

# In-Space Transportation Infrastructure Architecture Decisions Using a Weighted Graph Approach

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**Abstract**—The selection of an architecture is a key step in complex system development and has major, often irreversible effects on the performance, cost, and flexibility of the system. In addition to being a process heavily influenced by the technical performance and cost analysis of each individual architecture, the selection of the initial architecture is also determined by less quantifiable criteria such as architecture flexibility and extensibility. In this paper we study methods to analyze initial architecture decisions influenced by these two factors using a fully enumerated tradespace of architectures for the in-space transportation infrastructure for human exploration of Mars. Our approach is to transform this tradespace into a weighted graph with nodes corresponding to architecture-technology combinations and edges corresponding to the ability to transition between two architectures. We restate the problem of selecting an initial architecture as two simple problems on this graph, finding that this approach can determine a small set of non-dominated options useful to the architecture selection process.

its nature made early in the design lifecycle, in some cases architectural change is unavoidable as unforeseen technical issues, changes in system context, or changes in budget make the current architecture infeasible or suboptimal [14]. In other scenarios, current restrictions on the system architecture, which may themselves be functions of available resources or current technological capabilities, may constrain the initial architecture selection to be something other than the ‘desired’ architecture (perhaps for performance or recurring cost reasons). In this case, the architecture may be purposefully modified, or extended, after initial development as new capabilities become available over time.

In this paper we study the future in-space transportation infrastructure for human exploration of Mars currently under consideration by NASA [16] as a prime example of such a system where both types of architectural change mentioned above are likely occur. Any system for the transportation of humans to the surface of Mars and back will necessarily entail a number of large, uncertain development projects (e.g. deep space habitat, Mars descent vehicle, propellant boil-off control) that may fail due to cost, schedule, or performance slips and force the architecture to change as a result. In addition, NASA and its international partners are highly sensitive to changes in high-level mission requirements and allocated budgets that can shift over the lifecycle of such a large system as a result of changes in national priorities. The tradespace of potential infrastructure architectures also includes many ‘high-performance’ architectures that require more advanced technologies such as nuclear thermal propulsion and surface in-situ resource utilization that necessitate major investments of time and resources possibly beyond the scope of initial budget and schedule constraints. If and when these more advanced technologies are developed, the architecture could be changed to realize their benefits in performance and cost.

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## 1. INTRODUCTION

### *Motivation*

When a decision is made regarding a system’s architecture, the functionality of the system, its decomposition (both functional and organizational) into smaller subsystems, and its ability to be extended or upgraded over time are restricted [5]. Making large changes to the architecture after system deployment or partway through system development can have major impacts on system cost, schedule, and performance as architectural changes require rework of the existing design and redefinition of interfaces between subsystems.

However, since the selection of a system architecture is by

For both cases of architectural change, intelligent initial selection of the architecture is key to mitigating the negative effects of being forced to change the architecture during development or deciding to change it after deployment. In the case where some desired ‘goal’ architecture or family of architectures is known (e.g. architectures that decrease the launch mass required or that allow for longer duration stays at Mars), the initial architecture should require a minimum number of major modifications to be transformed to the goal architecture. In other words, the initial architecture selection should be made with *extensibility* in mind. In the case that no ‘goal’ architecture has been identified and the uncertainty in budget, technology development, or mission

requirements is the primary decision driver, an architecture should be selected that can be transformed into a different feasible architecture for each of the identified risk factors with a minimum number of modifications. Here the initial architecture selection should be made with *flexibility* in mind.

### Approach

In this paper we develop a decision support framework for initial architecture selection in an in-space transportation infrastructure tradespace of tens of thousands of distinct architectures. The core of our approach is to transform the large tradespace into a weighted graph of architecture nodes connected by edges whose existence and weight is determined by a high-level approximation of the feasibility and difficulty of changing from one architecture to another. We decompose the initial architecture selection problem into two classes: one where the final or goal architecture is known and one where the final or goal architecture is uncertain. We restate both of these abstract problems as well-studied and easy to understand problems on the tradespace graph, with the first equivalent to finding the shortest path through the graph from one node to another, and the second equivalent to finding nodes with the most immediate neighbors.

In the remainder of this section we will present a short literature review of relevant past work and discuss the enumeration and structure of the tradespace that we will be using throughout the rest of this work. In Section 2 we will discuss the development of the tradespace graph and the important metrics that will be utilized in our architecture selection method. Section 3 contains the detailed description of the two initial architecture selection problems as well as the development of our decision support method. In Section 4 we present the results of our framework as applied to the in-space transportation infrastructure tradespace. Finally in Section 5 we close with the conclusions of our work and discuss a number of directions for future work.

