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Optimal Launch Vehicle Size Determination for Moon-Mars Transportation Architectures

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NASA's human Lunar and Mars exploration (HLE/HME) program requires a sustainable and affordable transportation system between Earth and Moon/Mars. A crucial element of this system is the launch vehicle. Much debate has centered on the trade between expendable launch vehicles and heavy-lifters; however, arguments to date have been largely qualitative or limited in scope. This paper provides a quantitative enumeration of the launch vehicle trade space (in terms of both cost and risk), based on a generalizable process for generating launch manifests from transportation architectures (sets of vehicles for carrying out Lunar/Mars missions). For the baseline HLE/HME architecture considered here, an optimal launch vehicle size is found at approximately 82 metric tons; a 28-mt EELV emerges as another good option. The results show optimal launch vehicle selection is highly dependent on the transportation architecture. Therefore, launch vehicle selection should be considered an integral part of the design of the Moon/Mars exploration transportation system.

I. Introduction

NASA's recent focus on human Lunar and Mars exploration (HLE/HME) has raised a number of challenges, including the development of a sustainable and affordable transportation system to the Moon and Mars. One of the major questions driving the design and cost of such a system is the availability of launch vehicles: is the current arsenal of evolved expendable launch vehicles (EELV's) sufficient to launch manned Lunar and Mars missions, or is a larger heavy-lift launch vehicle (HLLV) required? The advantages (low development cost/risk) and disadvantages (increased number of launches and on-orbit assembly operations required) of EELV's are well-known and widely understood, but the trade-off between the two has never been settled. To date, attempts to answer this question[1,2] have been largely qualitative or limited in scope, due in part to the lack of clearly defined requirements for human exploration missions. The question of launch vehicle sizing is clearly tied to the transportation architecture because launch vehicles are required to transport all exploration vehicles of given size and mass into space; therefore, the launch vehicle selection process should be considered as an integral part of the transportation system design.

This paper approaches the question of launch vehicle selection from a system-of-systems perspective, incorporating the relationship between the transportation architecture design and launch vehicle sizing. By choosing launch vehicles based on the transportation architecture and changing the architecture to accommodate various launch vehicles, we provide a quantitative enumeration of the launch vehicle trade space, and outline a possible approach to the launch vehicle selection process for NASA's HLE/HME efforts.

To that end, we first describe the Lunar/Mars transportation architectures, and discuss how to break large vehicles into 'chunks' that fit on each launch vehicle. Two approaches to the launch packing problem are then described, which employ different methods to optimally pack modules into launch vehicles. For each type of launch vehicle, this process computes the metrics of launch mass surplus ('wasted' launch capacity) and launch cost. Finally, a basic risk analysis is performed by examining the chance of launching all payloads successfully based on the number of launches required for each launch vehicle size. Thus, both the cost and risk of launching a given transportation architecture can be estimated; these metrics can aid in the selection of an optimally sized launch vehicle for that transportation architecture.

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II. Concept & Analysis

In this paper, we examine in detail one set of Lunar/Mars transportation architectures and design a process for optimal launch vehicle size selection. This section explains the transportation architectures selected for analysis and outlines the process used to generate launch manifests for these architectures.

A. Transportation Architecture

The selection of an optimal launch vehicle depends on the transportation architecture. A transportation architecture is defined as a set of vehicles used to transport crews and cargo between Earth and the Moon or Mars. Should NASA decide to make the significant investment required for designing and building a HLLV, it must take into account the launch requirements for both Lunar and Mars mission architectures. These requirements (especially the mass and size of vehicles) vary widely between Moon and Mars-bound missions. In this paper, we consider one

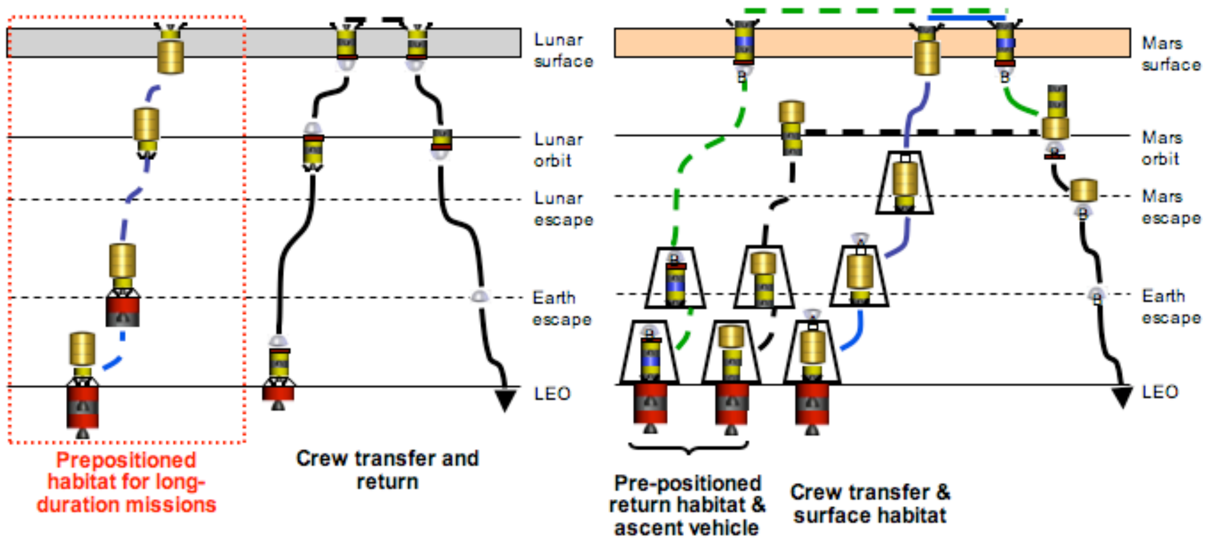

Figure 1. Operations Concepts for Lunar & Mars Missions. *For lunar missions (left), the crew transfers to the surface and returns to Earth in a single vehicle. For long-duration missions, a surface habitat can be pre-positioned on the surface. For Mars missions (right), the crew lands in the surface habitat. An ascent vehicle is pre-positioned on the surface, and a return habitat is pre-positioned in Mars orbit.*

