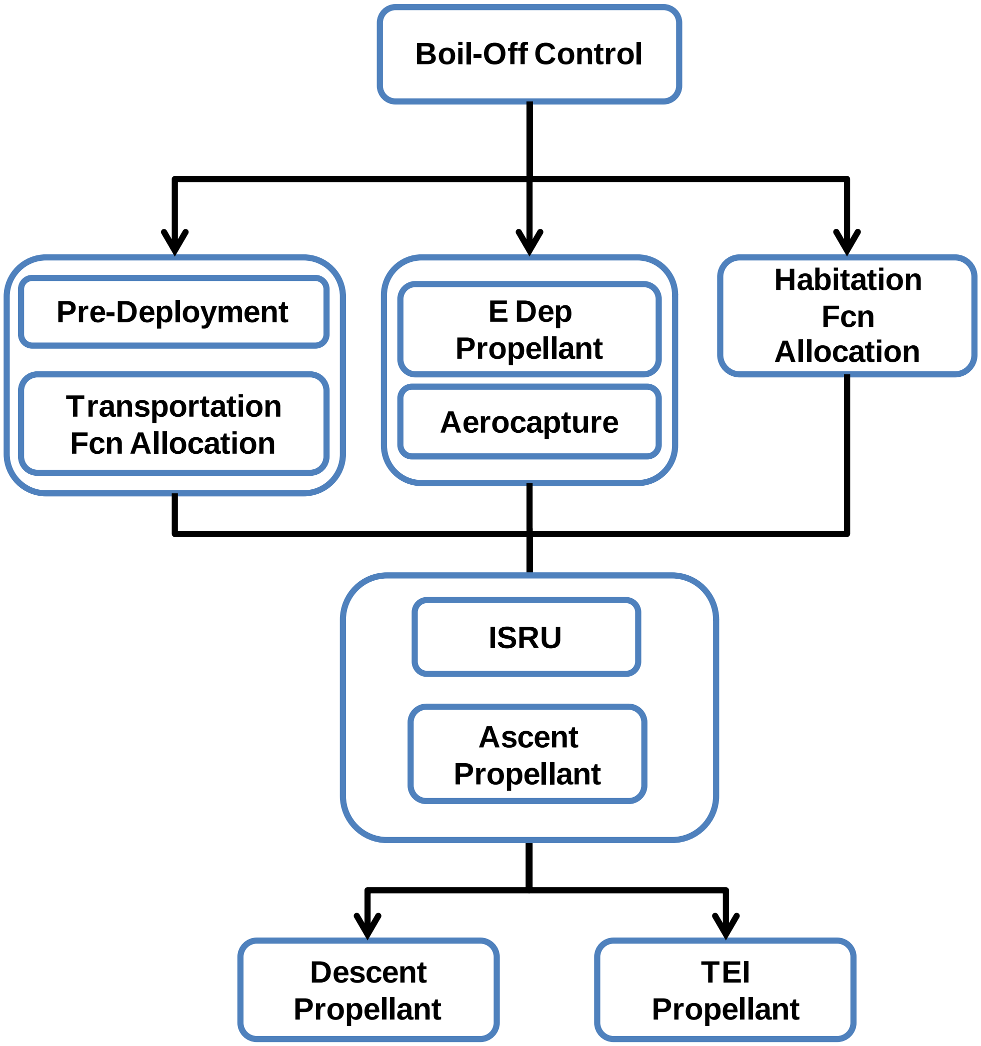


Figure 5-17 Organization of architectural decisions

In this organization some of the binary propellant technology decisions have been re-aggregated into their associated assignment problems as described in Section 3.3. The major sub-problems defined in Chapter 3 represent the decisions a trade study team might be responsible for, rather than explicitly picking out individual binary features within these sub-problems.

As an extremely sensitive decision, boil-off control comes early on. Despite the fact that future exploration mission requirements have not even been set yet, NASA has already begun to pursue the development of cryogenic storage capability, validating the early importance as described by the model in this thesis. In 2011 as part of the Exploration Technology Development Program, NASA put out a request for "In-Space Cryogenic Propellant Storage and Transfer Demonstration Mission Concept Studies" .

Next are three sets of decisions which can be treated somewhat in parallel. They all have very significant influence over the whole system and while ideally they would all be treated together, there is an efficient decomposition of the decision space that allows for much more rapid but still detailed analysis.

NASA's Design Reference Architecture 5.0 is exactly the kind of reference design mission study that could have benefitted from this organization. In the NASA DRA 5.0 addendum it describes how "trade-tree trimming" was performed to limit the concepts considered in the actual reference architecture development. Each of these decisions came from single variable considerations that did not consider the potential for strong interaction effects based on other decisions that could influence the decision-driving assumptions. Furthermore, in speaking to the editor of the mission it was clear the rationale for this limited view of the architecture tradespace was a need for all analysis to be performed in parallel due to schedule pressure.

KEY POINTS

- *Important features of the set partitioning variables can be treated just like the binary technology decision variables in measuring coupling interaction effects.*
- *Anecdotal evidence suggests sensitivity and interaction effects have not been considered in major design reference studies.*
- *By combining all decision variable influences and coupling interactions we can recommend a structure for future architecture-level trade studies, allowing for parallelized efforts where possible but making sure decisions that influence each other the most are considered serially.*

6 TRANSPORTATION SYSTEMS TO THE MOON AND NEAR EARTH ASTEROIDS

6.1 OVERVIEW

As the long-term focus for an exploration campaign, the previous chapter was entirely dedicated to the space transportation system for exploring the surface of Mars. However it is desirable to understand the influences of various technologies to the other destinations and how we can take into consideration the possibility of an exploration program to multiple destinations when defining near term investments for long term technology development.

In this chapter the same analysis that was presented in detail for Mars in Chapter 5 is presented for the other destinations considered of the Moon, a representative low delta-v Near-Earth Asteroid (NEA), and a representative high delta-v NEA. If a fundamental assumption is that the eventual purpose of human space exploration is settlement at Mars, it makes sense to filter the architectures and technology development projects for other destinations through a filter of preparation for Mars. That is to say from a set “good” technologies and architectures to other destinations, they can also be rated for exploration preparation as they contribute to progress on the overall plan to create sustainable transportation architecture to Mars.

For each additional destination, the best architectures and influence of various technologies on the system architecture tradespace will be presented. By matching the preferred technology subsets to each destination with those that provide benefit to Mars, recommendations are provided on near term investments for the entire long term campaign of human exploration beyond LEO.

6.2 LUNAR TRANSPORTATION SYSTEM ARCHITECTURE

The baseline lunar surface mission requirements have been taken from NASA's Exploration Systems Architecture Study (ESAS) that was completed as preparatory analysis for the Constellation Program . Each transportation architecture considered, delivers a crew of four people to the surface of the Moon for one week. The delta-v allocated for the mission provides the lander with access to either 84% surface coverage or 100% surface coverage with the addition of a 3 day loiter period. Sufficient delta-v is allocated such that any-time return is feasible in case of required contingency operations. The baseline mission assumptions are summarized in Table 6-1.

Table 6-1 Lunar mission assumptions

Surface duration	7 days
Crew size	4
Total crew mission duration	14 days
Total mission delta-v	10.95 km/s

6.2.1 BEST ARCHITECTURES: MOON

The tradespace produced by the search algorithms presented in Chapter 3 is shown in Figure 6-1. It is interesting to note that beyond a technology LCC proxy of 3.83, there are no further reductions in IMLEO. This indicates overall that significantly less technology is required for the Lunar transportation system as compared to the Mars system which had no architectures in the fuzzy Pareto region beyond a LCC proxy of 5. The benefits of several technologies are only realized with long times of flights or large delta-v. For example the NTR system has a large dry mass penalty and only becomes useful with very large delta-v maneuvers. Similarly the application of ISRU requires a large descended dry mass and will only provide benefit in a single mission if it manufactures more mass than it adds to the mission.

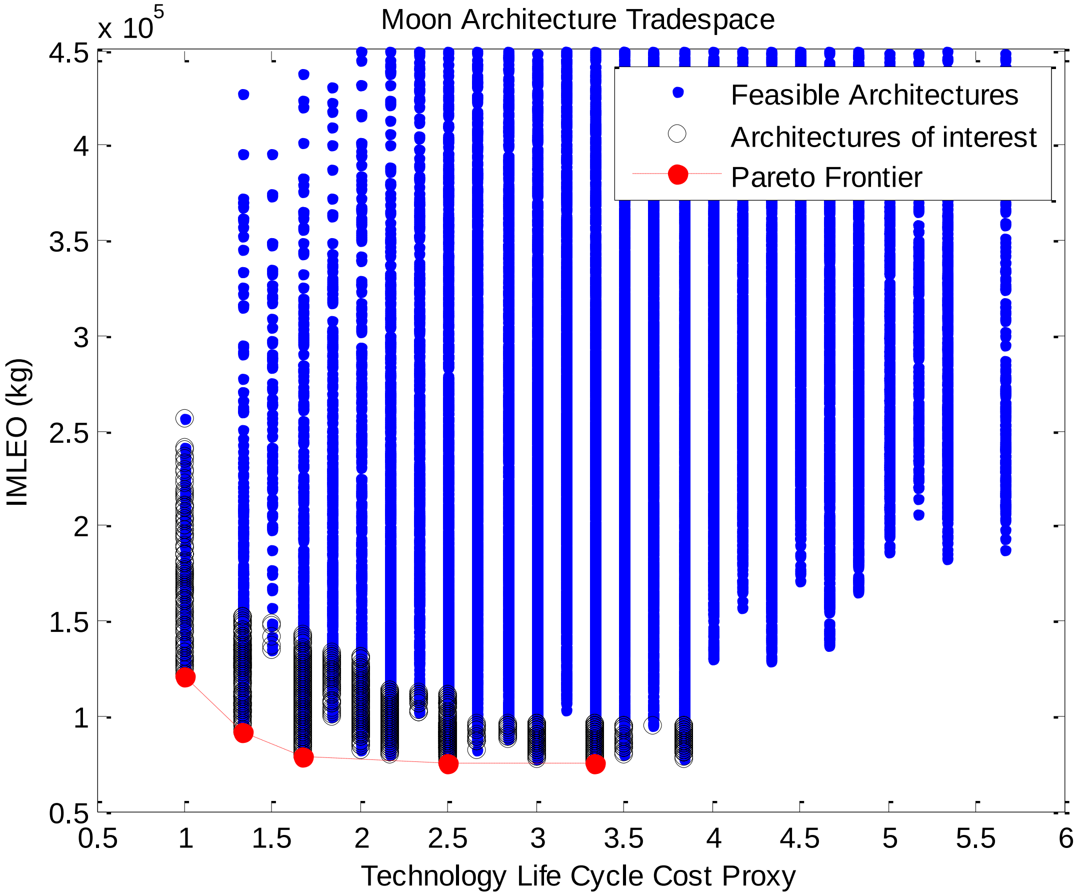


Figure 6-1 Lunar transportation architecture tradespace

Overall we see a trend that as the time of flight and delta-v requirements of a mission are lower, the benefits of additional technologies become outweighed by their costs.

