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Technology Decisions Under Architectural Uncertainty: Informing Investment Decisions Through Tradespace Exploration

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Although NASA has yet to choose an architecture for human spaceflight beyond Earth orbit, they must pursue near-term investment in the enabling technologies that will be required for these future systems. Given this architectural uncertainty, it is difficult to define the value proposition of technology investments. This paper proposes a method for evaluating technology across a tradespace defined by architectural decisions. Main effects analysis is taken from design of experiments to quantify the influence that a technology has on the system being considered. This analysis also identifies couplings between technologies that are mutually exclusive or mutually beneficial. This method is applied to the architecture tradespace of transportation for future human exploration at Mars with a set of possible propellant, propulsion, and aerobraking technologies. The paper demonstrates that the evaluation of technologies against an individual reference architecture is flawed when the range of architectures being pursued remains diverse. Furthermore, it is shown that comparisons between fuzzy Pareto optimal architectures and heavily dominated architectures will distort the evaluated benefit of a technology. The resulting tradespace can be structured as the sequence in which technology decisions should be made, in order of their impact on the tradespace and their coupling to other decisions.

Nomenclature

X	=	specific metric, units vary
$\bar{M}\{X\}$	=	mean metric value for relevant subset of architectures X, units vary
P	=	full set of evaluated architectures across the tradespace, dimensionless
S	=	set of architectures in the fuzzy Pareto front, dimensionless
T^n	=	specific technology (n is an index that is dropped if only one is considered), dimensionless
T^n_{state}	=	set of architectures with the nth technology either on or off (represented by state), dimensionless

I. Introduction

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 costs of potential investments. Although the cost of technology development is often the primary uncertainty considered, in wide-open tradespaces like exploration, 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.

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In practice, prioritization of technology investments are based on an assumed system or mission architecture, so that a quantitative evaluation of the performance of a technology development can be used. For example NASA's Office of the Chief Technologist has presented a specific technology prioritization based on the NASA Mars Design Reference Architecture (DRA) 5.0 [1,2]. Existing space technology portfolio literature has focused on implementing financial techniques to evaluate technology alternatives and manage investments accordingly [3–5]. Other work seeks to combine nonfinancial attributes within a single assessment and selection framework [6]. A common theme through the existing literature is that a baseline system architecture definition is required for evaluation and prioritization of investment opportunities. However not all systems have a well-defined system architecture. A far future system such as the transportation for future human exploration of the surface of Mars cannot be realistically predicted in the short term. Multiple reference architectures have been published in literature characterized by different technical strategies [7]. Considering technology investment decisions are currently being made, it does not make sense to determine these decisions based on a limited subset of the available information.

The overall goal of this paper is to prioritize technology development projects for near-term investment considering the ambiguities in system architecture in the long term. After a discussion of relevant literature, a methodology of quantitative technology evaluation that is able to consider the value a technology provides across a range of favorable system architectures is proposed. The Mars transportation tradespace to which the methodology is applied is briefly described before a discussion of the results of the presented technology evaluation. The paper concludes with a framework for organizing future studies based on the influence and coupling measures proposed in this paper.

II. Background and Literature

Historically, NASA studies have provided quantitative justification for technology prioritization. By considering the beneficial influence of certain technologies on a single reference architecture, one can prioritize the major investments that will enable and improve the mission objective being pursued. For example, the chart displayed in Fig. 1 [2], has been used to demonstrate the benefits of potential technology investments associated with the NASA Mars DRA 5.0 such as improved cryogenic propellant handling or in situ resource utilization (ISRU) [1].

Using the metric of mass (as a proxy for cost), benefits are demonstrated as mass savings associated with each technology.

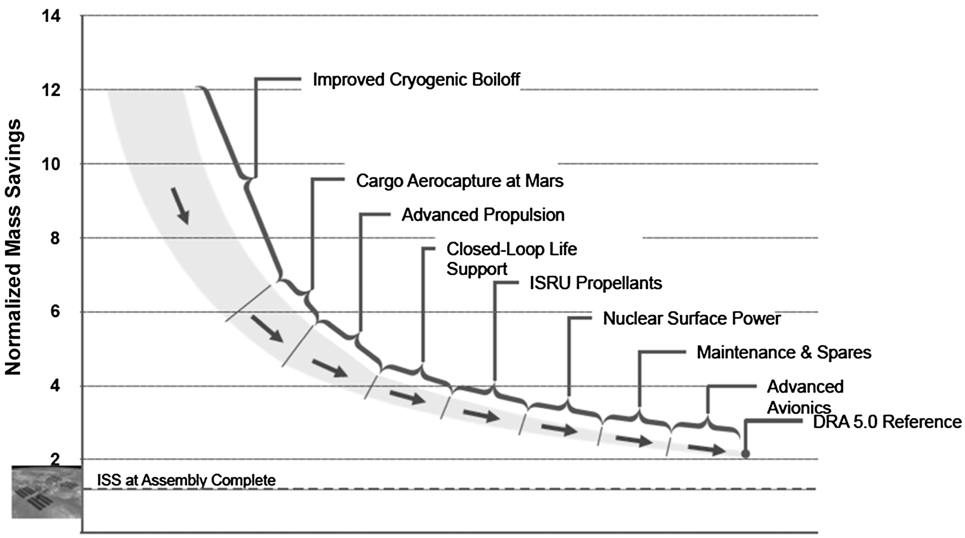

Fig. 1 Technology prioritization based on the NASA DRA 5.0 study [2].

Although it is valuable to gain an understanding of technology benefits based on physical modeling (rather than subjective opinions) some problems quickly become clear with this prioritization. The results presented in Fig. 1 are entirely based on the DRA 5.0 reference architecture. These technology benefits may significantly change if a different exploration strategy is pursued, rendering the prioritization irrelevant. Although consideration of a single design reference architecture may not be sufficient to prioritize technology investments, measuring benefits from a quantitative understanding of mission performance is desirable.