### Relevant Background

The process of analyzing a tradespace of architectures to select architectures for further investigation, determine possible development pathways over time, or provide decision makers with relevant information to guide architecture selection is commonly known as Tradespace Exploration. A number of tradespace exploration tools have been developed in the field of aerospace systems, and in particular space systems, to extract as much useful information as possible from an uncertain and complex tradespace since the space of possible architectures is often large and the impact of selecting a good or bad architecture is far reaching.

One method often employed by NASA and other large organizations is to develop a high fidelity point architecture using the input of engineering, science, and policy experts as in the Design Reference Architecture 5.0 study for human exploration of Mars [16]. These point designs can provide a baseline for future architecture studies or help to define current prioritization of technologies and long term development projects, however they are more focused on depth rather than breadth of exploration.

Other methods such as [11] and [1] begin with a baseline architecture and then make incremental adjustments to search for the optimal architecture. Genetic algorithms have been applied in a similar role to study tradespaces that are too large or too complex to fully enumerate [4],[23] and to search for the optimal architecture within a tradespace that has

requirements that evolve over time [10],[12].

If the tradespace is fully enumerated and evaluated as in [13],[18],[20] multiple metrics can be defined over all architectures and combined to determine the Pareto set of non-dominated architectures. A number of architecture evolution tools have also been developed for fully enumerated tradespaces that allows decision makers to analyze pathways through the tradespace either for flexibility or extensibility of the architecture. De Weck, de Neufville, and Chaize develop a tool for analyzing the staged deployment of communications satellites to determine which architectures make the satellite constellation robust to uncertainty in demand using a real options approach [8]. Using this analysis a suboptimal initial constellation might be chosen as a way of buying the option to extend the constellation at a later date should demand increase.

A number of other tools study this same problem of how best to develop an architecture to meet changing future performance or cost goals. A retrospective analysis of architecture development for software systems is studied in [15] to determine how the architecture changed across multiple releases of a system to inform future software evolution efforts. Arney studies the relationships between possible human exploration architectures across multiple destinations to determine possible flexible paths through the tradespace by examining the overlap of major system elements between missions along the path [1]. Finally, Silver and de Weck develop a quantitative tool to determine feasible evolutions of launch vehicle architectures over time. They form a dynamic network using cost information and then develop a time-expanded static network to analyze the sequential decisions of whether to keep the current architecture or change to a different one at each time step [22].

### Tradespace Description

The in-space transportation infrastructure tradespace used in this paper is generated using the HEXANE tradespace enumeration tool developed by Rudat et al. in [20] and [19]. This tool allows the user to define input parameters such as mission destination (e.g. Moon surface, Mars surface), number of crew, and destination visit time, defining these as constants across the tradespace so that all architectures deliver the same benefit to stakeholders. HEXANE then enumerates and evaluates all architectures within its high level modeling assumptions.

The problem of defining an architecture within the HEXANE model is divided into a number of architecture subproblems classified by Selva [21], the most important of these being the partitioning of system functions into elements of form. Rudat et al. argue that all manned exploration missions include seven top-level habitation functions (e.g. surface habitation, deep space return habitation) and ten top-level propulsion functions (e.g. earth departure burn, destination arrival burn). The *functional architecture* of a system defines how these functions are partitioned into elements of form.

By enumerating all possible functional architectures and then combining this subproblem with other subproblems such as the propellant used for each maneuver and the presence or absence of certain technologies (discussed below), the complete tradespace is enumerated. By enforcing logical and physical constraints on this enumerated set, the feasible tradespace is extracted and each architecture is sized using parametric models for propulsion and habitation elements, and an iterative solver is used to determine propellant masses.