Table 6-2 Pareto architectures for Lunar transportation system

Index	IMLEO (mt)	Tech LCC Proxy	Habitats	Transportation Stages
0001	74	3.33	Monolithic hab, separate entry capsule	Serial stages for each maneuver
0002	75	2.50	Monolithic hab, separate entry capsule	Serial stages for each maneuver
0010	78	1.67	Monolithic hab, separate entry capsule	Serial stages, combined departure & LOI
0377	91	1.33	Monolithic hab, separate entry capsule	Serial stages for each maneuver
2544	121	1.0	Separate outbound and return habitats (LOR)	Serial stages for each maneuver

Index	EDS Prop Type	Descent Prop Type	Ascent Prop Type	TEI Prop Type	Predeployment	Boil-Off Control	ISRU	Aerocapture
0001	LH2	LH2	LH2	LH2	Yes	Yes	No	Yes
0002	LH2	LH2	LH2	LH2	No	No	No	Yes
0010	LH2	Hypergol	Hypergol	LH2	Yes	No	No	Yes
0377	LH2	Hypergol	Hypergol	LH2	No	No	No	Yes
2544	LH2	Hypergol	Hypergol	LH2	No	No	No	No

Table 6-2 details the five architectures that come out on the Pareto frontier. Note that none use NTR or ISRU and boil-off control is only applied in the most mass-optimized architecture. Hypergols often come out favorable in the descent and ascent stages for their lower LCC proxy, and the poor performance of methane as compared to hydrogen keeps it off the frontier entirely.

6.2.2 TIM FOR THE LUNAR TRANSPORTATION SYSTEM

As with the Mars case, the influence of each major technology can be defined for the lunar transportation system according to Equation 4-2. The influence of each major technology project is quite different for the Lunar system as compared to the Mars transportation system shown in Figure 5-9. The TIM of each technology for the Moon is shown below in Figure 6-2.

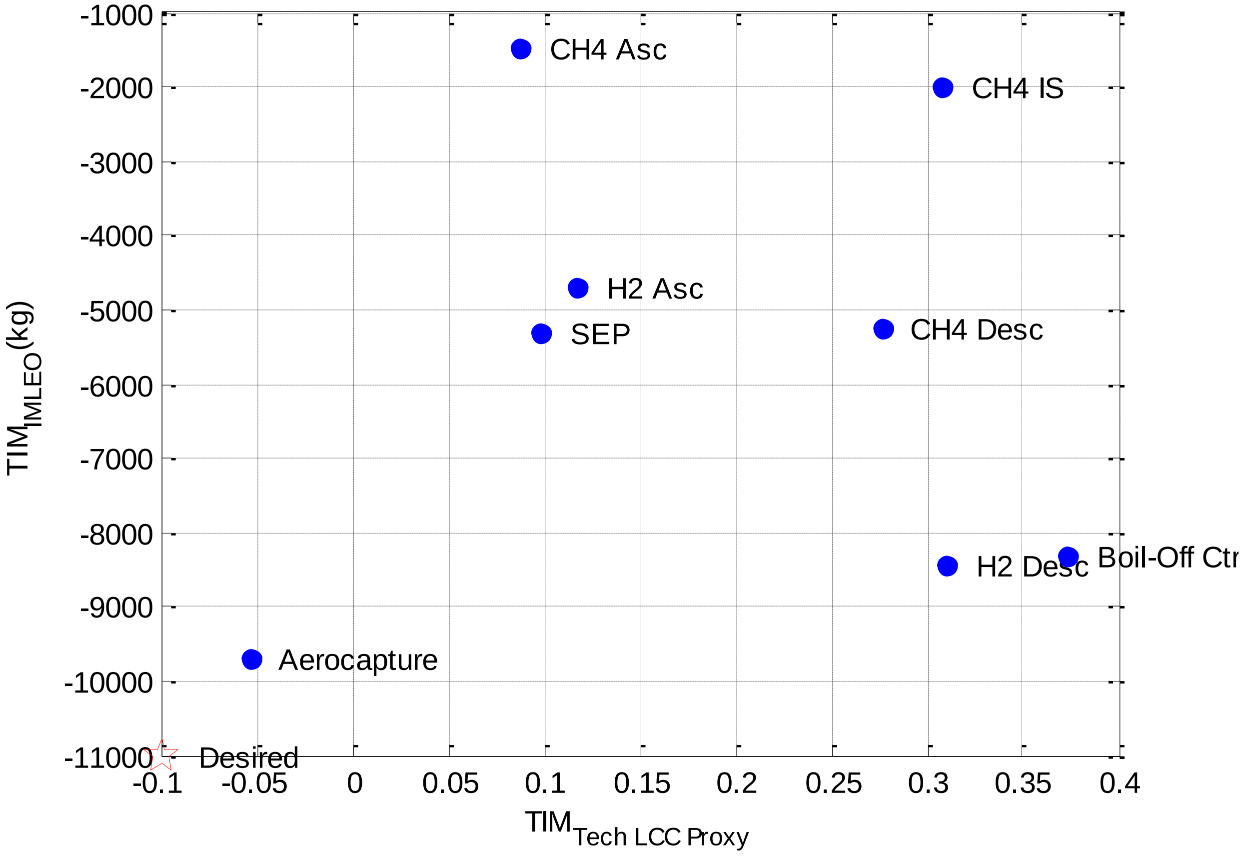


Figure 6-2 TIM for the Lunar transportation system

The first major thing to note is that NTR and ISRU do not appear on this chart. They are both technologies that have large dry mass penalties and benefits in the sizing of propulsion stages. No architectures included in the fuzzy Pareto region had those technologies, so they were not overall preferable considering the impulse required for maneuvers in the lunar transportation system. In this tradespace then, ISRU and NTR's impact would be off the chart in the positive direction of both LCC proxy and IMLEO. As heavily dominated technologies, they are not applicable in the desirable region of the tradespace. Since the value of these technologies is dependent on the impulse desired, results may vary when considering a campaign of multiple missions over time. However in the context of this thesis it is assumed that Mars is the ultimate destination and so the value of technologies should be taken in the context of individual preparatory missions to other destinations.

The impact of aerocapture is quite significant for the Moon transportation architecture. Although this technology only provides benefit for the braking maneuver at Earth, as a total percentage of delta-v this impact is quite significant. Aerocapture also is the only technology that results in an average net decrease in technology LCC. Overall this is reflecting that as compared to Mars, which has much more stringent propulsive requirements, the Lunar transportation system benefits less from a wide array of technologies. This does not mean they can not be applied to the system, but it will not result in an efficient architecture.

KEY POINTS

- *Overall we see a trend that as the time of flight and delta-v requirements of a mission are lower, the benefits of additional technologies become outweighed by their costs*
- *NTR and ISRU do not appear in the good architectures to the Moon, (this does not mean they can not be applied to the system- only that they are not the most mass and LCC efficient)*
- *Aerocapture, hydrogen descent/ascent stages,and SEP are all highly beneficial for the lunar transportation system.*

6.3 NEA CASE 1 TRANSPORTATION SYSTEM ARCHITECTURE

This destination is the first of two Near-Earth Asteroid cases that are presented. As opposed to the Lunar and Martian surface missions already discussed, planning an architecture to a NEA has the added uncertainty of not knowing the specific body to plan for and the associated surface, astrodynamics, and other parameters that will drive the design. Without giving a full treatment of the various destinations and implications of precise changes in delta-v, we can take into consideration the variability that exists in visiting asteroids by providing two cases that represent different ends of the design spectrum in terms of driving requirements that influence the system architecture. In particular since this study is mostly focused on the propulsive transportation system, the major distinguishing factors are the delta-v and time of flight to reach different destinations. A distribution of delta-v beyond escape to different asteroids is presented in Figure 6-3 with data taken from .

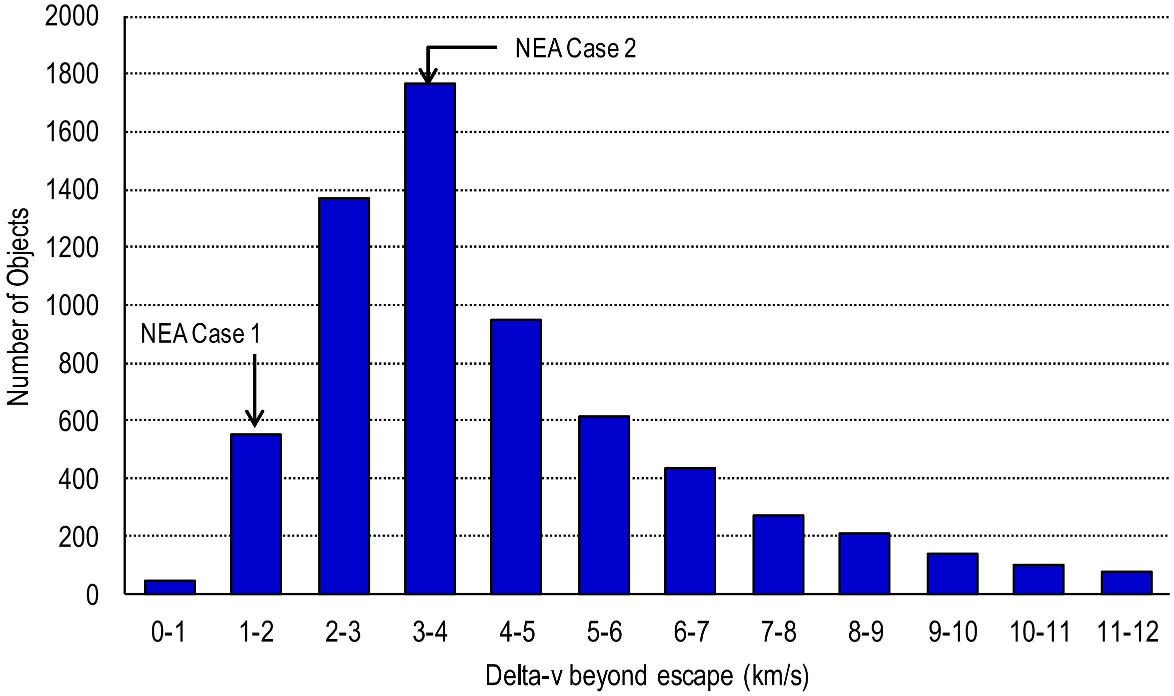


Figure 6-3 Distribution of delta-v for missions to NEAs with data from

The two NEA cases representing a "low" delta-v mission and "high" delta-v mission are pointed out on the distribution. Both NEA cases are taken from mission concepts put forth by the NASA Human Space Flight Architecture Team . The first is a minimalist low delta-v mission and case two is a more robust relatively high delta-v mission with longer duration surface stay. As of writing, the reference design materials have not been released to the public but they are expected to be published in the next year.