Technology development is considered a major contributor to overall project cost and schedule overruns in aerospace applications [8]. The difficulties of managing large government technology programs have been well documented [9] to the point that technology development uncertainty can be used to model schedule slippage [10]. The literature related to aerospace technology investment strategy focuses heavily on incorporating the knowledge of the uncertainty surrounding technology development in the definition of investment portfolios.

Heidenberger and Stummer describe a multitude of quantitative tools available to support the process of selecting projects for a technology portfolio and allocating funds accordingly [11]. They categorize six distinct groups of methodology for defining portfolios: benefit measurement, mathematical programming, decision and game theory, simulation models, heuristics, and cognitive emulation. These categories are not all necessarily applicable to NASA's technology investment strategy. The most relevant methods rely on the general category of benefit measurement techniques that create a project prioritization and then selection within budget constraints. These methods include single and multi-objective criteria evaluation, with figures of merit derived from expert opinions, physical modeling, and financial modeling. Simulation techniques such as Monte Carlo modeling and decision support frameworks such as decision trees may feed into benefit comparisons by calculating expected value of uncertain development processes.

Although the potential list of portfolio methods available is large, there are some specific attributes of the NASA technology enterprise that must be considered, in particular, as described by Wicht and Szajnfarber [12]. Successful aerospace technology maturation is often dependent on multiple other technologies due to the nature of tightly coupled integrated systems. Additionally, aerospace projects may be subject to architectural uncertainties as a result of unexpected system development evolution [13]. Wicht and Szajnfarber describe the current mechanism for NASA's technology project selection as a result of the complexity and wide range of technologies to pursue [12]. Overall strategic goals for technology development are set based on long-term road mapping activities. This determines strategic buckets that provide recommendations for allocation across different technology areas. Within the recommended spending of a given technology area and overall budget constraints, projects are then picked by expert peer review from submitted proposals. As a result of this process, projects are evaluated based on inconsistent criteria, and synergies between projects are often not considered [12].

There have been several portfolio methodologies proposed in the literature specifically for technology portfolios in the NASA context. The use of real-options modeling has been implemented for technology evaluation [3,4] and technology portfolio definition [5]. This tool is particularly useful in incorporating the extreme uncertainty associated with the resources required for maturation of technology through NASA's development efforts. The Jet Propulsion Laboratory (JPL) Strategic Assessment of Risk and Technology team proposes a framework for technology portfolio definition focused on deriving benefit measures from functional requirements to define a return on investment of proposed technologies [6]. Although they consider uncertainty in development and mission success, these frameworks rely on assessing the expected value of a technology in relation to a particular defined system or mission architecture. In the context where the overall system architecture has yet to be defined, it is difficult to build a valuation of these technologies to input into the proposed frameworks.

A framework that allows for technologies that modify the system architecture through representation in a design structure matrix is provided through a framework focused on technology infusion [14,15]. This framework provides a methodology to evaluate costs and benefits associated with particular technologies, but the technology infusion is based on an existing baseline architecture that is incrementally modified. However, in the evaluation of technologies for future human space transportation, there is no existing system architecture to reference as a baseline.

Tradespace exploration of system architectures for space transportation infrastructure has been previously considered. Because of the difficulties of generalizing the complex architectures of space transportation, studies have performed tradespace exploration by providing comparison across multiple individual existing reference designs [7,16], however, it is often difficult to evaluate all architectures with the same performance requirements for a fair comparison. Although reference missions are able to provide detailed analysis, more recent architecting methods have relied on generalized descriptions of system architecture for wider tradespace exploration. These approaches yield rich tradespaces that discriminate between thousands of potential architectures [17,18]. A generalized model of the system as a transportation network with nodes through which elements must travel [19] has provided a flexible framework for defining architectures, however, currently there is limited facility for autogeneration of architectures [20]. A method has been developed that is particularly well suited for autogeneration of architectures using an executable meta language, allowing for rapid evaluation of thousands of unique architectures [21]. This same line of work produced early results considering "technology switches" within the tradespace [22], however, analysis techniques are limited by visualizations of the performance of each candidate architecture with each technology, a process that does not scale well. As a result, a large tradespace with architectural uncertainty where hundreds or thousands of possible architecture/technology combinations may be considered are cumbersome to visualize. Using similar model-generation techniques, a more systematic way to evaluate the influence of certain decisions (including technological decisions) is provided by the "Architectural Decision Graph" developed by Simmons [23]. Simmons provides measures that consider the sensitivity to an architectural decision and coupling to other decisions. Although his method provides a measure of the sensitivity of performance to an architecture decision, it does not provide the influence of implementing a given technology or a measure of the technology's performance. Further, Simmons's coupling measure is a model input and does not capture complex interactions within the model evaluation.

In architecture tradespace exploration that has little definition, the wide range of available architectures can be difficult to interpret. The proposed method seeks to evaluate individual technologies within the tradespace, measuring how they influence architectures across a wide tradespace. It is desirable to be able to interpret the interactions that occur between technologies and look at those that do or do not appear together in the same architecture.

III. Methodology

Tradespace exploration and system definition of future human space transportation will proceed over a long development timeline. In this paper, main effects analysis from design of experiments literature [24] is used to isolate various technologies within a complex tradespace and to understand explicitly how those technologies influence the full range of system architectures possible in an undefined system.