Technology Description	Score
In-Space Nuclear Thermal Propulsion	1
In-Space LOX-Hydrogen Propulsion	1
In-Space LOX-Methane Propulsion	1
Descent LOX-Hydrogen Propulsion	1
Descent LOX-Methane Propulsion	1
Descent Hypergol Propulsion	1
Ascent LOX-Hydrogen Propulsion	1
Ascent LOX-Methane Propulsion	1
Ascent Hypergol Propulsion	1
Solar Electric Propulsion	1
Propellant Boil-Off Control	1
Aerocapture	1
Surface In-Situ Resource Utilization	1

**Table 1.** List of technologies and development scores. [2]

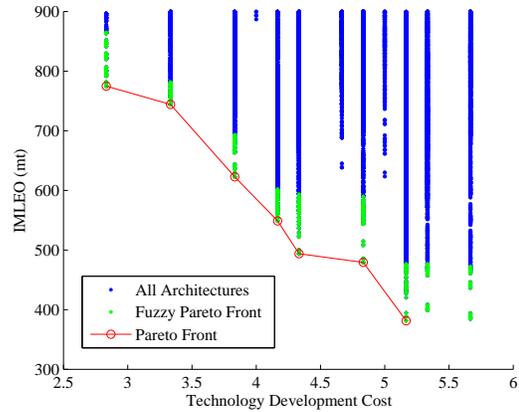
This sizing of the architecture determines one of the primary evaluation metrics used to analyze the tradespace: the initial mass of the system as launched to low earth orbit (IMLEO).

The other important evaluation metric is a proxy for the difficulty of developing the technologies required by the architecture, which we will call the Technology Development Cost (TDC). Battat et al. define 13 high-level technologies that are modeled in the HEXANE tradespace and that can be used to differentiate architectures from one another [2]. These technologies are then scored according to their current maturity and their utility to multiple stakeholders, with higher values corresponding to more costly development. The TDC for a particular architecture is the sum of the technology scores for all technologies utilized in the architecture. The list of modeled technologies and their corresponding scores is given in Table 1.

By combining these two metrics, TDC and IMLEO, we can generate a simple view of the tradespace on a two dimensional plot as shown in Figure 1. The red line connects points on the Pareto front of the tradespace, which are those points for which neither IMLEO nor TDC can be reduced without reducing the other. The green points on the plot represent the *Fuzzy Pareto set* introduced in [25], which is the set of points closest to the Pareto front that make up a given percentage of the tradespace.

## 2. TRADESPACE GRAPH FRAMEWORK

In this section we discuss the transformation of the tradespace discussed above into a weighted graph, reusing much of the development outlined in [6]. This tradespace consists of a set of evaluated architectures with identical functionality in terms of number of days spent on the Martian surface and the science payload available. The key metric used to characterize the ‘performance’ of an architecture is the evaluated initial mass to Low Earth Orbit (IMLEO) required to close the design. Although strictly speaking IMLEO is a proxy for the recurring cost of manufacturing and launching the transportation system, it is a simple, objective measure that we can use to compare architectures with identical functional performance [20].



**Figure 1.** The evaluated in-space transportation infrastructure tradespace with architectures plotted according to IMLEO and Technology Development Cost. Pareto optimal architectures and Fuzzy Pareto Front shown.

### Distance Metric

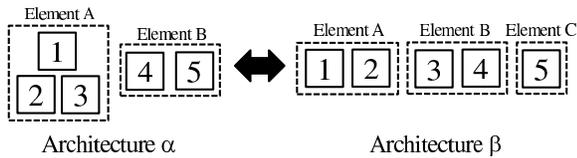
In order to understand how architectures are connected and how easy it is to change from one architecture to another, we need a concept of distance which encodes the switching cost between architectures. This need for a measure of switching cost appears in a variety of other architecture exploration tools [1],[15],[22]. Notably Silver and de Weck use a detailed cost model of the cost of decommissioning and developing elements at the subsystem level to estimate the actual cost of changing the architecture of launch vehicles [22]. Ideally, such a monetary measure could be used in our current tradespace, however the relatively low level of fidelity of the architecture model and the large number of points in the tradespace make this level of detail infeasible.

As an alternative we use the assignment of function to form, which we argue is one of the primary defining features of the architecture, as the means of determining a proxy for the switching cost. Since the assignment of function to form, which we call the functional architecture, is modeled as a partition of the high-level system functions, and a variety of metrics have been developed in other fields to measure the distance between two partitions, we can use existing methods to simplify the development of our approach.

We make use of a simple metric on sets of partitions defined by Day in [7] as the sum of the number of elements that are merged, divided and transferred to make two partitions equal. In the language of our current problem, the distance between two functional architectures is the number of functions that must be moved from one element of form to another to equate the two partitions. Figure 2 shows a simple visual example of how this metric is calculated for the current application. We argue that this distance provides a high-level proxy for the switching cost between two architectures as the transfer of functions between elements drives up both the formal complexity [3] and structural complexity [24] of the project due to rework of interfaces and development of new hardware, resulting in increased cost and schedule.