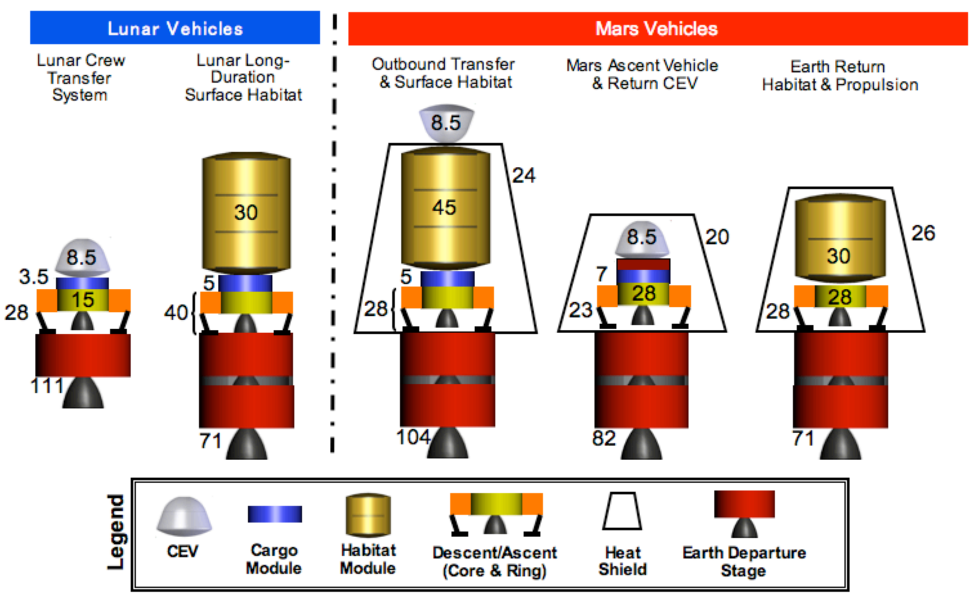

Figure 2. Vehicles and Mass Breakdowns for Lunar & Mars Missions. *Mass breakdowns (metric tons) are provided for each of the vehicles shown in Figure 1.*

set of Lunar and Mars transportation architectures developed as part of the Concept Exploration & Refinement (CER) study at MIT/Draper.[3] These architectures were created using a "Mars-back" approach, considering requirements for missions to the Moon and Mars in parallel and designing common elements (modules) to be used in both types of missions. The resulting architectures consist of sets of modular vehicles that transport crew and cargo between Earth and the Moon or Mars. Figures 1 and 2 outline our baseline transportation architecture. Figure 1 illustrates the operations concepts for Lunar and Mars missions, and Figure 2 provides mass breakdowns for each of the vehicles used in these missions.

For short lunar missions, a single 'vehicle' (stack of modules) ferries the crew to the lunar surface and back (the Lunar Crew Transportation System, or CTS). The crew compartment is the Crew Exploration Vehicle (CEV). For longer lunar missions, a long-duration surface habitat is pre-positioned on the lunar surface. A common CH_4/LOx descent/ascent stage provides the propulsion for landing on the Moon, and a H_2/LOx stage performs the trans-Moon injection (TMI) and lunar orbit insertion (LOI) burns. Mars missions utilize the same set of hardware, with the addition of a heat shield for aerocapture.

B. Launch 'Chunking'

With a baseline transportation architecture defined, the next step is to determine how many launches are required, and what elements are launched on each vehicle. This is a three-step process, consisting of:

1. Logical rules governing allowable combinations of modules on launch vehicles.
2. Division of large modules into elements that fit on smaller launch vehicles.
3. Packing elements efficiently into launch vehicles.

Figure 3 shows an overview of this process.

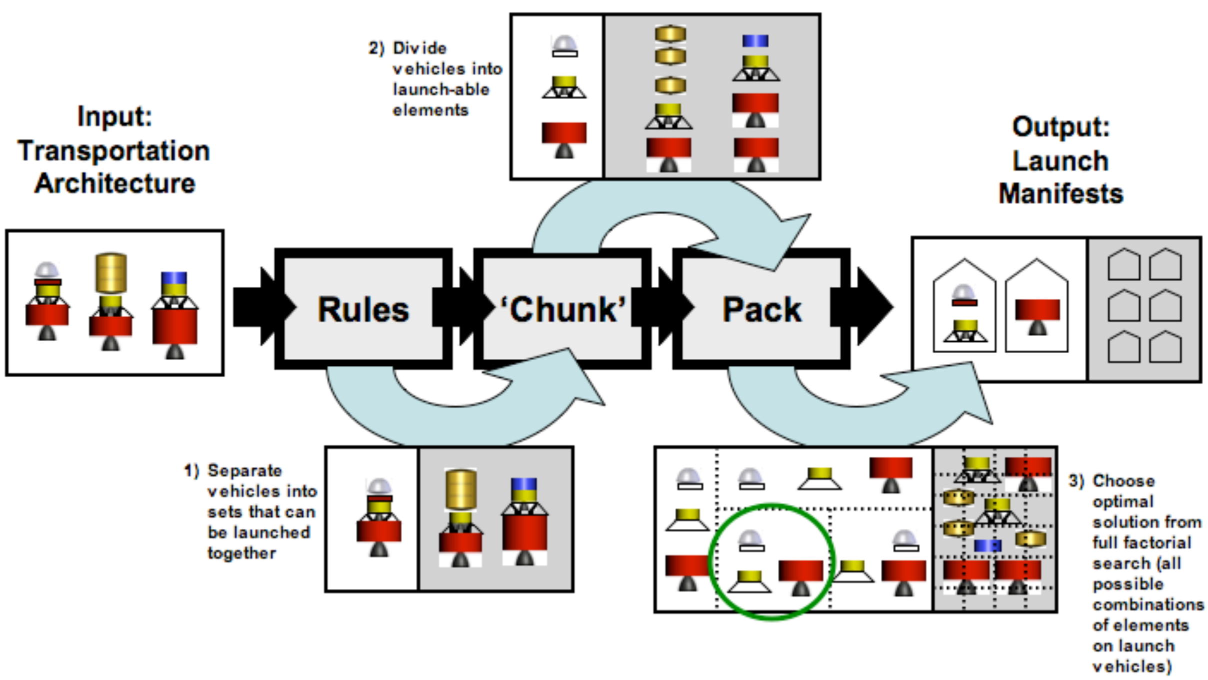

Figure 3. Overview of Launch Manifesting Process. *The input is a transportation architecture (set of vehicles), which is divided according to a set of rules into combinations of modules that can be launched together. The modules are then divided into launch-able 'chunks.' In order to pick the optimal launch vehicle packing arrangement, all possible combinations of modules and launch vehicles are generated, and the set of launch-able manifests with the fewest launches is chosen.*