To ensure that the analysis presented is robust to modeling uncertainties, a set of "good" architectures is defined by a fuzzy Pareto-optimal region of the tradespace. The concept of a fuzzy Pareto set as defined by successive Pareto fronts is described in detail by Smaling and de Weck [14]. 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 front. This process is repeated in succession until 5% of the feasible architectures have been included. Although the architectures included in the fuzzy Pareto front are no longer optimal by the two metrics included in the analysis, it provides for a much more rich set of architectures that are all within a few percentage points of the original frontier. In this tradespace, 5% is an assumed good value to define the fuzzy Pareto front because it increases the variety of architectures considered without including any architectures that are heavily dominated in any one metric.

A. Measuring the Influence of Technology

A measure of the influence of a technology in the tradespace on a system-wide metric is desired. For the purposes of decision making, this measure should not consider architectures that are conceivable but outside the realm of consideration. Measuring the "impact" in relation to an architecture that is infeasible does not realistically represent the benefits associated with the technology. This is exemplified by Fig. 1, in which an architecture with no new technologies, an order of magnitude larger than the International Space Station (ISS), is used as a baseline to measure relative technology investment improvements. Using the previous descriptions of a set of good architectures in the fuzzy Pareto front restricts the measure of influence over only these preferred points in the tradespace.

The technology impact measure (TIM) provides the average influence of a technology in a system without knowing the specific architecture being considered. It is defined as the difference between the average of a metric over architectures within the fuzzy Pareto front that do have the technology and the average of a metric over those architectures in the region that do not have the technology. Equation (1) defines TIM and the constraint that the fuzzy Pareto front can be split into two subsets: those with and without the technology included. In the formulation of TIM as the average influence, it is assumed that all architectures considered in the fuzzy Pareto front are equally likely to occur. This assumption is chosen because there is insufficient information to populate relative probabilities across architectures. Future work may seek to create weighted averages of architectures based on measured stakeholder preferences for particular designs.

$$\mathrm{TIM}_{M,T} = \bar{M}\{T_{\mathrm{on}}\} - \bar{M}\{T_{\mathrm{off}}\} \quad T_{\mathrm{on}} \cup T_{\mathrm{off}} = S \tag{1}$$

Although the TIM does not provide the specific interactions of any given technology for a single selected architecture, it gives a broader view of how specific technologies will influence the tradespace. TIM looks at a realistic set of architectures and measures the influence on the final system, considering ambiguity of system definition. It requires a realistic consideration of all major relevant system architecture decisions. By restricting architectures in the calculation to feasible realistic architectures TIM couples 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 technologies have on metrics that is realistic and does not favor any given architecture in the tradespace.

B. Coupling Between Technologies and Other Design Decisions

The coupling measure presented in this paper must be defined by the metrics after evaluating the tradespace and not necessarily dependent on the problem formulation. The proposed measure of technology interaction coupling effects (TICE) provides a rich understanding of the various interaction effects that arise by addressing specific coupling between any two technologies. TICE measures the influence of one technology on the TIM of another technology. Assuming metrics are designed to be minimized, a large positive TICE value means the technologies or design features do not go well together, whereas 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 TICE in either direction means the presence of one technology does not strongly influence the other.

Although 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 TICE measures for all interactions. In particular, strongly detrimental interaction effects between two technologies may result in architectures that are heavily dominated and do not appear in the fuzzy Pareto front. For example, two technologies may represent different strategies that create architectures on opposite ends of the Pareto front. It may be that both these technologies would not be present in any one architecture in the fuzzy Pareto front 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. There is a balance to be struck between identifying strongly detrimental couplings, while not biasing the influence measure based on a sample of designs that have outlandishly poor performance. For this reason, the TICE is evaluated over the entire evaluated tradespace. As a result, the magnitude of TICE values is only meaningful as a relative measure (i.e., in comparison with other TICE). This contrasts with the TIM, which represents an absolute measure of the magnitude of influence that various technologies and design features have on the system design. TICE is defined by Eq. (2), including constraints that technologies 1 and 2 are different, and the full set of evaluated architectures across the tradespace can be described as either having a technology or design feature or not.

$$
\begin{aligned}
\mathrm{TICE}_{M,T^1,T^2} &= \bar{M}\{T^1_{\mathrm{on}} \cap T^2_{\mathrm{on}}\} - \bar{M}\{T^1_{\mathrm{on}} \cap T^2_{\mathrm{off}}\} - \bar{M}\{T^1_{\mathrm{off}} \cap T^2_{\mathrm{on}}\} \\
&\quad + \bar{M}\{T^1_{\mathrm{off}} \cap T^2_{\mathrm{off}}\} \\
&T^1 \neq T^2 \\
T^1_{\mathrm{on}} \cup T^1_{\mathrm{off}} = P &\qquad T^1_{\mathrm{on}} \cap T^1_{\mathrm{off}} = \varnothing \\
T^2_{\mathrm{on}} \cup T^2_{\mathrm{off}} = P &\qquad T^2_{\mathrm{on}} \cap T^2_{\mathrm{off}} = \varnothing
\end{aligned}
$$

C. Problem Formulation

A large tradespace model is used to uncover interesting technology effects and couplings. This model defines architectures in terms of a series of habitation and propulsion elements, which are then evaluated against physical and cost models to yield total mass in low Earth orbit and a relative estimate of the architecture's cost. The model used for defining and evaluating architectures is highly abstracted to capture a wide range of system architectures. The evaluation model, described in detail by Rudat et al., begins by defining a series of architectural subproblems as shown in Table 1 [25]. These subproblems organize habitation and propulsive requirements into distinct elements (design decisions). Technologies are then assigned to each element, defining the performance with which propulsive and habitation requirements are met. The propulsion technologies available for each major propulsive maneuver are given in Table 2. The model scope excludes launch to Earth orbit to be launch vehicle invariant.