For both asteroid mission cases, ascent and descent stages are left out of the system. At this level of abstraction they do not represent significant maneuvers that would have distinct stages or propulsion systems. In addition we leave out ISRU for propellant manufacturing as there is no guarantee that the body will provide the necessary resources for manufacturing propellant. In addition there is no guarantee of multiple mission opportunities to the same destination that would allow for a system to be pre-deployed with enough time to manufacture the propellant.

The first NEA case is a mission to asteroid 2000 SG344 with parameters as shown below in Table 6-3.

Table 6-3 NEA Case 1 mission assumptions

Surface duration	14 days
Crew size	4
Total crew mission duration	362 days
Total mission delta-v	6.93 km/s

6.3.1 BEST ARCHITECTURES: NEA CASE 1

Without the alternatives of ascent and descent propellant types and the ability to implement ISRU, the NEA architectural tradespaces are much more sparsely populated. As a result there are noticeable "holes" in the tradespace that represent significant increments between two metrics where no architectures reside. The tradespace for NEA Case 1 is shown in Figure 6-4 below.

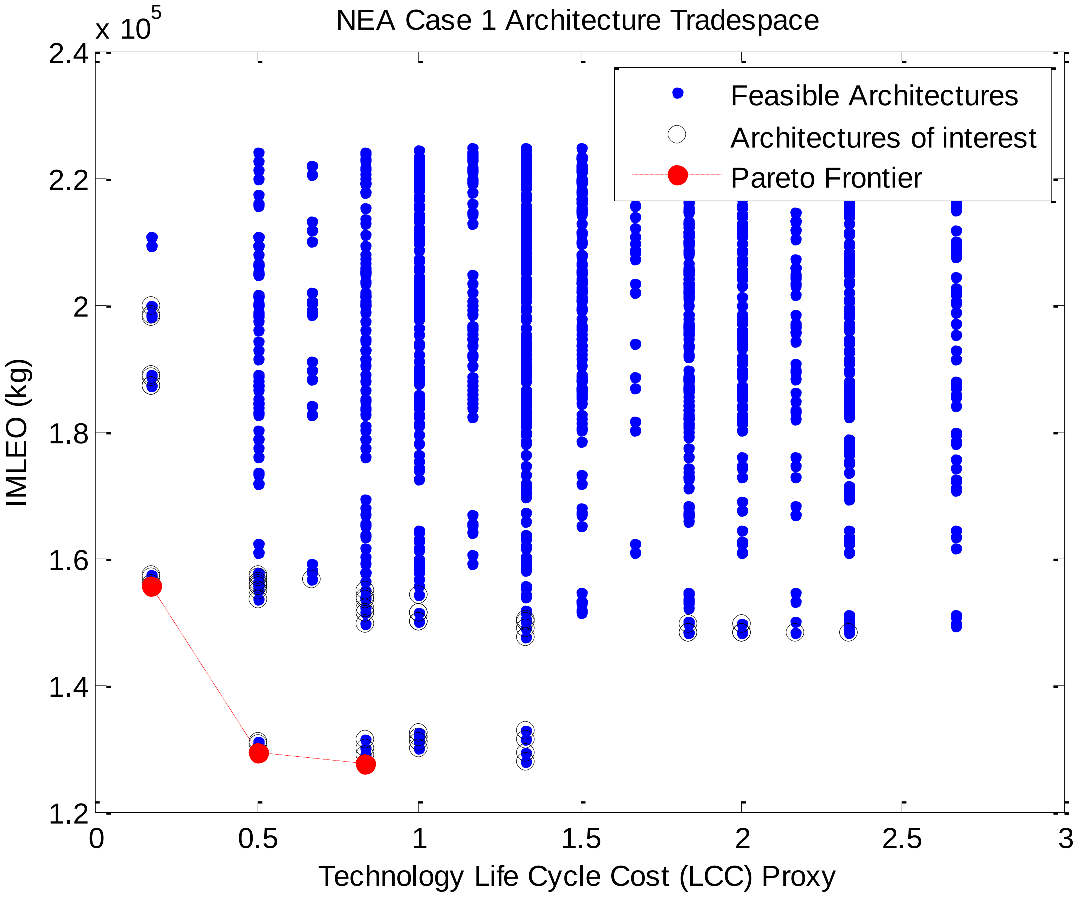


Figure 6-4 NEA Case 1 transportation architecture tradespace

A specific noticeable gap in the IMLEO metric appears at about 140 metric tons. While sometimes gaps in the tradespace can be attributed to a certain constraint or natural phenomenon, there is no single variable that defines the lack of architectures in this region. The contributing factors are certain features within the partitioning problems defining habitats and transportation stages and the system dry mass penalties associated with boil-off control and NTR. With a lower overall mission delta-v the mass penalties associated with these technologies become severe and so neither is present in any of the lowest IMLEO architectures. This also results in a lack of minimal IMLEO architectures above a technology LCC proxy of 1.33. As compared to all the other destinations considered, technologies provide minimal benefit on this low delta-v mission.

The three Pareto efficient architectures are described in Table 6-4.

Table 6-4 Pareto architectures for NEA Case 1 transportation system

Index	IMLEO	Tech LCC	Habitats	Transportation Stages

	(mt)	Proxy		
0001	127	0.833	Large habitat, separate Earth entry capsule	Serial stages only
0004	129	0.500	Large habitat, separate Earth entry capsule	NEA orbit rendezvous-like
0078	156	0.167	Single large habitat	NEA orbit rendezvous-like

Index	EDS Prop Type	TEI Prop Type	Predeployment	Boil-Off Control	Aerocapture
0001	LH2	LH2	Yes	No	Yes
0004	LH2	LH2	No	No	Yes
0078	LH2	LH2	No	No	No

Few of the technologies considered make it into architectures on the Pareto front. All major propulsion segments are performed with liquid hydrogen-liquid oxygen and none receive a net benefit from boil-off control over the relatively short duration, low impulse mission.

6.3.2 TECHNOLOGY IMPACT MEASURE: NEA CASE 1

Without the descent and ascent stages or ISRU, only five unique technologies to be developed remain in the tradespace for NEA missions from the subset originally considered for the Mars transportation system. The TIM for these technologies is shown in Figure 6-5.

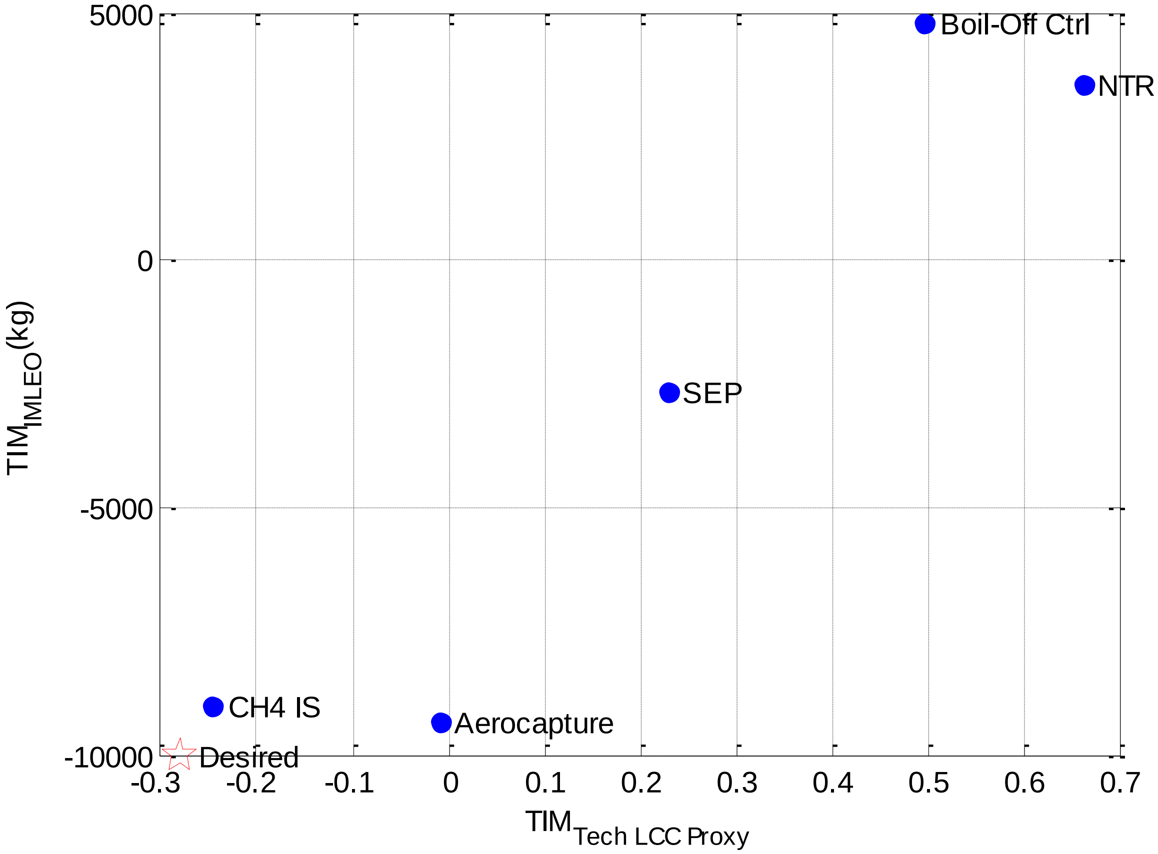


Figure 6-5 TIM for the NEA Case 1 transportation system

It is particularly interesting to note that with the drastic reduction in time of flight and delta-v compared to Mars, two of the most important technologies, boil-off control and NTR, are now clearly not desirable for this transportation system. This begins to suggest that considering the TIM across multiple destinations is very important for a full exploration campaign design. This will be treated in more detail in Section 6.5.

Additionally the TIM at Mars created two groups of technologies- those that reduced IMLEO for an increased technology LCC, and those that reduced technology LCC at the expense of increased IMLEO. Now the technologies are roughly aligned along the other diagonal of the plot indicating some technologies are overall better than others in the tradespace. For example the boil-off control that is no longer so useful produces relative increases in both technology LCC and IMLEO while in-space methane stages produce relatively better architectures by both metrics- particularly because it does not require boil-off control.