### Node Definition

In addition to the architecture itself, which consists of the functional architecture, the deployment timeline, maneuver propellants, and required technologies, the other key aspect



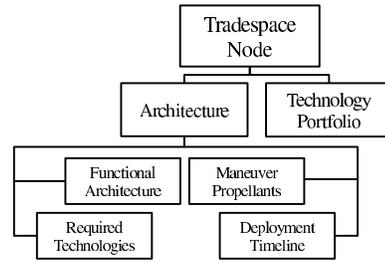
**Figure 2.** Two possible architectures  $\alpha$  and  $\beta$  for five functions. Each solid box labeled with a number represents a function while each dashed box is an element of form, which is assigned one or more functions. To transform  $\alpha$  to  $\beta$  Function 5 is split off to create Element C. Function 3 is then transferred to Element B from Element A. Since there are two operations the distance between  $\alpha$  and  $\beta$  is two. Reproduced from [6].

considered in the tradespace graph is the technology portfolio. The technology portfolio consists of the technologies identified by Battat et al. [2] that the project has *available* to implement in the architecture. This idea of availability could mean that the technology is ready to be deployed in its current state, or that an investment has been made in the development of the technology and it is projected to be mature upon flight system development. In order for an architecture to be feasible with a given technology portfolio, the portfolio must contain at least the required technologies of the architecture. Note that a portfolio may contain excess technologies unused by the architecture, but that these are undesirable since they represent an unused investment. The inclusion of the technology portfolio as an entity separate from the architecture is key to the connectivity of the tradespace graph as discussed below.

Like any graph, our tradespace graph consists of nodes connected to one another by edges of a given weight. Nodes in the graph represent a pairing of a technology portfolio with an architecture. Only nodes for which all of the required technologies are contained in the technology portfolio are enumerated. An additional constraint is placed on each enumerated node that the number of excess technologies does not exceed some number  $K$  (for Problem 1 we set  $K = 2$  and for Problem 2  $K = 0$ ). Figure 3 gives a summary of the decomposition of a node into its lower level components.

#### Edge Definition

The existence of an edge between nodes is determined by the relationship between the two technology portfolios of the nodes. If the portfolios are the same or differ by a single technology (i.e. one technology needs to be added or deleted), then an edge exists between the two nodes. The reasoning behind this edge criterion is that it allows us to explicitly identify which nodes can be reached from a given node through an incremental technology investment. Since the purpose of creating this graph is to use it to understand how an architecture can evolve in steps through a tradespace from one point to another, restricting the change in technologies to a single switch per step allows the ‘step size’ of the evolution to be as small as possible. The reason that connections are made based on technology portfolios rather than required technologies of the architecture is that it allows the investments in technologies to be ‘retained’ along the evolution path even if required technologies change. For instance, if we initially invest in developing an in-space liquid hydrogen propulsion stage and then implement an architecture that does not make use of this technology, we should later be able to switch to an architecture that does require in-space liquid hydrogen without having to reinvest in maturing the technology.



**Figure 3.** Overview of the decomposition of a tradespace node. Reproduced from [6].

Finally, for those edges that do exist, the weight of the edge is determined by the distance between the functional architectures of the two nodes. As detailed above, this distance encodes the cost of moving from one architecture to another and thus connections between architectures that are similar to one another will be favored when investigating paths through the graph. With the tradespace graph generated, we can then implement our simple graph algorithms on the tradespace to provide insight into the initial architecture selection problems we are studying.

### 3. PROBLEM FORMULATION

In this section we will present the problem formulation and solution approach for the initial architecture selection problem introduced in Section 1. In its general form, the problem is one of selecting an architecture for the system from the tradespace of possible options, taking into account both immediate IMLEO performance and future development options. As suggested in Section 1 we decompose this ambiguous problem into two more exact problems: find the initial architecture with a known final architecture in mind (Problem 1), and find the initial architecture without a known final architecture (Problem 2).

#### Problem 1: Known Final Architecture

The primary assumption underlying Problem 1 is that the system designer must pick an architecture for the system under development, but that this architecture is not necessarily the ideal architecture in the long run. This discrepancy could be a result of initial development cost constraints which force the system designer to select a lower-performance architecture that can be modified over time to the ideal high-performance architecture. An example of such a decision scenario can be seen in NASA’s plan for the evolution of the Space Launch System (SLS) [17]. The selection of the current 70 metric ton launch vehicle as the initial architecture is a function of budget, reuse, and schedule constraints. NASA’s plan calls for the evolution of this initial architecture into a 130 metric ton launch vehicle after initial development, which represents stakeholders’ ideal performance preferences.