Given the complexity of architectures considered, it is useful to set up the problem as an isoperformance analysis as described in [26]. As applied in this problem, isoperformance means each architecture fulfills a specific mission profile, including a crew size of four, set surface duration, and payload. An overview of the mission considered is provided in Table 3. Set constant, these parameters fix the science and exploration benefits for all architectures considered.

Two proxy metrics for cost are then examined for their ability to discriminate between architectures. Initial mass in low Earth orbit (IMLEO) is a proxy metric for recurring operational cost. Because 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.

Table 1 Subproblems that define a single transportation architecture

	Architectural subproblem
Design decisions that define the requirements that must be fulfilled by the architecture	Destination Habitat element definition Propulsive stage definition
Technology decisions that define how the requirements of each element are fulfilled	Transdestination propellant type Descent propellant type Ascent propellant type Trans-Earth propellant type Predeployment of cargo with solar electric propulsion (SEP) Boiloff control technology ISRU technology Aerocapture technology

Table 2 Propulsion alternatives for each major mission segment

Transdestination 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)			

Note: Nuclear Thermal Rocket (NTR).

Table 3 Mars mission overview

Trajectory type	Mars conjunction class
Surface duration	500 days
Crew size	4
Total crew mission duration	860 days
Total mission delta-v	17.9 km/s

The other metric considered for this high-level architecture evaluation is a technology life-cycle cost (LCC) proxy. The proxy is designed to account for both the development and operation of technology projects that do not rely on specific (and highly uncertain) cost-estimating relationships. The fundamental assumption embedded in this coarse metric is that, although 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 cost coefficients C_i that define the LCC proxy of each technology element are assigned based on the readiness of the technology (simplified from the Technology Readiness Level scale [27]) and the potential for other users (a measure of demand) for the capability according to Table 4. Details of the development and implementation of this LCC proxy are available in [28].

Table 5 lists the available technological capabilities that can be included in the tradespace and their associated cost coefficients.

IV. Results

A. Mars Transportation Architecture Tradespace

The population of evaluated architectures for the Mars transportation system can be viewed in Fig. 2, which shows a plot of the two high-level metrics considered. There is a tradeoff between IMLEO and the technology LCC proxy, creating the convex space about the utopia point in the bottom left-hand corner. Architectures that are nondominated define a Pareto frontier, where no architecture does better than any other in both metrics at the same time. Architectures in the previously defined "fuzzy" Pareto front region are also indicated.

Table 4 Cost coefficients C_i

	Technology has other users?	
	No	Yes
Low readiness	1	0.5
Relevant demonstration	0.667	0.333
Existing capability	0.333	0.167

Table 5 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	Demo'ed	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	Demo'ed	No	0.667
	Boiloff control	Low	Yes	0.5
	ISRU	Low	No	1.0
	Aerocapture	Demo'ed	Yes	0.333

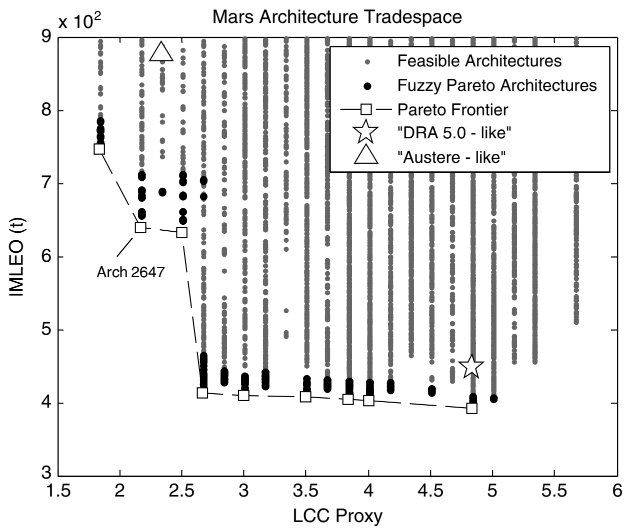

Fig. 2 Mars architecture tradespace viewed by metrics.

Two reference points are marked in the tradespace. The star in Fig. 2 marks an architecture that is similar to the NASA Mars DRA 5.0 [29], whereas the triangle denotes an architecture similar to the JPL Austere reference mission [30]. 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. It is important to note that DRA 5.0 and Austere differ from the presented model with respect to the mission objectives, requirements, and modeling approach. Although the sizing assumptions used here are different from the reference studies, the fundamental architecture defined by the subproblems is the same. 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 (which would not necessarily be delivered in the operational transportation scenario considered here). A validation of the model was conducted with DRA 5.0 generating agreement to within 5% of IMLEO by implementing comparable assumptions from the reference study [25].

To give an example of an architecture on the Pareto frontier, architecture 2647 is highlighted in detail in Fig. 3. Because predeployment 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 predeploy descent, surface, and ascent habitats and stages on a more efficient but longer time-of-flight trajectory (compared with impulsive propulsion technologies). Hydrogen is used for in-space propulsion of all crewed elements, and each major maneuver has a separate stage. The benefits associated with predeployment with SEP are significant when the Mars orbit insertion (MOI) and trans-Earth injection (TEI) maneuvers are performed by separate stages because the TEI stage is a large element that can be predeployed. Finally, the descent and ascent stages use storable hypergolic propellant. Although requiring the development of high-power SEP capability, this architecture takes advantage of this efficient propulsion technology with a system decomposition that allows for predeployment of elements that are not time sensitive and, at the same time, uses other propellants with lower specific impulse but less development risk.