When considering the plot of TIM for different technologies at different destinations, it is important to remember that these are the average influences within an already limited set of preferred architectures. TIM captures the influence of technologies between architectures that are already deemed to be realistically feasible. This means that the general layout of technologies for the low delta-v NEA case does not necessarily indicate that boil-off control and NTR should not be considered for this particular

NEA mission, only that an architecture optimized only for this mission would most likely not have those technologies.

KEY POINTS

- *As compared to all the other destinations considered, technologies provide minimal benefit on this low delta-v mission.*
- *The technologies of methane in-space propulsion and aerocapture provide the greatest benefits if considering the low delta-v NEA mission in isolation.*

6.4 NEA CASE 2 TRANSPORTATION SYSTEM ARCHITECTURE

The second NEA case is from the same set of reference design missions as the first case presented in . This higher delta-v mission is to asteroid 2008 EV5 with mission parameters shown in Table 6-5 below. As compared to the first NEA case, this mission has double the surface duration and a 27% increase in total mission delta-v.

Table 6-5 NEA Case 2 mission assumptions

Surface duration	28 days
Crew size	4
Total crew mission duration	428 days
Total mission delta-v	8.77 km/s

6.4.1 BEST ARCHITECTURES: NEA CASE 2

The transportation architecture tradespace for the second NEA case reflects some similarities to the first NEA case. The extra constraints in the NEAs produce a relatively sparsely populated tradespace as compared to the Moon and Mars tradespaces. For NEA case 2, there are more beneficial technologies that improve IMLEO. As a result there is no large vacant region in the low IMLEO-high technology LCC area. There are however diminishing returns to the extra technologies beyond a technology LCC of approximately 1.67. The tradespace is shown below in Figure 6-6.

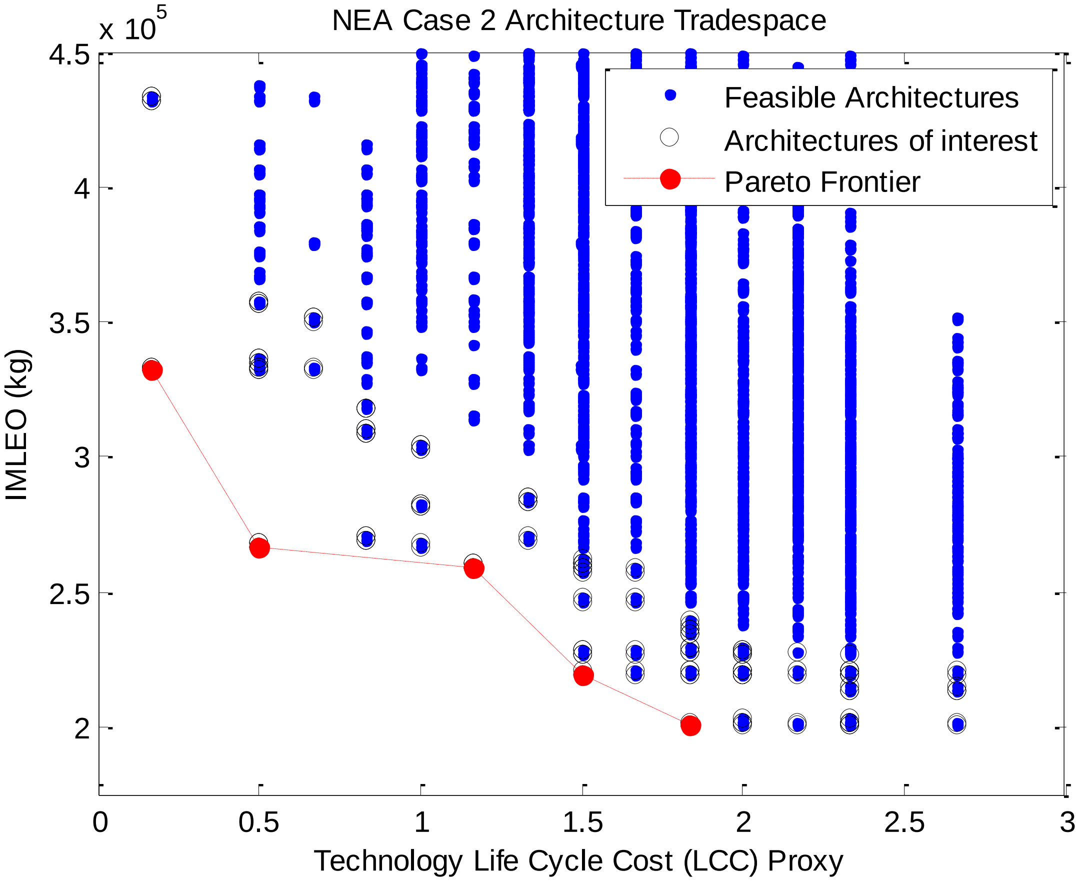


Figure 6-6 NEA Case 2 transportation architecture tradespace

Since NEA case 2 has more opportunity to benefit from various technologies as compared to NEA case 1, more architectures appear on the Pareto front, trading IMLEO for technology LCC. The Pareto architectures are described in Table 6-6.

Table 6-6 Pareto architectures for NEA Case 2 transportation system

Index	IMLEO (mt)	Tech LCC Proxy	Habitats	Transportation Stages
0001	200	1.833	Large habitat, separate entry capsule	Single large stage
0031	219	1.500	Single large habitat	Single large stage
0185	259	1.167	Single large habitat	NEA orbit rendezvous-like
0265	267	0.500	Large habitat, separate entry capsule	NEA orbit rendezvous-like
1090	332	0.167	Single large habitat	NEA orbit rendezvous-like

Index	EDS Prop Type	TEI Prop Type	Predeployment	Boil-Off Control	Aerocapture
0001	NTR	NTR	Yes	Yes	Yes
0031	NTR	NTR	No	No	Yes
0185	NTR	LH2	Yes	No	Yes
0265	LH2	LH2	No	No	Yes
1090	LH2	LH2	No	No	No

6.4.2 TECHNOLOGY IMPACT MEASURE: NEA CASE 2

The TIM for the second NEA case are presented in Figure 6-7.

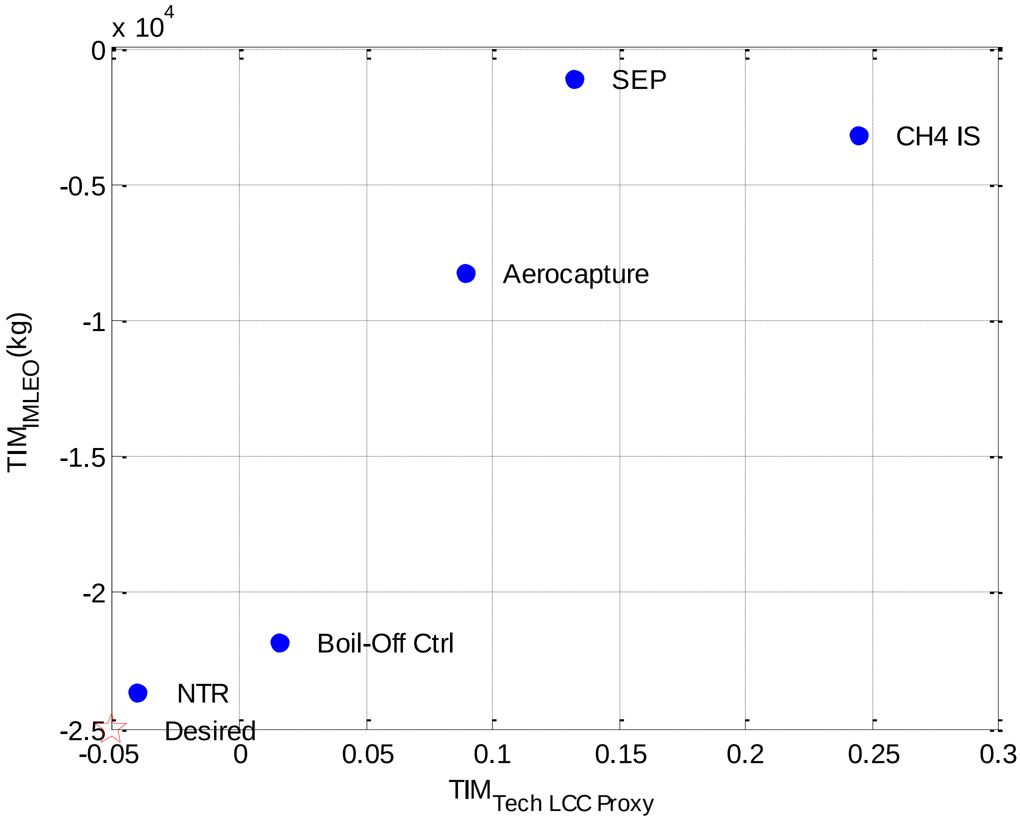


Figure 6-7 TIM for the NEA Case 2 transportation system

Again it is interesting to note some similarities and differences between the two NEA cases. Like the first NEA case, the technologies applied to this higher delta-v system lie roughly along a diagonal representing how much benefit they provide. That is to say there is not such a distinct trade off between the way technologies influence two metrics as there is with the Mars transportation system. However the influence of the technologies is nearly reversed for this second NEA case as compared to the first. Now, NTR and boil-off control produce architectures with lower IMLEO and technology LCC as compared to those architectures that rely more on aerocapture, methane, and pre-deployment with Solar Electric Propulsion (SEP).

The reversal of preference for different technologies between the two NEA cases is due to the time of flight and delta-v involved as there are no other distinguishing differences in the mission requirements or architecture modeling. This indicates that there is something of a threshold in mission difficulty, beyond which certain technologies become more preferable.

It may seem counter-intuitive that a technology such as NTR can result in a reduction of technology LCC proxy. While NTR does represent a major project that needs to be developed, in reference to other good architectures to a high delta-v NEA, NTR can replace the need for several technologies. Having a negative TIM for LCC indicates there are NEA missions with NTR and fewer overall technologies as compared to other favorable architectures.

KEY POINTS

- *The technologies of NTR and boil-off control are most beneficial for this high delta-v NEA case.*
- *The prioritization of technologies for the high delta-v NEA case is reversed from that of the low delta-v NEA case.*

6.5 CONSIDERING TECHNOLOGIES ACROSS DESTINATIONS

Until this section, each destination has been considered a separate tradespace exploration problem. There has not been significant consideration of planning a campaign of missions that span several destinations. However charting a long term program of exploration is one of the main ultimate goals of designing a system architecture for space exploration beyond Earth orbit. As such, we would like to use the tools presented to understand the influence of technologies on system architecture to begin to organize the methodology for more detailed exploration campaign definition.