The first step – defining rules – is relatively simple; our baseline analysis utilizes only very basic rules. Each vehicle stack is launched separately from all others. In some cases, we further assume that crewed modules (the Crew Exploration Vehicle) are launched on a separate human-rated launch vehicle (not considered in this analysis). Other rules can potentially be added to support trade studies; for example, in order to assess the value of a low-cost, low-reliability consumables launcher, we could further require that consumables (e.g. propellant) not be launched with any other type of cargo.

The second step is to divide large vehicles into 'chunks' that fit on smaller launch vehicles. While the modular vehicle design provides natural breakpoints, dividing vehicles into their component modules does not always generate elements that can be launched on small (e.g. 28 mt) launch vehicles. Simply dividing an element's total mass into launch-able 'chunks' does not take into account the extra mass required to create separate modules (e.g. docking hardware). A 'mass penalty' can be imposed on any elements divided in this manner to account for this extra mass. However, we employ more accurate methods of modeling this modularization for specific types of modules.

In the case of our baseline architecture, two types of modules require further division into launch-sized chunks: the trans-Moon/Mars-injection (TMI) stages and the habitats. The TMI modules are relatively simple (tanks, propellant, and engines) and can be modularized into launch-sized elements by staging the TMI burn. The rocket equation is used to model the mass of each stage based on a maximum allowed stage mass, the required ΔV, and a mass fraction of 0.11. Thus, the TMI stage can be broken down into any number of stages in order to generate modules that fit on any launch vehicle. The habitats are more difficult to divide, but a modularized habitat divided into launch-sized 'plugs' can be created (sections of the habitat that can be plugged together with end-caps to create a single pressure vessel). Habitat plug masses are found using a modified version of the model used to size the vehicles in the original transportation architecture.[3] All other elements are either small enough to fit on launch vehicles, or cannot reasonably be broken down into smaller elements.

C. Launch Packing

The process outlined above creates a series of launch-able 'chunks' that must be packed into launch vehicles. For each launch vehicle size, an optimal packing solution must be found that minimizes the number of launches required for the overall architecture. This is a nontrivial task, because the problem grows rapidly with an increasing number of modules.

The most straightforward method of solving this problem is a full factorial search. A full factorial search is performed by generating all possible combinations of modules on launch vehicles. The optimal solutions are those with the lowest number of launches. When several different optimal solutions exist, one can be chosen arbitrarily, or other screening criteria can be included here (e.g., give preference to configurations that launch elements in their final assembled configuration).

With this full factorial search process, optimal launch manifests can be generated for a wide range of module sets and launch vehicle sizes. However, the time required to solve the problem grows rapidly with the number of modules because all possible combinations of modules on launch vehicles must be computed. For example, the lunar vehicles outlined in this paper can be packed into launch vehicles using this method, but the time required to find optimal launch manifests for the Mars vehicles is prohibitively long. Therefore, we attempt to formulate the problem so that we can take advantage of existing optimization methods. To that end, we define the problem more formally, incorporating cost into the objective function (rather than simply minimizing the number of launches):

1. Formal Problem Definition

There is a set of n items. Each one of the items has a mass of m_i, ($\forall\ i = 1, \cdots, n$). There is a set of M vehicles each having a mass capacity of v_j, ($\forall\ j = 1, \cdots, M$). Each vehicle has a fixed launch cost c_j as well as a variable cost per unit of mass surplus denoted by α_j. The objective is to find the best way to put the items into a subset of vehicles such that the launch and mass surplus cost are minimized. In this section we first give a mathematical formulation to the problem and then see some of the implementation aspects of this formulation.

2. Problem Formulation

The variables in the formulation are defined as follows:

- n: number of items
- M: number of vehicles
- m_i: mass of item i, ($i = 1, \cdots, n$) [mt]
- v_j: capacity of vehicle j, ($j = 1, \cdots, M$ [mt]
- α_j: variable cost per each unit of mass for vehicle j, ($j = 1, \cdots, M$) [\$/kg]
- c_j: launch cost of vehicle j, ($j = 1, \cdots, M$) [\$]

The decision variables are:

$$x_{ij} = \begin{cases} 1 & \text{if item } i \text{ goes into vehicle } j \\ 0 & \text{otherwise} \end{cases}$$

$$y_j = \begin{cases} 1 & \text{if vehicle } j \text{ is not empty (i.e. used)} \\ 0 & \text{if vehicle } j \text{ is empty (i.e. not used)} \end{cases}$$

With this notation, the objective function is

$$Z = \sum_{j=1}^{M} c_j y_j + \sum_{j=1}^{M} \alpha_j (v_j - \sum_{i=1}^{n} m_i x_{ij}) y_j \tag{1}$$

Although there is a nonlinear term in the objective, note that this term can be ignored in the case that all values of α_j are equal (i.e. $\alpha_j = \alpha_k = \alpha$, $\forall j, k$):

$$\begin{aligned} Z &= \sum_{j=1}^{M} c_j y_j + \sum_{j=1}^{M} \alpha \left(v_j - \sum_{i=1}^{n} m_i x_{ij} \right) y_j \\ &= \sum_{j=1}^{M} c_j y_j + \alpha \sum_{j=1}^{M} v_j y_j - \alpha \sum_{j=1}^{M} \sum_{i=1}^{n} m_i x_{ij} y_j \\ &= \sum_{j=1}^{M} c_j y_j + \alpha \sum_{j=1}^{M} v_j y_j - \alpha \sum_{i=1}^{n} m_i \end{aligned} \tag{2}$$