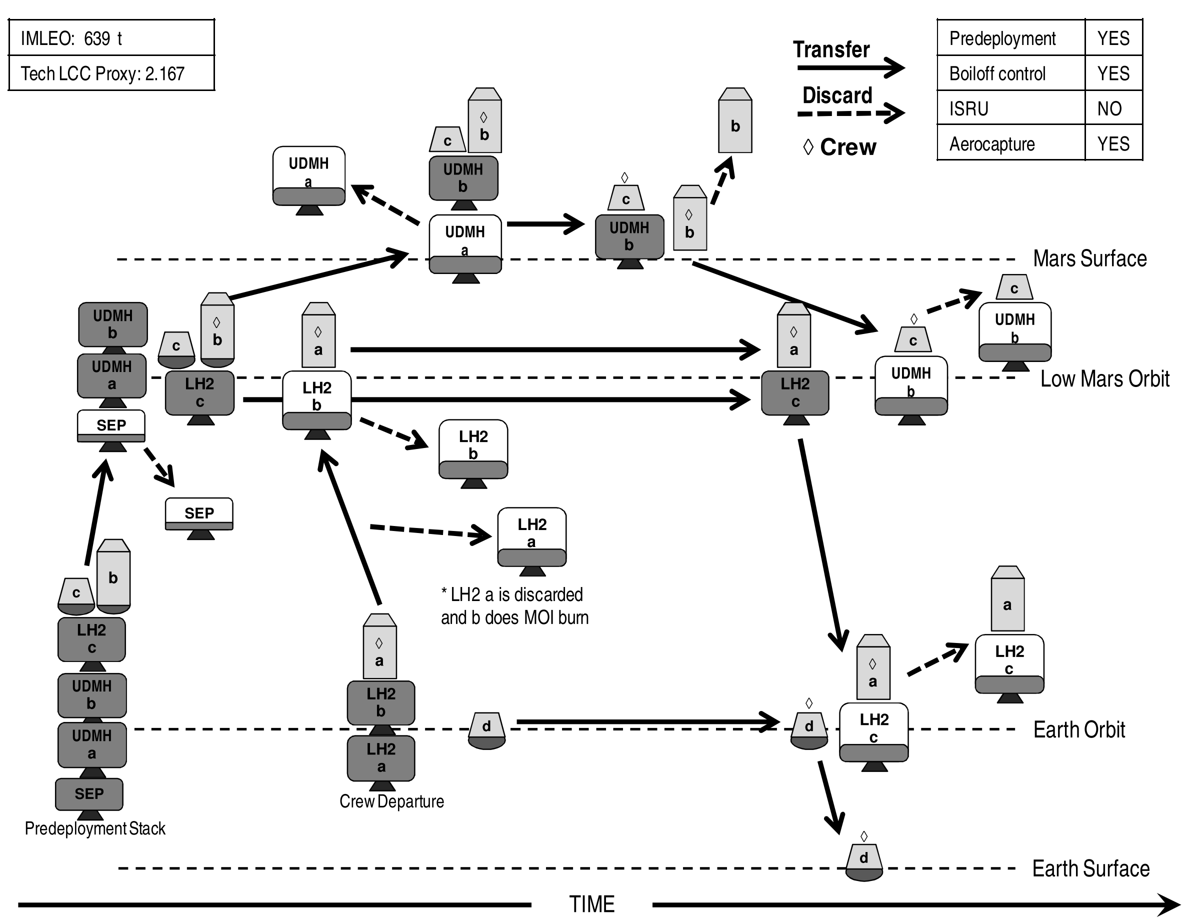

Fig. 3 Mars architecture 2647 from the Pareto frontier.

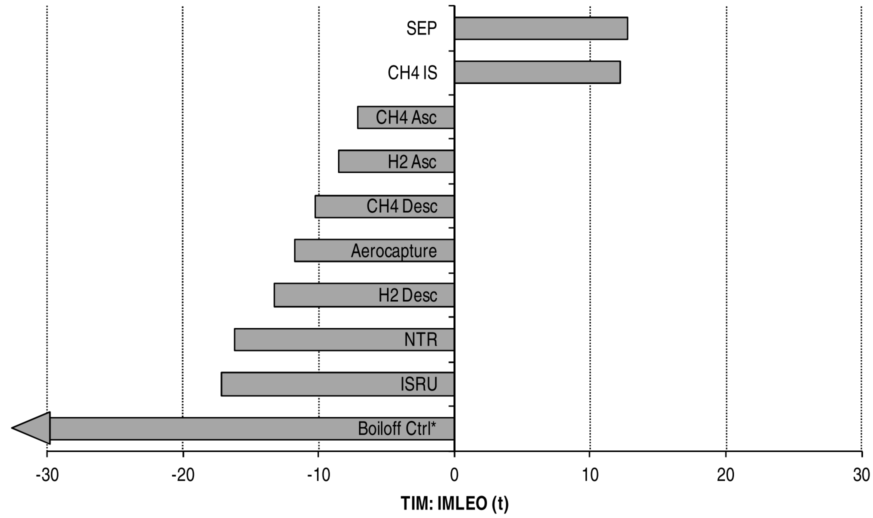

Fig. 4 Technology impact measure for IMLEO for Mars transportation architectures. *Note that TIM_{IMLEO} is negatively infinite for boiloff control because every feasible architecture has the technology included.

B. Technology Influence

The benefits from implementing technologies vary according to other architectural decisions. Although it is interesting to consider the short list of architectures on the Pareto frontier, the exact influence of each technology is subject to ambiguity in which the architecture is chosen. The following sections explicitly measure the influence of these technologies across good architectures, and the coupling to other architectural decisions, to create a more comprehensive view of the implications of developing any given technology.

As previously described, the TIM [see Eq. (1)] 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 indicates the influence in mass savings (or growth) and technology LCC savings (or growth) that come as result of implementing a new technology. In Fig. 4, the TIM of IMLEO is shown for each technology considered in the design space.