Ideally the highest performing architecture that is feasible given the initial constraints would also be the one closest in terms of switching cost to the goal architecture, however this is not always the case. For example NASA may have had a choice between a 70 mt vehicle with a projected \$2B development cost to reach the 130 mt version, and a 75 mt vehicle with a \$4B cost to develop the follow-on 130 mt vehicle. With this example in mind we can see that the need to select an architecture that can most easily evolve into the final architecture must be traded against the performance of

the initial architecture itself. Since this trade for the in-space transportation infrastructure would take into account a variety of technical, social, and political factors far beyond the scope of our tradespace model, our goal here is simply to present the best options to be traded against one another as input for the decision maker.

To find these options, we first define a subset of candidate architectures for the initial selection. For our tradespace, we simply use constraints on the Technology Development Cost and IMLEO to define the set of feasible candidates. For the results presented in the next section we define the set as all architectures with  $TDC < 3$  and  $IMLEO < 810mt$ , which we see in Figure 1 is the bottom portion of the ‘stack’ farthest to the left. To reduce the size of the graph and computational time, we consider only architectures in the Fuzzy Pareto Front to be feasible. For our application our fuzzy set consists of the 2% of the architectures in the tradespace that are closest to the TDC-IMLEO Pareto front. This reduction of the tradespace also enforces an implicit constraint that the sequence of architectures which define the path through the tradespace should themselves be acceptable architectures, though not necessarily independently optimal.

Using this reduced tradespace with a subset of candidate initial architectures and a single final architecture, we then generate the tradespace graph by combining the architectures with technology portfolios and defining edges as described in Section 2. In order to find the optimal sequence of architectures and technology portfolios from each of the initial candidates we calculate the shortest path through the tradespace graph from each initial candidate to the final node using Dijkstra’s shortest path algorithm for weighted graphs [9].

This single calculation is not quite enough however, since Dijkstra’s algorithm only returns the first path of minimum length it finds. In fact there could be multiple minimum length paths from the initial candidate node to the final node since the path length is the sum of the edge weights between sequential architectures in the path. If multiple shortest paths exist through the space (which we found is usually the case for the current application) then we need a way to find and compare all of the shortest paths between the same two nodes in order to select the optimal one in terms of a different metric. For this purpose we use a variation of Yen’s algorithm [26] which deletes edges along the path to determine the set of all shortest paths between the two nodes of interest. We then select the path which minimizes the sum of IMLEO for nodes in the sequence under the assumption that decision makers would wish to maximize performance of the intermediate architectures.

With the optimal path from each of the candidate architectures to the goal architecture found we can use this information to inform the decision maker regarding the trades between different selections. By plotting the length of each of the paths against the IMLEO of the corresponding initial architecture candidate. The Pareto front of this plot will represent the non-dominated initial architecture choices in terms of the direct trade between immediate performance and future ease of extensibility.

#### *Problem 2: Uncertain Final Architecture*

For Problem 2 we assume that no such final goal architecture exists in the mind of the system architect, so he or she wants to select an initial architecture that is flexible to both exogenous changes to system requirements, budget, and operating

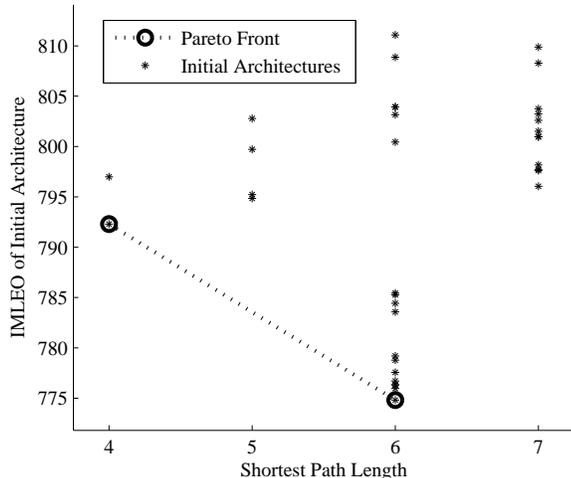
context and to internal issues such as technology development failure or discovery of errant assumptions. In the context of the transportation infrastructure for Mars exploration, such negative ‘development disturbances’ are not only possible but also likely given the long development period of such large, complex systems that could overlap multiple administrations, see drastic changes in national economic priorities, and be exposed to a changing geopolitical environment. Also possible are positive disturbances such as the unexpected development of a useful technology or increases in system budget that could push the system in the direction of lower cost or higher performance. In either case decision makers would want the ability to make incremental, relatively inexpensive changes to the architecture to respond to these disturbances in a flexible manner.