While to a certain extent it is expected that a long term presence at Mars is the ultimate goal of the entire human exploration program, it is not clear exactly which destinations will lie on the path to this goal. The destinations and other ambiguities involved in defining this exploration campaign were discussed throughout Section 1.1. Considering different transportation architectures, with different technologies, to different destinations, evaluated with multiple metrics is a rather cumbersome problem. We can visualize however the overall influence for each technology to each destination. When defining the preparatory missions within a campaign leading to Mars, this can be used as a tool to quickly identify the technologies that provide most benefit at a given destination. An explanatory diagram of the figures comparing TIM across destinations is provided in Figure 6-8. When a metric is moved to a more preferable state (in this analysis by reducing IMLEO or reducing technology LCC), the point is plotted closer to that destination. When TIM demonstrates an increase in a metric, reducing the preference for the technology at a given destination, the point is plotted closer to the center of the graph.

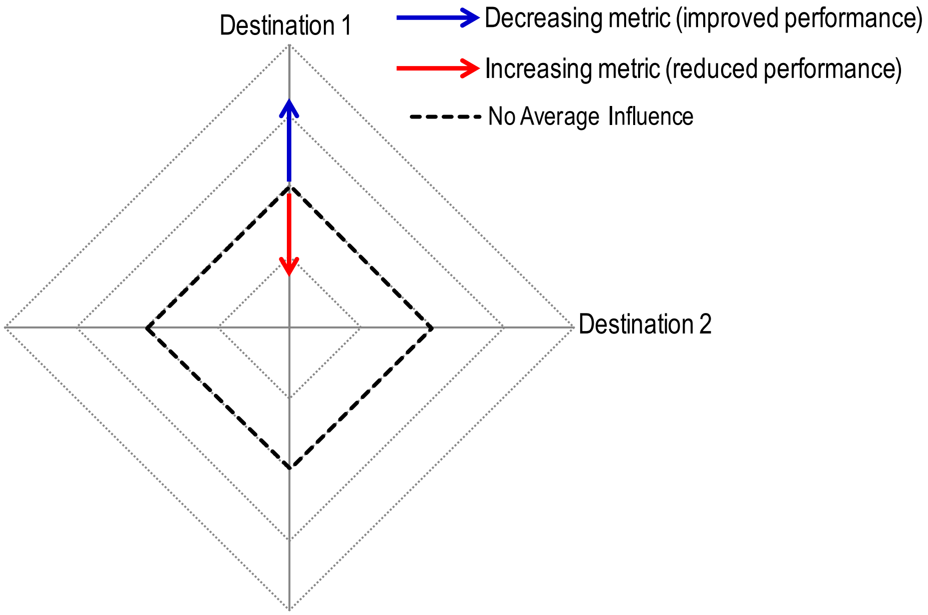


Figure 6-8 Explanation of following figures visualizing TIM across multiple destinations

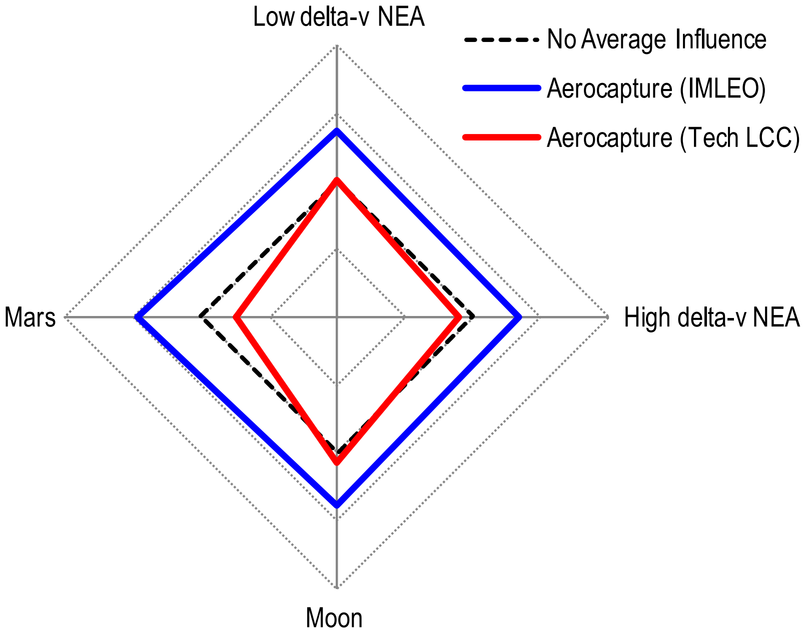


Figure 6-9 TIM for aerocapture at all destinations

Considering TIM, or the influence of aerocapture across all destinations is fairly simple as demonstrated by the corresponding diagram in Figure 6-10. By reducing the mission delta-v requirements for all destinations when the crew must brake at Earth, aerocapture creates a fairly sizable reduction of IMLEO across most architectures to each destination. Since aerocapture has the additional benefit of braking at Mars, the mass savings are slightly larger at that destination. There is an associated technology LCC penalty that varies depending on how aerocapture couples to other technologies at each destination.

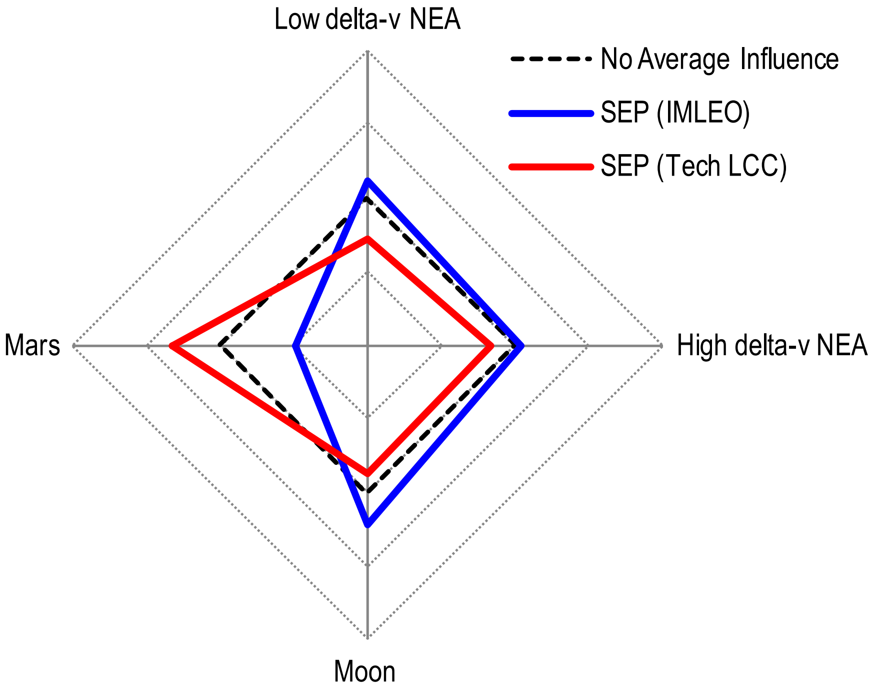


Figure 6-10 TIM for SEP at all destinations

SEP is a bit more interesting than aerocapture as it presents quite different tradeoffs at different destinations. As discussed in Chapter 5, at Mars SEP provides a tradeoff offering a reduction of technology LCC but an increase in IMLEO. However at the other destinations the opposite is true. SEP to these destinations offers a lower overall IMLEO but has a higher technology LCC as compared to the other preferred architectures.

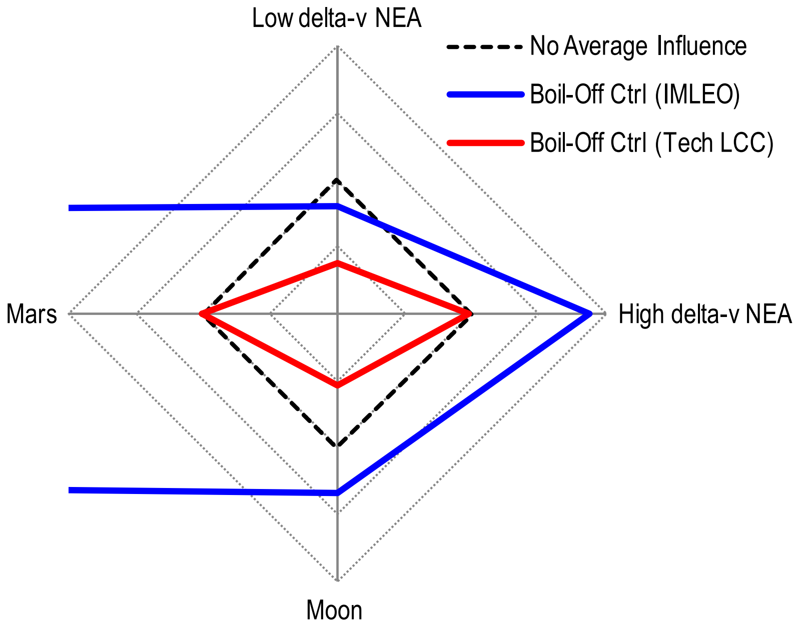


Figure 6-11 TIM for boil-off control at all destinations

Boil-off control is another interesting technology. It is required to make the Mars mission feasible from a mass perspective (and so goes off the chart), but offers significantly less benefit to the other destinations with shorter duration missions. It does however provide significant benefit on the high-delta-v NEA mission, opening up the capability for long duration missions that rely on cryogenic propellant.

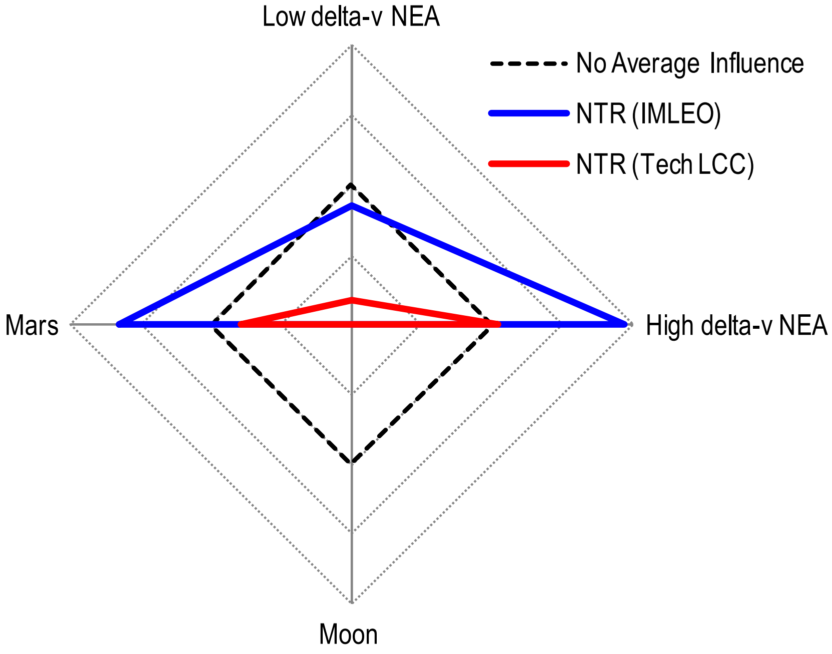


Figure 6-12 TIM for NTR at all destinations

NTR provides significant benefit at Mars and the higher delta-v NEA mission. However it results in such a high-mass architecture for the Moon, it is outside the defined feasible region of that tradespace in this modeling environment. It is also interesting to note that while it presents a significant technology LCC penalty at the low delta-v NEA and Mars, NTR results in a net reduction of technology LCC for the high delta-v NEA mission as it removes the necessity for most other technologies.