The influence of boiloff control is arbitrarily large for IMLEO because all feasible architectures require that boiloff control is implemented (within the fidelity of the evaluation model that was used). SEP and CH4 in-space propulsion have positive TIM values rather than negative TIM values, indicating that the average influence of these technologies in the region of preferred architectures is an increase in IMLEO relative to the remainder of the fuzzy Pareto population. Additionally, TIM_{IMLEO} captures only one of two metrics; it might be expected that architectures that require few development projects to produce higher IMLEO architectures still represent a favorable cost–IMLEO tradeoff. Although increasing IMLEO may not seem desirable, this is the influence within a region of the tradespace that is already considered to be of high performance.

Plotting each of these influence measures in Fig. 5 provides a more complete representation of the cost versus mass tradeoff.

An inherent tension between influencing IMLEO and influencing technology LCC proxy is seen as the clustering of technologies in opposing corners of Fig. 5. 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 architectures that are on the higher end of the acceptable IMLEO range while presenting some technology LCC savings. This effect is particularly strong and unique to implementing SEP for predeployment 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 predeployed 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

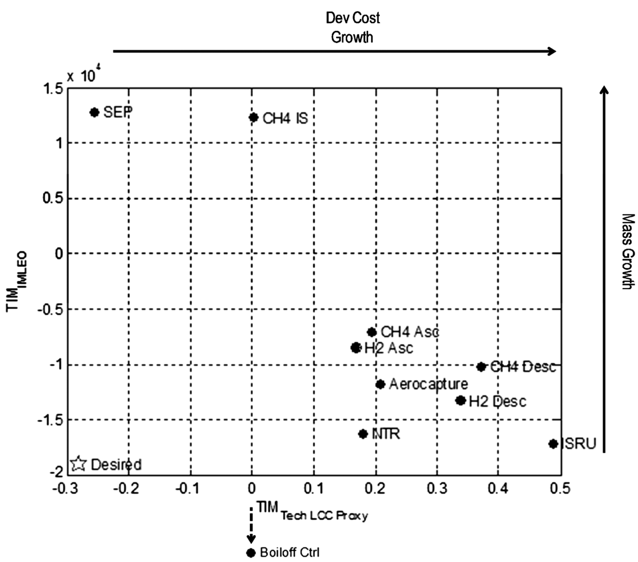

Fig. 5 TIM: IMLEO vs technology LCC proxy for Mars transportation technologies.

tradespace in comparison with other nondominated architectures relying on higher specific impulse propellants, but causes virtually no increase in technology LCC.

The ideal desired technology would sit in the lower left-hand corner of Fig. 5. That region of the plot represents a technology that provides reduction in both IMLEO and technology LCC proxy. Although no technologies considered are able to provide this influence for the Mars transportation system considered, the inherent differences between NTR and SEP are immediately clear. NTR is a high-cost, high-performance technology, whereas SEP is a technology that can reduce overall cost but will not provide the same mass efficiency in performance.

C. Highlighted Couplings

By considering the specific coupling or interaction effects that occur between technologies, pairs of technologies that should be combined to achieve the best performance (or those features with which it should not be combined to avoid performance losses) are identified.

Implementing boiloff control technology is modeled as a system dry mass penalty and a reduction in the rate of propellant loss over time. However, the boiloff rate for methane propellant is significantly lower than that of the liquid hydrogen present in the other in-space propellant alternatives (nuclear thermal rockets and LOX-LH2 chemical propulsion). It is expected that there will be some important couplings between implementing methane for various propulsion stages and the implementation of boiloff control technology. To understand the differences that occur with boiloff control on and off, the TIM (influence measure) of the major methane stages is evaluated for two different subsets through the architecture tradespace: those architectures with boiloff control and those architectures with no boiloff control.

The TIM for implementing methane stages across the four major propulsion segments is shown in Fig. 6, evaluated for architectures both with and without boiloff control, respectively. Recalling the definition of TIM [Eq. (1)], the lower the value in the figure, the greater the relevant benefits derived by implementing the associated technology. The corresponding TICE values for IMLEO are given as follows: LOX-methane Earth departure, −2885 t; LOX-methane descent, 852 t; LOX-methane ascent, 955 t; LOX-methane Earth return, 24,196 t.

The overall magnitude of influence of methane in the presence of boiloff control is smaller than the influence of methane without boiloff control, as demonstrated by the solid line in the figure remaining closer to the zero (no influence) line. This makes intuitive sense because the primary benefit from implementing methane is a reduction in boiloff rate. Boiloff control therefore reduces sensitivity to the decisions of implementing methane in each stage; by reducing the overall influence of the technology, boiloff control makes the tradeoff between methane and other propellants more even.

Looking at one maneuver at a time, a methane Earth departure stage creates a positive change in mass, indicating that it is not a preferred technology compared with the alternative choices. The influence of methane 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 large difference in the benefits of methane with and without boiloff control.

Relative performance of these stages depends primarily on the impulse requirement for the stage and also on the time that passes before the stage is expended, that is, how much propellant there is to dissipate (boiloff) and the time it has to do so. With the return stage, it becomes clear that methane's low boiloff rate is important for a stage that has to remain in space for years before being used. When boiloff control is implemented, other propellants like hydrogen have their boiloff rates reduced to near that of methane, and therefore the advantage of methane is nullified. As a result, the TICE value for the methane return stage and boiloff control is a large positive number, indicating these two technologies result in performance loss when combined. 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 boiloff control in that stage.