Note that the last equality is obtained because in any feasible assignment $\sum_j x_{ij} y_j = 1$, and since $\alpha \sum_i m_i$ is a constant, we can simply ignore it in our optimization objective function. As a result, the overall optimization problem is as follows:

$$\min \quad \sum_{j=1}^{M} (c_j + \alpha v_j) y_j \tag{3}$$

subject to

$$\begin{aligned} &\sum_{j=1}^{M} x_{ij} = 1; \quad \forall\, i = 1,\cdots,n \\ &\sum_{i=1}^{n} m_i x_{ij} \le v_j y_j; \quad \forall\, i = 1,\cdots,M \\ &x_{ij} \in \{0,1\}; \quad \forall\, i = 1,\cdots,n, \quad \forall\, j = 1,\cdots,M \\ &y_j \in \{0,1\}; \quad \forall\, j = 1,\cdots,M \end{aligned} \tag{4}$$

The first constraint ensures that every item will be assigned to a vehicle. The second constraint ensures that if a vehicle is used (i.e. $y_j = 1$), it satisfies the capacity constraint. Moreover, if a vehicle is not used (i.e. $y_j = 0$), the second equation forces $x_{ij} = 0\ \forall\, i$ (i.e. no items can be assigned to this vehicle).

In this problem, since we want to find the optimal capacity for vehicles, we do not have the exact value for M, the number of vehicles. However, since each item would be assigned to at most one vehicle, the number of vehicles needed is bounded by the number of items. As a result, we need to consider at most n vehicles of each type; thus, M is the product of n and the number of types of vehicles.

Before going to the implementation phase, we mention a few comments on the formulation. Note that the above formulation is an *integer optimization* problem, since x_{ij} and y_j are integer variables. These types of problems are known to be *hard* problems in the context of mathematical programming. In fact, there is not a known algorithm to solve these types of problems efficiently. More specifically, the problem posed here is known to be hard even when there is only one type of vehicle, since it reduces to the classical bin packing problem.[4]

One of the most effective methods of solving these types of problems is the OPLstudio software package. It attempts to first solve the same model without the integrality constraints, called the linear relaxation model. Then by using the solution of this relaxation and implementing branch and bound and sometimes some heuristic methods, it tries to get feasible and optimal solutions. To implement this formulation in the software, we also added a set of inequalities known as *valid inequalities* to strengthen the formulation and improve the solving time of the problem. Initial attempts to solve the launch packing problem have been successful for significantly larger problems (i.e. more modules to be packed) than the full factorial method, but an effective solution method for all types of problems has not been found. However, this formulation shows potential for efficiently solving the launch packing problem, and incorporating the essential cost metric into the objective function. Moreover, the stated formulation and solution methods are very flexible in terms of adding more constraints to the model (e.g. incorporating volume constraints) unlike the classical packing algorithms, which break when the formulation is changed.

III. Results

The final step is to determine what launch vehicle size is the best choice. The answer depends on the standard metrics of cost and risk. The integer optimization problem formulation above incorporates cost in the metric, but results have not been consistently produced using this method for the full range of launchers and modules desired. Therefore, we turn to the full factorial search method outlined above, in which the 'surrogate' metrics of number of launches and launch mass surplus are substituted for cost in the objective function. The number of launches affects the total launch cost as well as the mission risk (both in terms of launch reliability and required on-orbit assembly operations). A low launch mass surplus also leads to reduced launch costs (less 'wasted' launch capacity). Therefore, the optimal launch vehicle choice should have a low mass surplus and a relatively low number of launches (to minimize risk). The first section below summarizes the results from the full factorial solution method; subsequently, we provide results from the integer optimization problem.

A. Optimal Launch Vehicle Size Selection

Results for the mass surplus and number of launches metrics for both lunar and Mars missions, across a series of launch vehicle sizes, are shown in Figure 4.

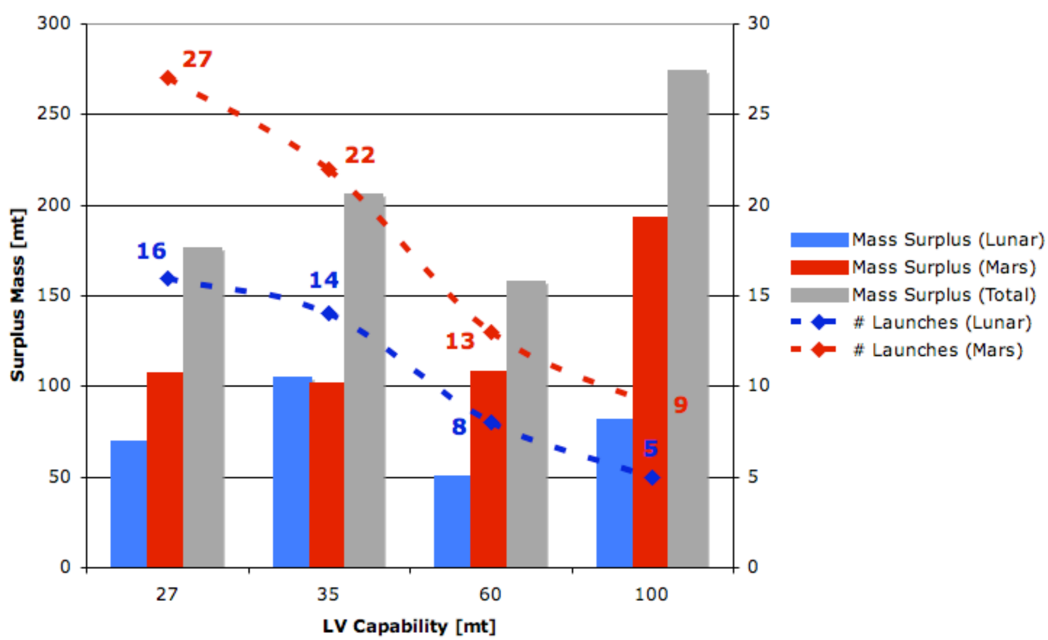

Figure 4. Surplus Mass & Number of Launches By Launch Vehicle Capability. *The launch surplus mass and number of launches required are plotted for several launch vehicle sizes (27, 35, 60, and 100 metric tons). Both Lunar and Mars missions are shown.*