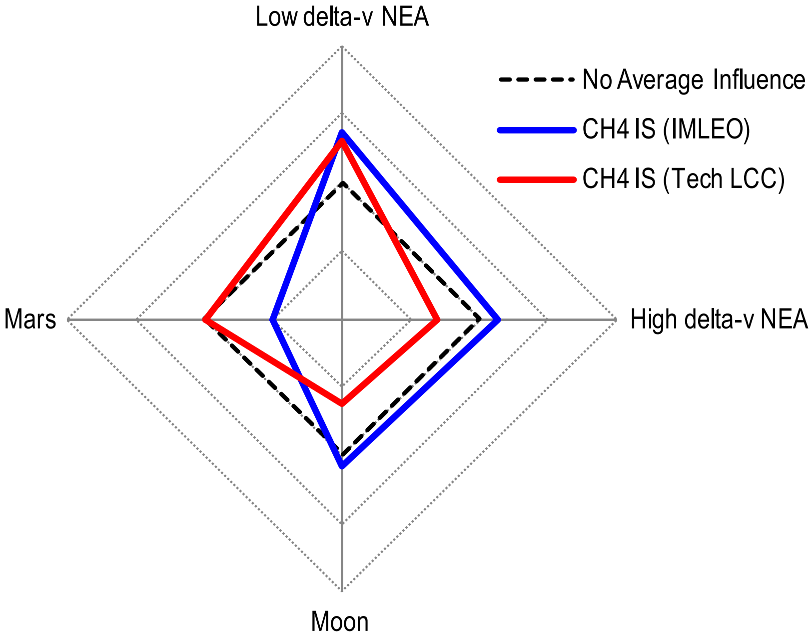


Figure 6-13 TIM for in-space methane propulsion at all destinations

Finally, the implementation of a methane propulsion system for in-space transportation is displayed in Figure 6-13. While methane generally reduces IMLEO at most destinations, it results in a large mass penalty for the system to Mars. However the methane stage also provides a large technology LCC penalty to the other destinations. While it is present in the fuzzy Pareto regions, methane does not appear as an optimal propulsion system for any of the Pareto architectures to any destination. The value proposition of significant investment in methane will be dependent on a change in the expected performance of other technologies. For example if controlling boil-off rates of liquid hydrogen proves to be infeasible, the methane system will become much more desirable. Additionally if an ISRU system is developed with lower power requirements and lower overall dry mass, methane may become extremely desirable for Mars architectures. However with the expected values taken from literature used in the models presented, methane is not likely to appear as a major architectural feature in the future human space transportation system.

6.6 TOWARDS DEFINING A TECHNOLOGY PORTFOLIO FOR MARS

While it is not entirely clear what the campaign of exploration missions will look like in the coming decades, the assumption that Mars is the ultimate goal must be considered in the near term technology investment strategy. Even if a mission to Mars will not be realistically executed for another two decades, there is no doubt that the supporting technology development activities have already started and will require significant expenditure of funds over a much shorter timeframe.

Recalling Section 1.2.1 we established that at least four factors need to be considered when defining a technology investment portfolio.

1. Expected performance of the technologies
2. Expected cost of the technologies
3. Risk associated with the development and realization of the capabilities in the portfolio
4. Opportunities for flexibility and an associated implementation framework to maximize return over the uncertain development process

With the limited scope of the metrics considered in this thesis we only approach the first two issues, however we can present an initial understanding of what the different portfolios of technologies might look like.

The portfolio of technologies to pursue is a down-selection problem as defined in Section 3.3.4. Many potential technologies can be pursued, but only a limited set will be included in the investment basket put together by NASA.

To define various technology portfolios, that is to say subsets of the technologies available, we can search through the already enumerated tradespace to Mars that was thoroughly discussed in Chapter 5. We would like to evaluate the performance of different sets of technologies to Mars so we limit the space to consideration of the preferred architectures in the Mars fuzzy Pareto region only. Within this limited space, we group together architectures that have a given basket of technologies included and take the average metrics associated with those technologies. Rather than look at the performance of a single architecture, we are defining an expected performance of a basket of technologies applied to the Mars transportation system. Each of these potential technology portfolios as defined by performance to Mars are plotted in Figure 6-14.

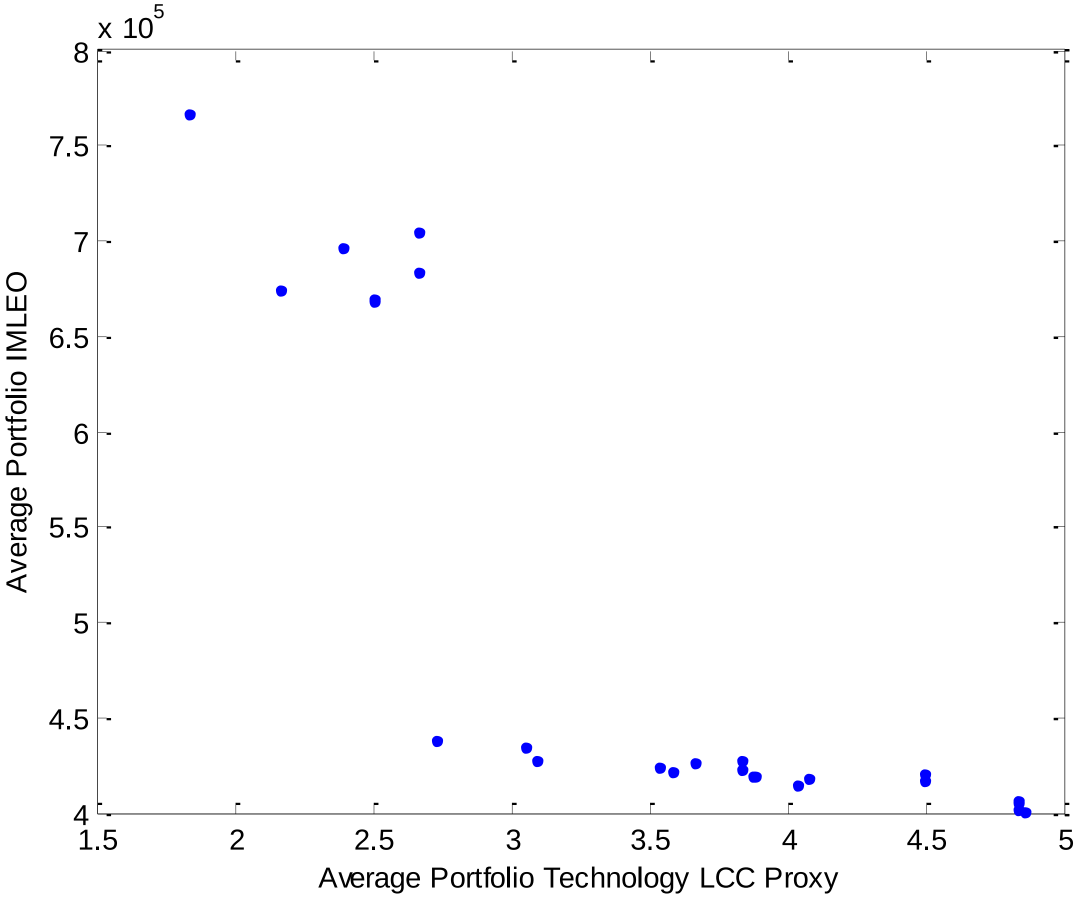


Figure 6-14 Performance of technology portfolios to Mars defined by architectures in fuzzy Pareto region

Within the defined set of already good architectures, a major distinguishing factor is combining NTR and aerocapture together. All portfolios with the lowest IMLEO (below the large gap between 4.5×10^5 and 6.5×10^5 kg) have both those technologies, and the other portfolios in this preferred region of the tradespace have at least one of these technologies. Combining aerocapture and NTR results in a higher technology LCC architecture but these portfolios sit in the lowest mass region of the tradespace.

The other set of technology portfolios include SEP and implement various hydrogen and methane propulsive stages allowing for significantly lower expected technology LCC but not quite as mass efficient architectures. To really understand what distinguishes these portfolios we need measures of the other two variables- development risk and identification of opportunities for flexibilities in development. We do not have the fidelity in modeling development to measure these factors but it is important to note the big difference NTR and aerocapture can make, and the associated development risk tradeoff.

Since the performance of these portfolios are defined by the fuzzy Pareto architectures already considered desirable, it is assumed that these are all promising subsets of technologies to pursue. While adding more metrics and modeling fidelity may change the specific results, these portfolios can be used to inform the selection of specific transportation architectures to other destinations. The list of portfolios defined by the preferred architectures in the Mars tradespace are provided in Table 6-7.

Table 6-7 Best subsets of technologies for Mars

Technologies in Portfolio						Avg Tech LCC Proxy	Avg IMLEO (mt)
BO Ctrl	ACap					1.833	766
SEP	BO Ctrl	ACap				2.167	674
NTR	BO Ctrl					2.389	697
H2 Asc	SEP	BO Ctrl	ACap			2.500	669
CH4 Asc	SEP	BO Ctrl	ACap			2.500	669
NTR	H2 Asc	BO Ctrl				2.667	683
CH4 IS	SEP	BO Ctrl	ACap			2.667	705
NTR	BO Ctrl	ACap				2.731	438
NTR	CH4 Asc	BO Ctrl	ACap			3.056	435
NTR	H2 Asc	BO Ctrl	ACap			3.091	428
NTR	CH4 Desc	BO Ctrl	ACap			3.537	424
NTR	H2 Desc	BO Ctrl	ACap			3.583	421
NTR	BO Ctrl	ISRU	ACap			3.667	426
NTR	H2 Desc	CH4 Asc	BO Ctrl	ACap		3.833	423
NTR	CH4 Desc	CH4 Asc	BO Ctrl	ACap		3.833	428
NTR	CH4 Desc	H2 Asc	BO Ctrl	ACap		3.875	420
NTR	H2 Desc	H2 Asc	BO Ctrl	ACap		3.881	419
NTR	H2 Asc	BO Ctrl	ISRU	ACap		4.033	414
NTR	CH4 Asc	BO Ctrl	ISRU	ACap		4.074	418
NTR	H2 Desc	BO Ctrl	ISRU	ACap		4.500	417
NTR	CH4 Desc	BO Ctrl	ISRU	ACap		4.500	421
NTR	CH4 Desc	H2 Asc	BO Ctrl	ISRU	ACap	4.833	406
NTR	H2 Desc	CH4 Asc	BO Ctrl	ISRU	ACap	4.833	405
NTR	CH4 Desc	CH4 Asc	BO Ctrl	ISRU	ACap	4.833	402
NTR	H2 Desc	H2 Asc	BO Ctrl	ISRU	ACap	4.859	401

Each of these portfolios defines an architectural strategy distinguished by the differences in required technologies.