In this example of technology coupling, the decisions for choosing propellant types for each stage do not necessarily happen all

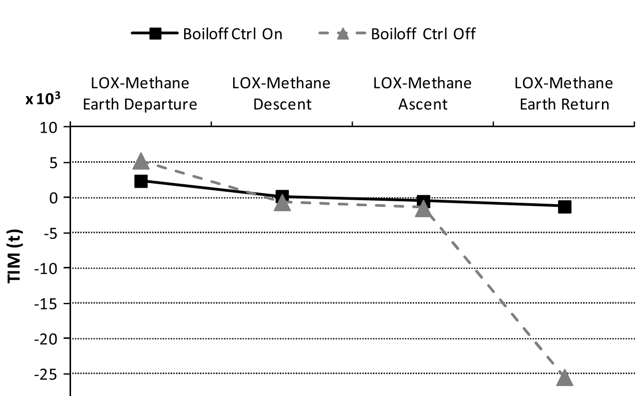

Fig. 6 Interaction effects between methane propulsion technology and boiloff control in IMLEO.

simultaneously. 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. Understanding that boiloff 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 boiloff control continues. As time passes and the uncertainty of the performance of boiloff control is resolved, the later stages (especially the in-space return stage) can be reevaluated based on a better understanding of the performance of boiloff 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 understanding boiloff control's interaction effects with propellant decisions.

Although the influence and coupling analysis has been focused on the technology-related decisions that define architecture, the other architectural decisions of transportation and habitat form–function allocation are also important. The coupling between the technologies and important architectural design features can help to identify the nontechnology features of architecture that are required to reap the benefits of each technology. One example feature is the combination of the Mars arrival (MArr) and Mars departure (MDep) burns in a single stage. This is a defining aspect of a "Mars-orbit rendezvous" scheme as described by reference design missions in literature [7]. Using the same methodology for technology–technology interactions, this analysis is used to evaluate technology–feature interactions. Features are specifically defined by a binary variable, indicating whether or not any two habitation or transportation functions are combined into a single element (one or zero, respectively).

Looking through a complex tradespace with many possible technologies to consider, this method provides a rigorous search for strong interaction effects between technologies and other architectural features. 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. Considering TICE can help sort through a large combinatorial space of couplings, identifying couplings that are worth considering in more detail. For any two technologies, the TICE is evaluated according to Eq. (2). Large magnitude negative TICE indicate strong beneficial interaction effects, or two technologies that benefit together. Large magnitude positive TICE indicate strong detrimental interaction effects, or two technologies that should not appear in the same architecture. These values are then organized in an n-squared matrix that encompasses the interactions between all design decisions in consideration.

The TICE matrix in Fig. 7 provides a quick view of the most sensitive interaction coupling effects by IMLEO. For readability, strong beneficial and detrimental couplings representing the top 10% largest magnitude TICE values have been highlighted. Design features described in the TICE matrix include a propulsive maneuver to brake at Earth orbit (EArr), habitation during Mars-bound in-space travel (ISOut), Earth-bound in-space travel (ISRet), habitation during the descent maneuver (Desc), and habitation during surface stay (Surf).

D. Organizing Architecture Decisions

With a comprehensive understanding of all the first-order influences these decision variables have (TIM) and all the couplings that go on in between architectural variables (TICE), recommendations can be made on how to pursue more detailed analysis by prioritizing and grouping decisions. 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, the broad high-level analysis performed here can help analysts study the interaction effects that are important and ignore those that are not.

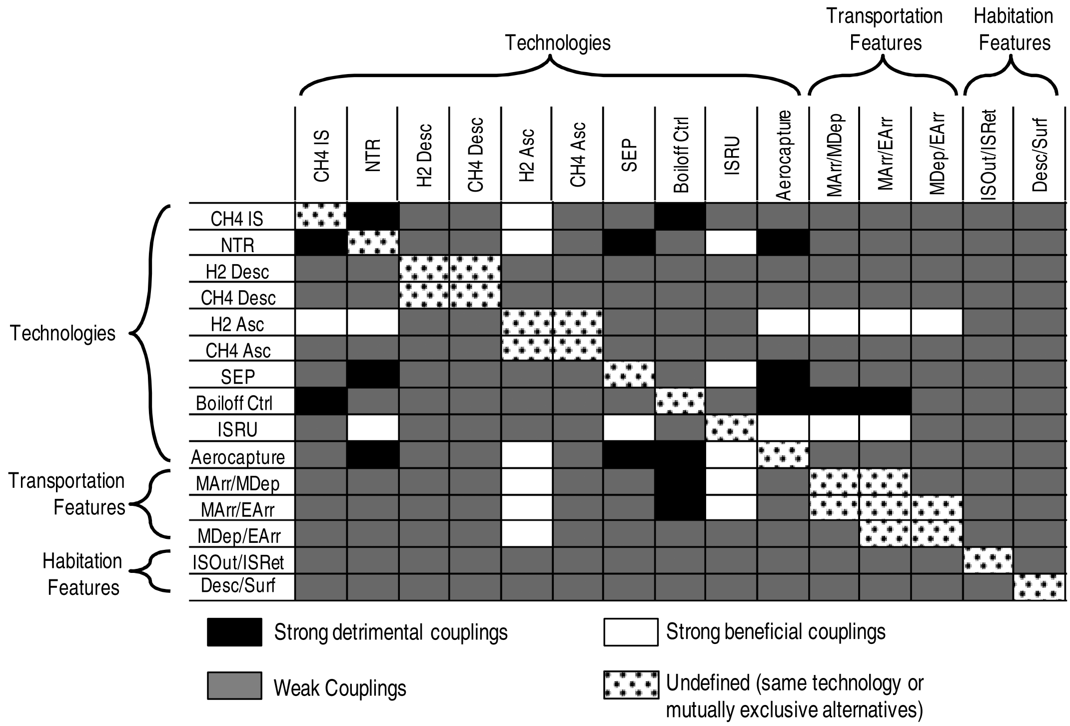

Fig. 7 $\mathbf{TICE_{IMLEO}}$ **matrix between technologies and design features.**