As a first approximation for the flexibility or robustness of an architecture, we can try to understand how many other architectures are in the immediate neighborhood of the architecture candidate. Although this concept does not take into account the type of disturbances that the architecture is flexible to (e.g. technology failure, budget changes), it does give a rough estimate for how large a region of the tradespace the architecture can access by making relatively small changes.

To define the neighborhood of an architecture, we will again use the tradespace graph developed in Section 2, but rather than relying on a shortest path formulation we will simply count the number of neighbors or each candidate architecture and use that as a proxy for flexibility. For this study, we define a neighboring architecture as any which differs by at most a single technology relative to the required technologies of the candidate architecture and has a distance of no more than one from the candidate architecture. In terms of our graph framework already in place, finding the number of neighbors by this definition is simple. Enforcing the constraint that the number of unused technologies in the portfolio is zero across the graph (i.e. making the portfolio equal to required technologies for a given node) we only need to count the number of edges from the candidate node with weight less than or equal to one.

As in Problem 1, we will specify a subset of the tradespace as candidate initial architectures, in this case investigating a different part of the tradespace with  $4.0 \leq TDC \leq 4.5$  and  $IMLEO < 600$ . For each of these initial candidates we will determine the number of connections to other architectures in the tradespace and divide by the maximum number of connections from among this subset to give a *Normalized Flexibility* from 0 to 1 for each architecture. It is important to note that we only consider a small portion of the entire tradespace when determining the number of connections for each initial candidate since we only want to consider near-optimal architectures is viable flexible options. For this reason we use only the fuzzy Pareto set that consists of 1% of the tradespace to build the tradespace graph.

Finally we can plot the values for the normalized flexibility of each initial architecture candidate against the IMLEO of that architecture to determine the Pareto front initial architectures which trade flexibility as we have defined it for initial IMLEO performance. Again, analyzing this trade in detail and selecting a ‘best’ initial architecture is beyond the scope of this work and of the fidelity of this model, however we present the options here as an additional source of information for system designers who must make these types of architecture decisions.



**Figure 4.** Set of 36 initial architecture candidates plotted on axes of IMLEO and length of shortest path to final architecture.

## 4. RESULTS

In this section we present the results of the two problems discussed in Section 3 for the in-space transportation infrastructure for human exploration of Mars.

### Problem 1: Known Final Architecture

For this problem we define the candidate initial architectures as the subset of the tradespace with TDC below 3.0 and IMLEO below 810 mt. In total this subset contains 36 initial architecture candidates. These architectures represent the minimum technology investment required to realize a feasible architecture within the architecture modeling framework used. Although these architectures span a variety of required technology sets and function to form mappings, in general we see that they all share basic technologies such as aerocapture and solar electric propulsion, and that the habitation and propulsion functions are distributed across many separate elements of form.

For the final architecture we select the minimum IMLEO architecture across the entire tradespace, which is a *technology rich* architecture incorporating nuclear thermal propulsion, boil-off control, and in-situ utilization. In terms of the functional architecture, we note that it is a *monolithic* mapping with many functions assigned to a single element of form, especially with respect to habitation.

The results of the calculation of shortest paths from each initial candidate to this final architecture are shown in Figure 4 as the length of each path plotted against the IMLEO of the initial architecture. From this figure we see that there are two Pareto optimal choices for the initial architecture in terms of these two metrics.

We plot the path through the tradespace from these two initial architectures to the final architecture in Figure 5. The candidate initial architectures are shown as the red points in both figures, with the selected initial architecture marked by the blue circle. Figure 5(a) shows the path for the minimum IMLEO initial architecture, while 5(b) shows the path for the minimum length initial architecture. Visually these two plots indicate that the minimum IMLEO initial architecture

takes an inconsistent route through the tradespace, with two very ‘small’ hops along the path (with one actually increasing IMLEO), while the minimum path length initial architecture takes a more direct and gradual route.

We can also note that the path in (a) has one additional hop relative to the path in (b), which causes the length of (a) to be two units greater than the length of (b). This difference in path length can be traced to the habitation functional architecture of each of the initial candidates. For the minimum IMLEO candidate, the habitation architecture is fairly distributed with Mars descent, Mars surface, and deep space return split into three separate habitats. For the minimum path architecture, all three of these functions are assigned to the same habitat. Since the final functional architecture assigns all habitat elements reentry to the same monolithic habitat, this means that more architecture modifications are required for the minimum IMLEO architecture, corresponding to a higher cumulative switching cost and a longer path through the tradespace.