KEY POINTS

- *NTR and aerocapture are driving factors in the approach to technology development for Mars transportation, at least one is required when creating a set of technologies to pursue.*
- *There is a tradeoff between technology LCC-optimized and IMLEO- optimized reduced sets of technologies to pursue. Most likely an overall philosophy of development approach (and associated funding levels) will drive a portfolio that sits in one of these two regions.*

6.7 TRANSPORTATION ARCHITECTURES THAT PREPARE FOR MARS

Looking at all Pareto fronts of efficient transportation schemes to each destination aggregated into a single plot, we can see the other destinations have lower IMLEO and technology LCC as compared to Mars. If architectures from other destinations are going to be used as precursors in developing technologies and operational experience for Mars, we want to understand how they contribute on the path of getting to the Mars architecture for which we are planning.

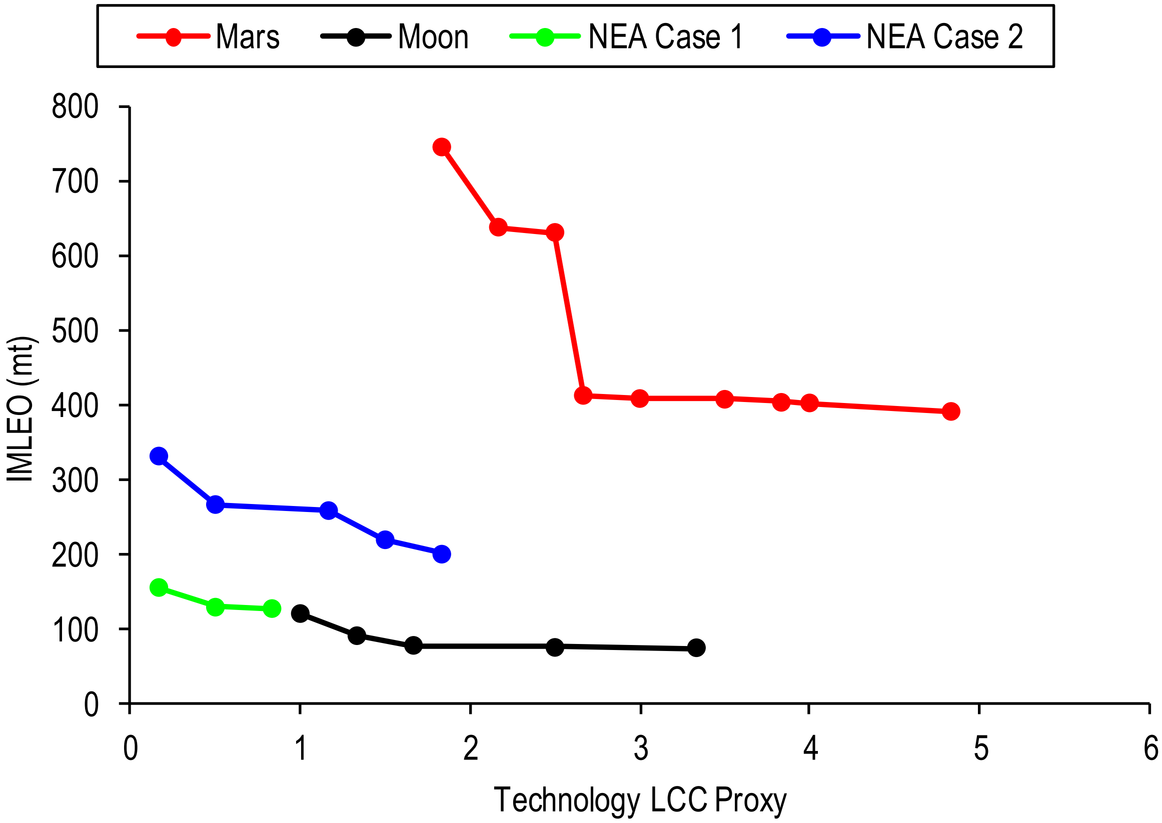


Figure 6-15 Pareto fronts for all destinations considered

In future work the goal is to design a campaign of missions with the long term goal of presence at Mars. In terms of technology development we can assume the portfolios identified previously in Table 6-7 are the types of technologies in which we want to invest. We can use this to downselect possible missions (from the Pareto fronts) at each destination.

In Table 6-7 we have a reasonable set of portfolios that might be pursued in the near term, the benefits of which are defined in relation to all the uncertainty considered in the modeling of Mars architectures presented in this thesis. In Table 6-2, Table 6-4, and Table 6-6 we have a set of the best architectures for the Moon, a low delta-v NEA case, and a high delta-v NEA case respectively (defined by those Pareto fronts). We can go through systematically and evaluate the preparation that each of those possible missions to other destinations, provides in preparation for future exploration in terms of the technology subsets considered for Mars.

A measure of Mars mission preparation is based on the technology LCC proxy. If a technology is included in a non-Mars architecture and not in an associated portfolio, it is not considered at all as we would not want major development efforts for a mid term goal that does not support the ultimate destination. Preparation for Mars exploration can be seen as a buy-down of risk in the technologies required for Mars missions, by demonstration through precursor missions to other destinations. While it will take more detail in modeling development and expected resources available to define a full exploration campaign, with the level of detail provided in this thesis we can suggest some missions that provide a significant amount of technology demonstration (or buy-down of risk), on the goal to developing a portfolio of technologies for Mars. Note that we do not necessarily seek pre-cursor missions with the entire set of technologies required for Mars, as the goal is to have an overall plan that delivers value incrementally.

The output of this approach to buy-down of risk, are some logical precursor missions that demonstrate key transportation technologies that will be required for Mars. Some of the suggested precursor missions are displayed in Figure 6-16 Pareto front architectures for Non-Mars missions define possible precursors that buy-down risk of Mars technologies (details in Table 6-8)Figure 6-16 and Table 6-8, demonstrating how they evolve into a Mars technology portfolio. Future work would need to consider common elements in addition to technology development to really support the definition of a campaign.

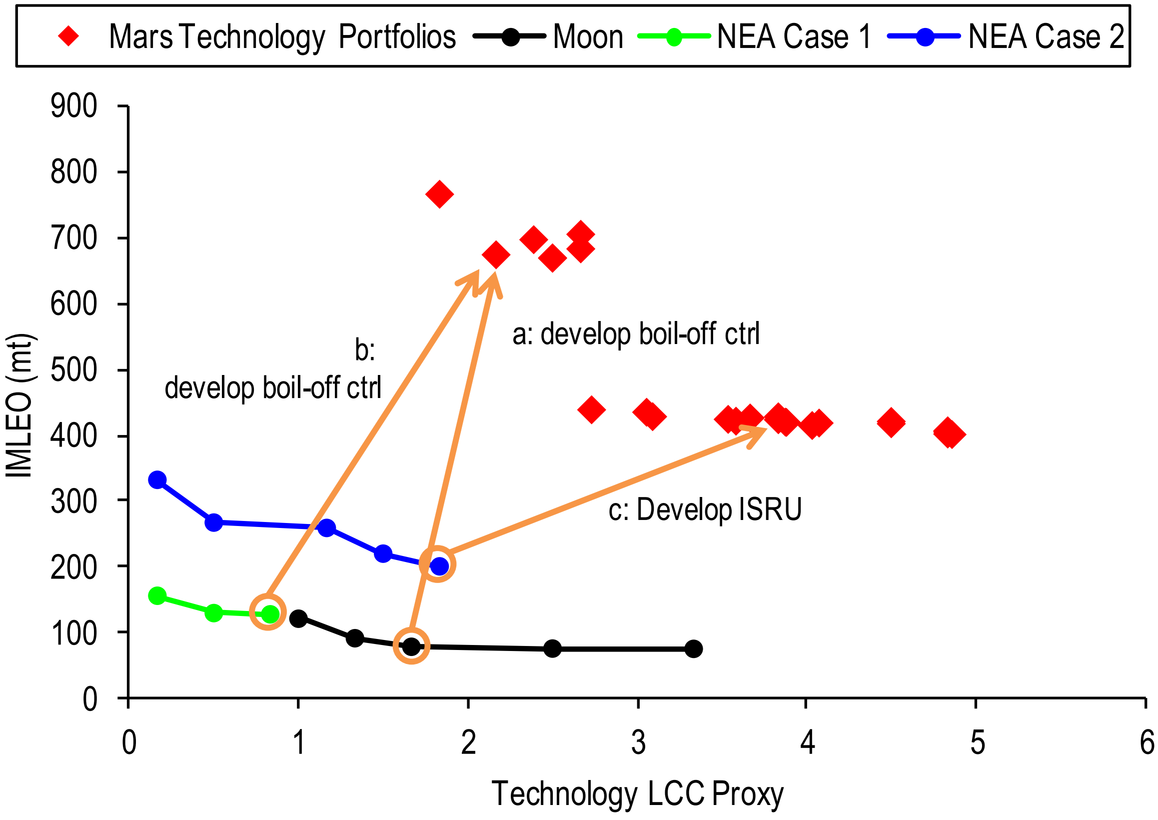


Figure 6-16 Pareto front architectures for Non-Mars missions define possible precursors that buy-down risk of Mars technologies (details in Table 6-8)

Table 6-8 Non-Mars transportation architectures that demonstrate technologies for the ultimate Mars technology infrastructure

Arrow label in	a	b	c
Architecture ID	Moon: 0010	NEA case 1: 0001	NEA case 2: 0001
Technologies Included in Precursor Mission	SEP, aerocapture	SEP, aerocapture	NTR, Boil-off control, aerocapture
Technologies still required for Mars technology portfolio	Boil-off control	Boil-off control	ISRU

Different strategies of pairing pre-cursor missions to Mars technologies become apparent. For example many technology subsets have NTR used in the system to Mars, but the value of NTR varies across other destinations. Selection of those destinations may drive the decision to include NTR in the Mars transportation strategy. SEP for example may be less valuable to the Mars transportation system, but provides significantly more benefit to other destinations. While details of budget and expected development progress are required to fully define a campaign of missions, we can identify some of the strategies that may prove favorable.