An effective use of the measures proposed in this paper is to group the major decisions that define the architecture to create potential analysis teams that interact where needed, but can efficiently work in parallel on decoupled problems wherever possible. Weakly coupled decisions should be treated in parallel because there is a high cost associated with waiting for one piece of analysis to begin before pursuing another. Likewise, it is a good idea to combine decisions that are highly coupled in a single trade 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 considered, there are two major desires to satisfy in organizing architecture trade studies. These desires define the heuristics that are used to organize design decisions. First, it is necessary to prioritize the high-influence decisions. Priority is given to those decisions with the highest absolute value of TIM (using IMLEO in this case). Second, the dependencies between groups of decisions are minimized. This is accomplished by clustering design decisions such that the absolute value of TICE for decisions between groups is as small as possible, whereas the large magnitude TICE values are retained between decisions within groups.

A structure that represents an idealized process flow for architectural trade studies is suggested. This grouping of design decisions comes from implementation of the previously described heuristics through use of the MATLAB® kmeans clustering algorithm. Although there is no guarantee of an "optimal" organization to these decisions, the most consistent results are taken as guidance for a relatively good solution shown in Fig. 8.

As the most sensitive decision in this analysis, boiloff control comes first. Although future exploration mission requirements have not been set yet, NASA has already begun to pursue the development of cryogenic storage capability. 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" [31]. Next, are three sets of decisions that can be treated in parallel. Although all three sets have very significant influence over the whole, there is an efficient decomposition of the decision space for them to be treated in parallel. Further, this analysis suggests that the choice of descent and TEI propellants should be left until other constraints and design decisions have been set, as they rely heavily on upstream influences.

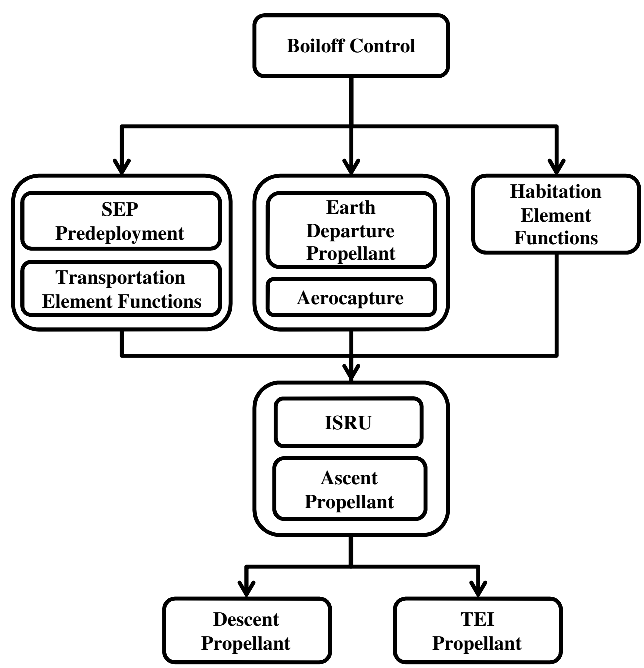

Fig. 8 Organization of architectural decisions.

NASA's Design Reference Architecture 5.0 typifies a reference design mission study that could have benefitted from this organization. In the NASA DRA 5.0 addendum [32], 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 scenarios that did not consider the potential for strong interaction effects based on other decisions that could influence the decision-driving assumptions.

V. Conclusions

This paper proposes a method for evaluating technology across a tradespace defined by architectural decisions, as applied to space transportation architectures for future human exploration. Main effects analysis is taken from design of experiments to quantify the influence that a given technology has on the system being considered, called the technology influence measure. This analysis also identifies couplings between technologies that are mutually exclusive or mutually beneficial, called technology influence coupling effects.

This analysis showed that the evaluation of technologies against an individual reference architecture is flawed when the range of architectures being pursued remains diverse and uncertain. A measure of the influence of a technology provides a sense of prioritization of technologies under architectural uncertainty about which a Pareto-optimal architecture will eventually be chosen. A measure of the coupling between technologies can help to inform what groups of technologies are worth considering together and those that represent different approaches to architecture design.

Boiloff control, solar electric propulsion, nuclear thermal rockets, and aerocapture are all shown to be highly beneficial technologies for the Mars transportation system. Solar electric propulsion and nuclear thermal rockets drive different strategies optimized for technology life-cycle cost or initial mass in low Earth orbit, respectively. Most technologies reduce the mass measure and increase the cost proxy for the infrastructure to Mars, but solar electric propulsion and in-space methane stages have the opposite influence on the system, resulting in relatively higher (but still acceptable) mass for the benefit of having a lower technology life-cycle cost. It is shown that boiloff control is required to realize a feasible architecture to Mars. This analysis produced a possible ordering of these technology development decisions, ranked by their impact on the tradespace and their coupling to other decisions.

Comprehensive architectural tradespace enumeration and evaluation demonstrates the limitations of existing long-term architecture tradespace analysis methods based on narrow-scoped detailed analysis of point designs. Introduction of the technology impact measure and technology interaction coupling effects allow for prioritization of long-term technologies and design decisions based on a more complete view of the architectures available to pursue. This method is limited to consideration of architectural uncertainty because it does not currently evaluate the likelihood of success of different technology development projects. Although the focus of this method is early-stage decision making when robust estimates of development project success are difficult to evaluate, it would be interesting to merge these two considerations, particularly when technologies with higher readiness levels are compared with technologies with lower readiness. By applying the proposed methodology, it is possible to design a set of trade studies that simultaneously allows a detailed exploration of a larger segment of the tradespace while limiting the number of trade studies that must be performed in contrast to NASA's trade-tree trimming process focused on a more narrow segment of the tradespace.

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