### Problem 2: Uncertain Final Architecture

For this problem we examine a set of initial architectures in a different region of the tradespace to evaluate architectures that have connection both to higher performance and lower development cost architectures. This set of architectures is shown as the set of red points in Figure 6(b).

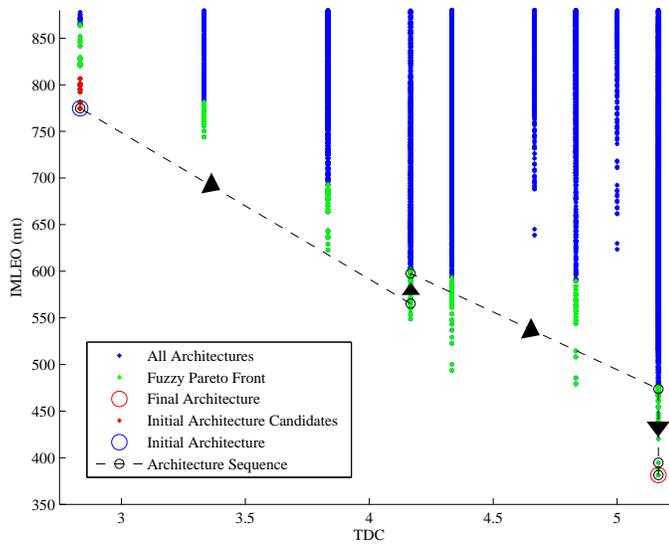
The normalized flexibility of each candidate architecture, which as a reminder is the number of neighbors of an architecture divided by the maximum number of neighbors, plotted against initial architecture IMLEO is shown in Figure 6(a). The Pareto front of this set is also plotted, indicating that there are three Pareto optimal architectures with similar flexibility scores. As a reference, the maximum number of connections (i.e. the number of connections of the architecture with normalized flexibility equal to one) is 22.

Under the assumptions of our architecture and tradespace models, the three Pareto optimal architectures labeled 1 through 3 are the initial feasible options for trading between performance and development flexibility as we have defined both metrics. As an example of how these initial architectures are connected to other architectures in the fuzzy Pareto set, we plot the connections of Pareto architecture 1 on the original TDC-IMLEO axes in Figure 6(b). We can see that this initial architecture (labeled with the blue circle) is connected to both higher performance architectures (indicating extensibility under positive exogenous impacts) and to lower development cost architectures (indicating flexibility to some types of negative impacts).

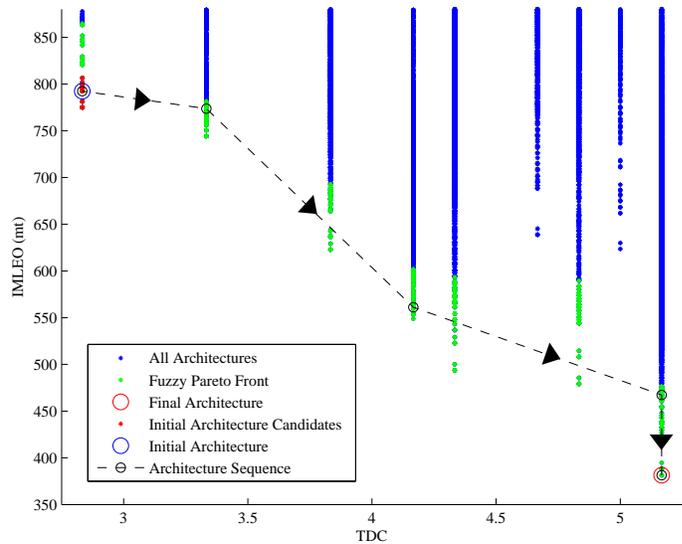
## 5. SUMMARY AND CONCLUSIONS

In this paper we present a set of methods for transforming an enumerated tradespace into a weighted graph and restate the ambiguous initial architecture selection problem as two precise problems on this tradespace graph. We apply these methods to a tradespace consisting of architectures for the in-space transportation infrastructure for future human exploration of Mars.