The results indicate that certain launch vehicle sizes are significantly more efficient (less mass surplus) than others; in the case of our baseline architecture, the 60-mt launch vehicle is the best choice. However, this analysis is limited in that the launch vehicle sizes are chosen somewhat arbitrarily and do not cover the entire range of possible choices. As discussed above, the current methods of solving this problem require significant amounts of time, so results could not be obtained for a continuous distribution of launch vehicle sizes. The main conclusion to be drawn from Figure 4 is that an optimal (or at least a *better*) launch vehicle size *does* exist for a given transportation architecture. It may lie at the 60-mt mark, or it may lie somewhere in between the four discrete launch vehicle sizes modeled here.

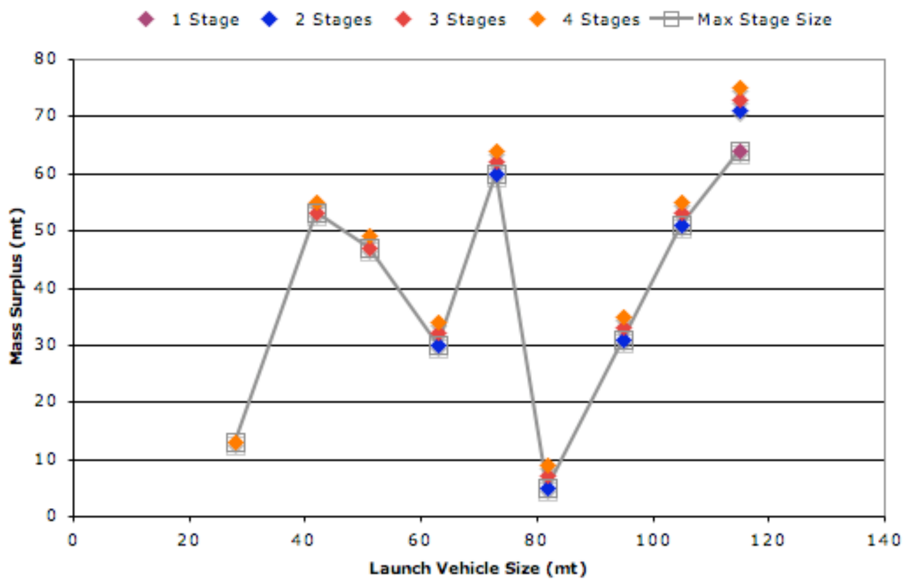

Figure 5. Lunar CTS Launch Mass Surplus for Various Launch Vehicle and TMI Staging Strategies. *The colors of each point indicate varying numbers of TMI stages for each launch vehicle size. The gray boxes highlight the largest possible TMI stage size for each launch vehicle.*

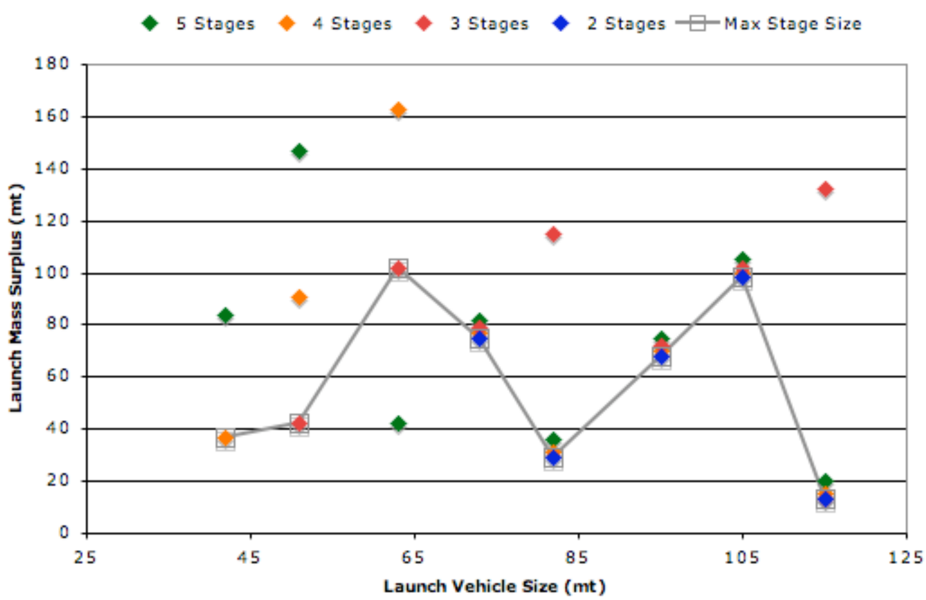

Figure 6. Lunar Habitat Launch Mass Surplus for Various Launch Vehicle and TMI Staging Strategies. *The colors of each point indicate varying numbers of TMI stages for each launch vehicle size. The gray boxes highlight the largest possible TMI stage size for each launch vehicle.*

Due to the smaller size of the problem, more detailed results could be computed for the lunar missions. In this case we use a larger set of possible launch vehicles [115, 105, 95, 82, 73, 63, 51, 42, 28] based on existing or projected launch vehicle designs (see Table 1). The data from this more detailed analysis can be used to study trends within the problem. One of the major questions arising from the launch vehicle sizing discussion is what size 'chunks' to create from large modules such as TMI stages. Figures 5 and 6 plot, for each lunar vehicle, the launch mass surplus for various launch vehicle sizes and TMI staging strategies. Each color indicates that the TMI stage has been divided into a different number of 'chunks'. The data indicate that in almost every case, the most efficient solution utilizes the largest possible TMI chunk size that fits in the launch vehicle.