KEY POINTS

- *The future goal of this work is to design a campaign of missions with the long term goal of presence at Mars.*
- *With the limited view of campaign design currently available, logical precursor missions can be defined as those that buy-down risk of Mars technologies by demonstration to other destinations.*

7 CONCLUSIONS

7.1 SUMMARY

This thesis provided a methodology to evaluate the influence of technologies in a system architecture tradespace. Measures of influence and coupling are provided to understand the influence and interaction effects of technologies in the tradespace. These measures are provided to capture emergent behavior that may not be explicitly encoded by the system modeler by focusing on a preferred set of architectures defined by a fuzzy Pareto front region. The influence and coupling measures are also applicable independent of the problem formulation and can be used to understand the influence of aspects of the architecture that are not originally considered as independent variables.

This methodology is then applied to the future human exploration transportation system beyond LEO. A case study is provided that motivates a technology LCC proxy metric. This cost metric and IMLEO are used to evaluate a tradespace of thousands of architectures within a set of millions. The transportation problem is composed of a combination of different types of sub-problems including assignment problems, partitioning problems, and down-selection problems. Heuristic search algorithms are provided to find feasible regions in the tradespace, optimize for IMLEO, and optimize over multi-objective criteria.

Results to four destinations are provided. Multiple transportation strategies exist with a strong tradeoff between IMLEO and technology LCC for technologies to Mars. The influence of different technologies are considered across each destination. A range of technologies are relevant at each destination and some suggestions are provided for possible demonstration mission architectures that prepare for a future transportation system to Mars. The following sections provide specific conclusions organized by those relevant to the general methodology and those that are particular to the space transportation problem presented.

7.2 CONCLUSIONS

7.2.1 METHODOLOGY CONCLUSIONS

From the case study on the RL-10 liquid hydrogen engine provided in Chapter 3, we found that low procurement rate is correlated to engine price spikes. The overall conclusion is that industrial base issues are important to consider at the early stage of system architecting, and can be used to influence system-wide metrics in architecture evaluation. In this case the possibility for non-NASA customers was integrated into a proxy metric for technology Life Cycle Cost.

The influence and coupling measures developed in Chapter 4, provide a way to evaluate technologies independent of a priori system knowledge. By deriving these measures from the evaluated tradespace we have the capability to capture any non-linear interactions present in the system metrics or that appear in the preferred architectures in the tradespace. By defining the measures in relation to system attributes either being included or not, (a binary encoding), features to be considered can be determined independently of the problem sub-classes. The influence of any distinguishing architectural feature, even if not explicitly encoded in architecture definition, can be evaluated.

A measure of influence that provides a direction and magnitude is able to capture tradeoffs in system strategy rather than just the sensitivity to an overall decision. This allows for prioritization of technology investments and a better understanding of the expected system influence from the technologies under consideration.

Providing a comprehensive view of pair-wise coupling between all technologies and architectural features allows for an overall understanding of decisions that can be treated separately and those that must be taken together. This can help to identify opportunities for flexibility in investment decisions. When combined with a measure of influence this information can help to build a decision structure that would relate to the organizational management of analysis teams for future design iterations.

7.2.2 SPACE TRANSPORTATION ARCHITECTURE CONCLUSIONS

The space transportation system architecture definition consists of a combination of several assignment, partitioning, and downselection problems. Multiple different reference missions can be captured by this architectural definition and the associated metrics of IMLEO and technology LCC proxy capture fundamentally different design philosophies.

Boil-off control, Solar Electric Propulsion (SEP), Nuclear Thermal Rockets (NTR), and aerocapture are all highly beneficial technologies for the Mars transportation system. SEP and NTR drive different strategies optimized for technology LCC or IMLEO respectively. Most technologies reduce the IMLEO and increase the technology LCC for the infrastructure to Mars, but SEP and in-space methane stages have the opposite influence on the system resulting in relatively higher (but still acceptable) IMLEO for the benefit of having a lower technology LCC. Some amount of boil-off control is required to realize a feasible architecture to Mars.

The coupling that occurs between boil-off control and other propellant decisions demonstrates that implementing boil-off control can reduce the sensitivity to propellant type decisions. Reducing the Technology Impact Measure (TIM) (seeEquation 4-2) of a technology indicates possible opportunities for flexibility in the development process of different segments of the architecture. Strong coupling interaction effects (see Equation 4-3) change the value proposition of one technology in the presence of another and so indicate those decisions should be made together. (See Figure 5-17 for a proposed organization of decisions).

There is an overall trend that as the time of flight and delta-v requirements of a mission are lower, the benefits of additional technologies become outweighed by their costs. This suggests that the Moon and some Near-Earth Asteroid missions can possibly be used as precursor destinations on a development timeline to future Mars missions.

Each destination has different technologies that provide the most benefit. Aerocapture, hydrogen descent and ascent stages, and SEP are all highly beneficial to the lunar transportation system. NTR and ISRU do not appear in the best transportation architectures to the Moon. For the low delta-v NEA case, fewer technologies provide significant benefit in defining the transportation system. In-space methane stages and aerocapture provide the most beneficial influences in terms of IMLEO and technology LCC to the low delta-v NEA. For the higher delta-v NEA mission, the prioritization of technologies is reversed from that of the first NEA case. For the higher delta-v NEA mission NTR and boil-off control are the most beneficial technologies.

In terms of defining investments into future technologies, NTR and aerocapture are major driving factors in optimizing the transportation architecture to Mars. At least one or the other technology is present in all of the best architectures to Mars. Deciding whether or not to pursue NTR for Mars represents a big decision that has been considered on its own in the past. It will take careful consideration of the overall budget available for technology development activities. Depending on that decision it makes sense to pursue an overall architectural strategy that is well suited either to the expected availability of NTR or to the higher mass, lower technology LCC types of architectures that gain more benefit from aerocapture and high power SEP. The pursuit of these technologies is also highly coupled to the destinations that are selected for pre-cursor missions, as the technologies provide widely different benefits depending on various mission parameters.

7.3 FUTURE WORK

7.3.1 METHODOLOGY FUTURE WORK

The approach we take in this thesis of considering technology influence provides different information from the sensitivity measures in previous work as described in Chapter 4. It is expected that future work will help to rigorously categorize the various tools of the system architect to different goals of system architecture analysis. While Simmons's PVS and the TIM provided in this thesis provide similar measures they are defined for different aspects of architecture problems and provide different information. Likewise the connectivity and coupling measures discussed are appropriate for different types of architecture problems and provide decision makers with different information. An integrated framework that classifies goals of the system architect to various tools would be very valuable.

Future efforts considering the technology development projects for space exploration must help to develop investment portfolios that will advance the capabilities available to system designers. For the purposes of portfolio design there must be a better understanding of a development timeline and available budget. Technology development and system development in general occurs in cost and schedule constrained atmosphere, and there must be reasonable constraints on what NSA's exploration enterprise can realistically pursue. These endeavors must model risk, cost, and uncertainty of performance both in terms of development progress and demonstration mission success.

Since it was identified that industrial base issues are important in technology development, it is also recommended that the contractor's influence on cost and risk of overall projects is considered. There should be detailed understanding of what assets are available for development capability and how the benefit of these assets can be maximized across multiple projects. There should also be consideration of flexibility in technology portfolio management, considering how switching projects or re-allocation of funds can be implemented when projects don't meet specific performance levels. At minimum a definition of criteria by which shutdown of a project should be taken so that those funds can be allocated to more productive projects.

7.3.2 SPACE TRANSPORTATION ARCHITECTURE FUTURE WORK

Collecting more data on previous space exploration technologies can help to build heuristic models to use in technology evaluation. In terms of investment activities the goal should be to associate individual development projects with relative levels of appropriate funding over time.

While the scope of the tradespace considered for individual missions is fairly broad, there are some considerations that should be included in the potential mission architecture. These aspects to the architecture definition may become particularly important when defining a campaign of missions that prepare for the ultimate destination of Mars. Intermediate staging locations between LEO and a destination do not necessarily provide benefit for a single mission due to the added delta-v and time of flight requirements. However, in a future campaign design there may be assets that are re-used across multiple missions to multiple destinations. In the case that a large habitat or propellant depot must be stably stored in space, access to certain astrodynamic locations such as an Earth-Moon Lagrange point or a highly elliptical Earth orbit may prove to be beneficial. Another factor that will greatly increase the number of alternatives in the tradespace but will increase the modeling fidelity is to split up individual propulsive maneuvers into multiple stages. Currently multiple maneuvers can be aggregated into a single element, but some large maneuvers may be better executed by multiple stages. This will also help to define a set of common elements that need to be built for the transportation system for a full exploration campaign.

There are at least two major factors that must be considered when defining a future exploration campaign. As mentioned, there should be a common set of elements that can be re-used for multiple purposes. In the current framework rocket stages are optimized for the given requirements based on the rocket equation. However in reality a smaller set of stages must be designed and then used for multiple purposes. While this will result in some loss of efficiency in terms of mass, it is expected to reduce the overall cost of the transportation infrastructure. Defining what these common elements may be is not a trivial task and doing so must take into consideration the ambiguity on destination and development strategy present.

The other major consideration for an exploration campaign is how to define a development pathway. A campaign of exploration will be defined by a series of missions. These missions must be organized to provide several attributes to the entire program. Precursor missions will provide benefit in the form of science and exploration return from the various destinations visited. They will also provide some measure of exploration preparation by proving out the systems and processes required for the eventual transportation system to Mars. Specifically in terms of technology development precursor missions represent a buy-down of risk, proving out the technical capabilities that have not yet been demonstrated. Overall the campaign must develop capability incrementally. That is to say if the first mission requires every technology and exploration element it will be too expensive and too much time before anything is accomplished. Both cost and benefits must come in increments so that the program is sustainable. The series of missions must also be somewhat flexible so that individual mission failures or partial successes do not derail the entire program. Some kind of search through a tradespace of development pathways will be necessary to consider the timeline over which elements and capabilities are developed and the missions that are defined to demonstrate those capabilities while returning science and exploration value.

The decision making process for a national space system is complex. Analysis of common elements or flexibility in exploration campaign design is only valuable if the results can be communicated and implemented. There is an entire aspect to the decision making process of architecture definition related to policy and engineering management that has not been rigorously treated in this thesis. Particularly in the field of technology portfolio management it is suggested that possible mechanisms for flexible implementation strategies are explored. The government procurement process is fairly rigid and identifying how to take advantage of productive work or to abandon unproductive work could increase the overall value proposition of development efforts in general.

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