The first problem, which arises when an initial architecture is selected with a goal final architecture in mind, is reformulated as a series of shortest path problems through the graph from the known final node to a number of candidate initial architectures. We can then view the selection of the

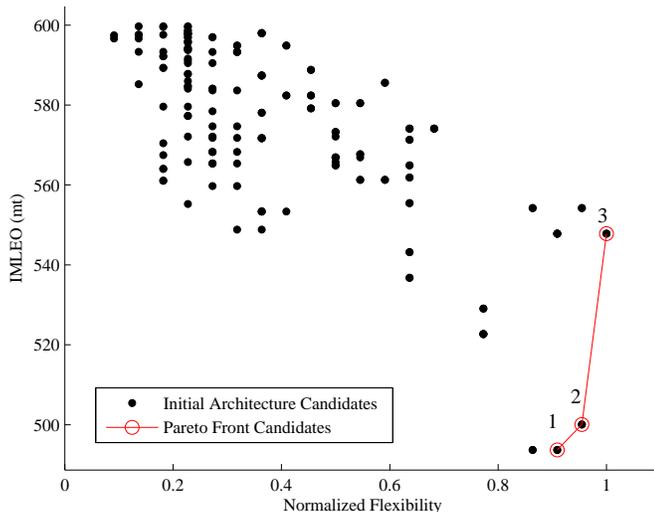


(a) Path from minimum IMLEO initial architecture

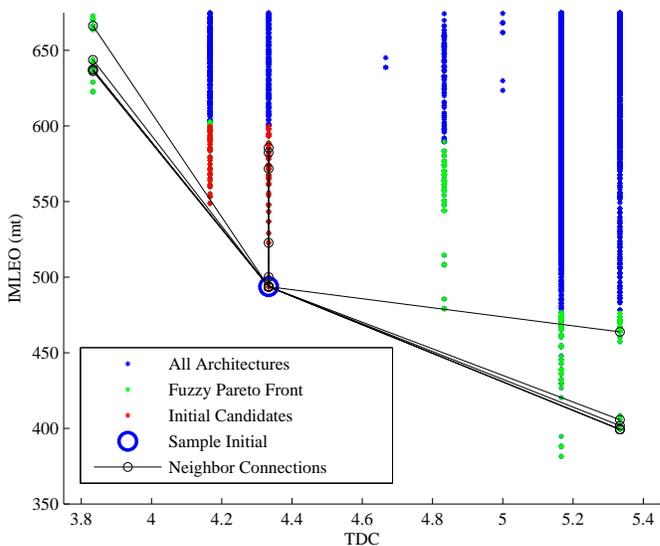


(b) Path from minimum path length initial architecture

**Figure 5.** Plots of the optimal paths to the final architecture for two Pareto optimal initial candidate architectures using Problem 1 analysis. Set of initial candidate architectures shown as red markers.



(a) Plot of candidate initial architectures along axes of IMLEO and normalized number of connections to fuzzy Pareto set architectures.



(b) Plot of tradespace along TDC-IMLEO axes, with connections of Architecture 1 in (a) shown.

**Figure 6.** Initial architecture analysis for Problem 2.

initial architecture as a decision to trade initial performance in terms of initial mass required to orbit against projected cost of developing the final architecture in terms of the length of the path required to reach it. By looking only at the non-dominated initial architectures in this IMLEO vs. path length space, we can provide decision makers with a small set of architectures which represents the ideal choices for this criterion. We leave it to the decision maker to determine how much of a premium in terms of initial performance he or she is willing to pay in order to have the option of more easily moving to the goal state.

The second problem we study occurs when no final architecture has been set or there is a large degree of uncertainty in the future context, performance or feasibility of the architecture. We argue that in such a case the decision maker would want to select a flexible initial architecture that allowed for easy and relatively inexpensive extension to both higher performing and lower cost architectures. We reformulate this problem as that of finding the architecture which has the optimal trade off between the number of neighbors on the graph and initial IMLEO. Again, we argue that the set of non-dominated initial architectures in the IMLEO vs. flexibility space is

more valuable to the decision maker than a single optimal architecture since the final decision will incorporate a variety of technical and nontechnical factors beyond the scope of this model.

A number of directions of future work have been discovered that would help make this framework for initial architecture more complete and more useful to general tradespace studies. One such direction that relates to the fundamental modeling of the tradespace is the development of a more detailed and more comprehensive measure of distance or switching cost between architectures. If this switching cost could be stated in the same units as the recurring cost for which IMLEO is a proxy and development cost for which TDC is a proxy, a much more rigorous decision model could be developed. A second direction is the application of real options valuation to the decision of how much initial performance to trade for future flexibility or extensibility, which would have the potential of making this framework more useful to decision makers.

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