Assuming that this trend holds for the data given here, Figure 7 plots the mass surplus and number of launches required for this more comprehensive set of launch vehicles. Note that the minimum launch surplus is *no longer* at 60-mt, although the CTS vehicle exhibits a local minimum at that point. For this transportation architecture, the optimal launch vehicle size is 82 metric tons, a launcher size not modeled in the previous analysis. Note that at this launcher size, there is also a 'knee' in the curve showing the number of launches required: increasing the launcher size to 95 or even 105 mt does not decrease the number of launches required. These minima in the number of launches and mass surplus suggest that the cost of launching this set of modules would be minimized by using a launch vehicle with a capacity near 82 mt. The data clearly show the existence of an optimal launch vehicle size for this transportation architecture.

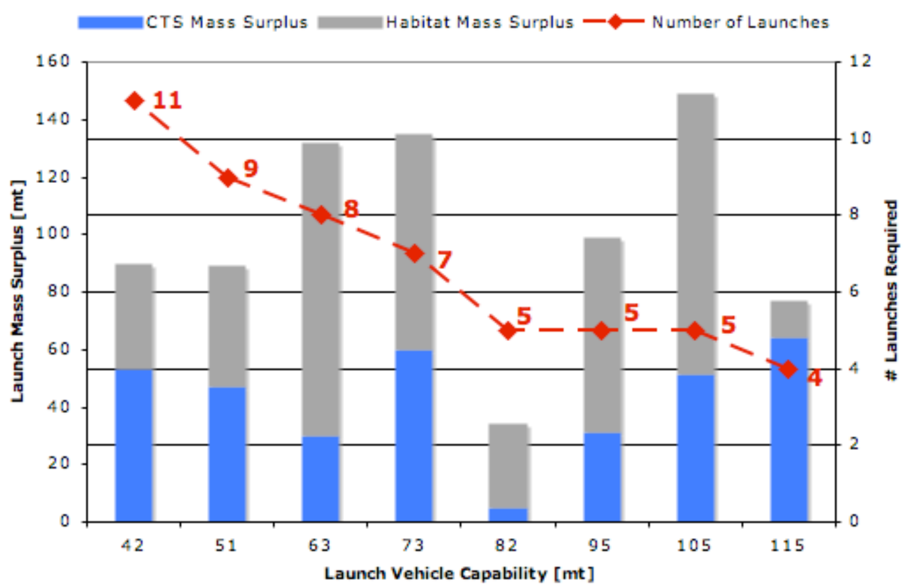

Figure 7. Number of Launches and Mass Surplus for Complete Lunar Missions. *The bars show the mass surplus contribution from each of the lunar vehicles, while the number of launches required for each launcher size is plotted in red.*

B. Integer Optimization Problem Results

While the full factorial search provides a method for finding an optimal launch vehicle size based on the launch mass surplus, the integer optimization formulation shows greater potential in terms of flexibility and also incorporates the cost metric directly into the objective function. Therefore, the variation in cost for various types of launch vehicles can be accounted for. A sample set of launch vehicles with associated costs is provided in Table 1. The set spans the range of possible launch vehicle capacities, but exhibits wide variability in terms of cost. (Note that it is difficult to estimate costs for various types of launch vehicles at this stage; these numbers are based on various sources,[5,6] and should be considered *only* as a sample dataset for this problem.)

Launch Vehicle Data			
Sample Vehicles	Capacity [mt]	Launch Cost [$M]	Unit Cost [$/kg]
EELV	28	170	6320
Clean Sheet 42	42	480	12069
Clean Sheet 51	51	590	12217
Clean Sheet 63	63	640	10728
Clean Sheet 73	73	720	10416
Shuttle-Derived (SDV) Sidemount 82	82	600	7727
Shuttle-Derived (SDV) Sidemount 95	95	980	10894
Clean Sheet 105	105	1300	11162
Shuttle-Derived (SDV) Inline 115	115	1390	12765

Table 1. Sample Launch Vehicle Data

As in the full factorial case, the results show that the best solution in nearly every case is to choose the largest possible TMI stage size that fits in a given launch vehicle. With this assumption, the cost and number of launches required to launch the Lunar Crew Transportation System are plotted in Figure 8.

The plot shows that the objective function is low for the 28-mt vehicle (EELV, e.g. Atlas V-HLV or Delta IV-Heavy) due to its low costs, and also for the 82-mt vehicle due in part to its low cost-to-capacity ratio, and in part to its low mass surplus (as shown in Figure 7 above). Recall that the full factorial results (Figure 7) also showed the 82-mt vehicle as the best choice, confirming that the mass surplus is a reasonable surrogate metric for cost. The 28-mt EELV did not show particular advantages in Figure 7, however, because its low cost was not taken into account. However, in this formulation, the EELV is the optimal solution even when other launch vehicles are available at the same time. For example, if the elements could be launched on either an Atlas V or a SDV, the optimal solution places all elements on Atlas V launch vehicles. This analysis thus indicates that the optimal solution is to split the TMI into four stages and use six Atlas V-HLV launch vehicles. Note that in this problem formulation, the optimal solution is driven in large part by the estimated cost of the launch vehicle.

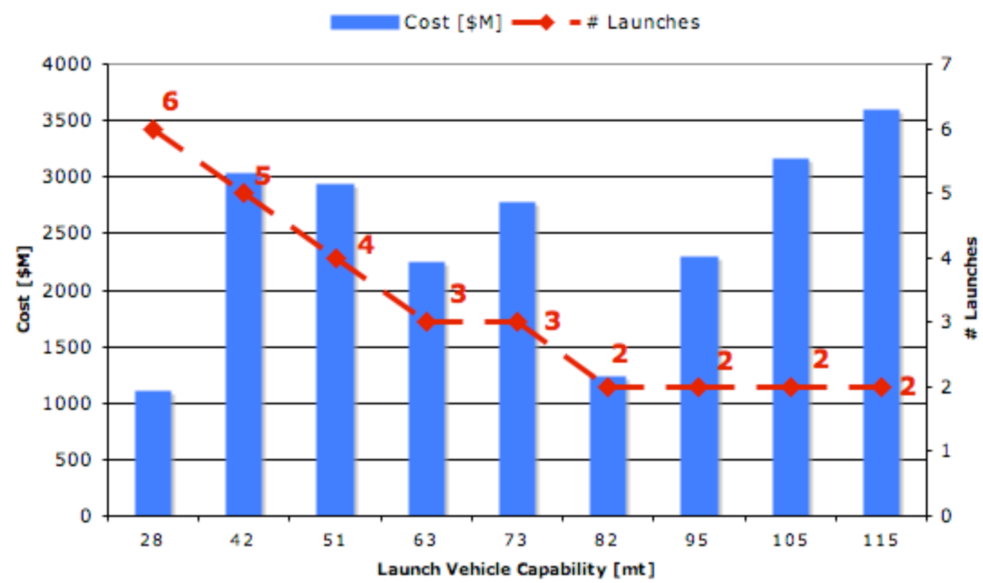

Figure 8. Number of Launches and Cost for Lunar Crew Transportation System. *The bars show the cost for each launch vehicle, while the number of launches required for each launcher size is plotted in red.*

C. Risk Analysis: Payload Sparing

The above analysis optimized the launch vehicle choice for reduced launch cost (driven by mass surplus and number of launches). The final step is to address the second major metric: risk (or reliability). The mission risk associated with a particular launch vehicle choice depends on the number of launches (with more launches, the risk of a launch failure increases) and on the *payload* of each launch. For example, the TMI stages are relatively simple and inexpensive to build, so if a launch containing a TMI stage is lost, it is easier to replace than, for example, the more complex habitats. To simplify the analysis, we classify the TMI stages as 'low-value' payloads, and all other items as 'high-value' payloads. Thus, mission risk can be analyzed in terms of the payload sparing requirements.

Assuming a launch success rate of 0.98, the total probability of achieving all desired payload in low Earth orbit (LEO) is determined for various quantities of payloads and available spares. In this analysis, available spares are equivalent to launch failures. This is the case because we are assuming that a spare is successfully launched if a primary launch fails. The overall launch sequence reliability is found from

$$P = \sum_{i=0}^{N_S} \binom{N_L}{i} p^{(N_L - i)} (1-p)^i \tag{5}$$

where P is the total probability of success of the set of required payload launches, N_L is the number of launches required for the payload assuming no launch failures, N_S is the number of spares needed, and p is the probability of successfully launching each individual launch vehicle. The first tem indicates the number of combinations of sparing payloads within the total number of payloads. The results for a varying number of launches and spares are shown in Figure 9 The black line indicates the probability of launching *all* payloads successfully for a given number of launches. The red line indicates the chance of launching *all but one* payload successfully, and so on. It is apparent that even for relatively small numbers of launches, the risk of losing a single launch is fairly significant; for example, for the optimal 82-mt launcher found above, 5 launches are required, and the chance that all would be successful is only 90%. On the other hand, if two spares are available, the probability of launching even twenty payloads successfully is nearly 100%.

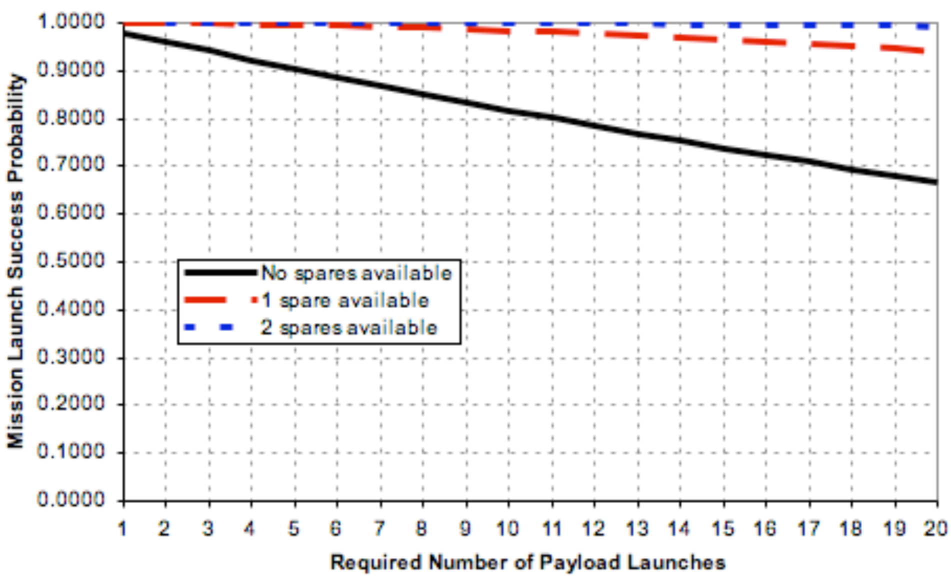

Figure 9. Overall Mission Launch Success Probability for Various Sparing Strategies. *Each curve shows how the mission launch success probability varies based on the required number of payload launches, for a particular staging strategy.*

The analysis was applied to two example sets of payloads for the Moon and Mars; results are shown in Figures 10 and 11, respectively. These figures break out the payloads into high-value and low-value modules. The data shows that without spares, the chance of launching all high-value payloads successfully is fairly high even for the smaller launch vehicles, while the chance of successfully launching all the low value payloads decreases to 83% and 82% for the smaller 35-mt and 51-mt launch vehicles, respectively. Based on this data, a sparing strategy could be formulated to keep several spares for the low-value payloads, but fewer for the high-value modules. This type of analysis shows that modularity, sparing strategies, and risk analysis can be used to strategically lower mission risk without incurring unnecessary costs. In addition, this method can be used to quantify the risk associated with the choice of a particular launch vehicle, aiding in the final selection of an optimal launcher in terms of both cost and risk.

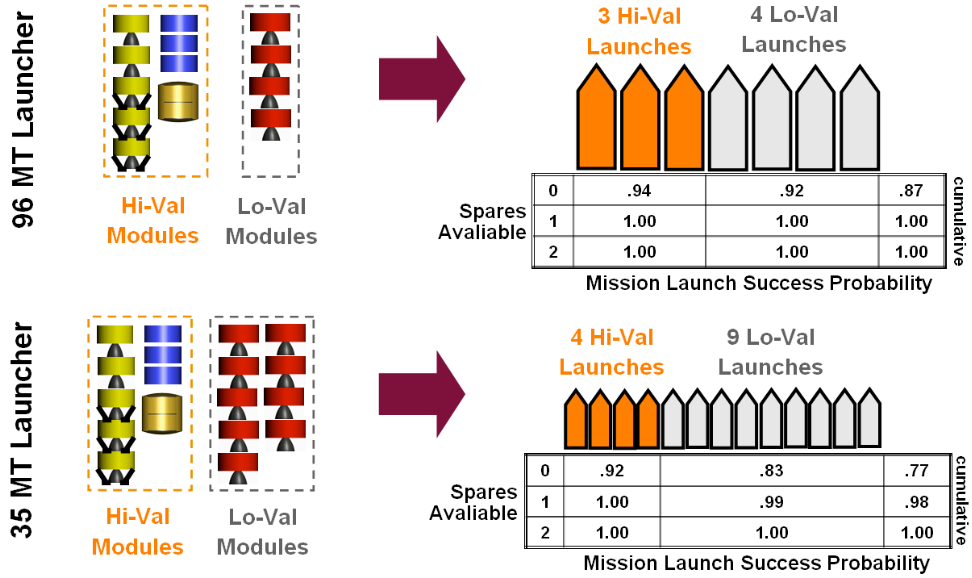

Figure 10. Mission Risk for Various Payload types for Mars Missions. *The high value and low value modules are separated on the left. More launches are required with a smaller (35-mt) launcher. The probability of mission success given various sparing strategies is given for each type of payload in the table at the right.*

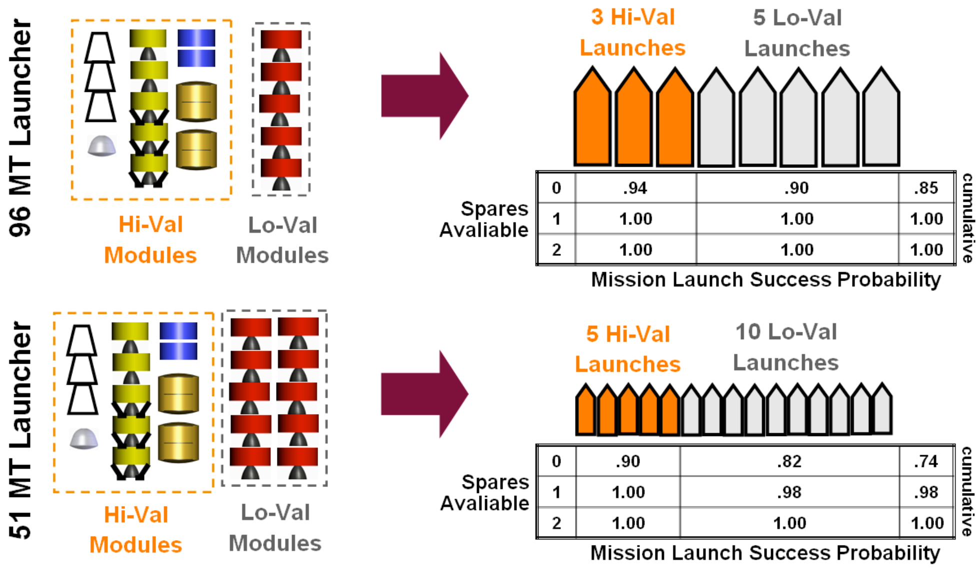

Figure 11. Mission Risk for Various Payload types for Mars Missions. *The high value and low value modules are separated on the left. More launches are required with a smaller (51-mt) launcher. The probability of mission success given various sparing strategies is given for each type of payload in the table at the right.*

D. Future Work

The methodology outlined here is by no means complete. Most importantly, the integer optimization problem formulation must be refined to compute results for a whole range of architectures. In addition, other types of problem formulations will be investigated. Finally, the problem will be expanded to include other aspects of the launch packing problem. For example, we plan to incorporate the launch volume constraint, which will require the solver to provide the optimal packing solution given both the mass and dimensions of each element.

IV. Conclusions

For the Draper/MIT lunar architecture, a clear optimal launch vehicle size emerged at 82 metric tons, requiring five launches to complete one long-duration lunar mission. Even with no spares, the chance of completing all launches successfully is approximately 90%; with one spare, the probability is nearly 100%. Another good choice emerged when the varying launch costs of the vehicles were taken into account: the same lunar mission can be launched on eleven EELV-type launch vehicles (28-mt capacity) for a slightly lower cost. However, the chance of launching all payloads successfully decreases to 80%. These results provide a solid quantitative basis from which to understand the launch vehicle selection tradespace for this set of lunar/Mars architectures. The data reaffirm the pre-existing supposition that the EELV's advantage lies in cost savings, while the HLLV has the edge in reducing risk by reducing the number of launches required.

The analysis discussed in this paper provides a method for selecting an optimally sized launch vehicle for a given transportation architecture, and suggests ways to optimize the architecture itself for the selected launch vehicle. Based on the launch vehicle size, an optimal 'chunk size' can be found to fit easily divisible modules (such as propulsion stages) onto the selected launch vehicle. At the same time, the best (or most efficient) launch vehicle size can be found using either a full factorial search to minimize the launch mass surplus, or using an integer optimization problem formulation to minimize cost. This type of analysis was here applied to a set of Moon/Mars transportation architectures developed at MIT/Draper, but should be generally applicable to any set of modular vehicles. The results of this analysis can help in the selection of a launch vehicle that will minimize mission cost and risk. Thus, these methods provide a much-needed quantitative method for understanding the EELV/HLLV trade space for Lunar/Mars transportation architectures.

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