NASA/TM-20250007999

Trade Study: Lunar Tank Welding

Level 0 Design Study

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December 2024

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December 2024

Available from:

NASA STI Program / Mail Stop 050
NASA Langley Research Center
Hampton, VA 23681-2199

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Executive Summary

The maturation of in-space manufacturing techniques requires understanding the impacts and shortfalls of their capabilities to inform technology investment strategies. The purpose of this trade study is twofold: to compare advanced manufacturing techniques that could be used to produce lunar storage tanks, and to capture the differences in terms of the benefits and drawbacks of each technique.

This study presents an approach that navigates the numerous difficulties in this area of investigation—the inherent technological uncertainty and need to elicit subject matter expert (SME) knowledge yields results that are qualitative and abstracted, alongside quantitative zeroth- and first-order analyses and estimates for the level of detail available regarding assumptions and background information. The approach is a framework that allows for revisions, refinements, and substitutions of the modules within the study as the uncertainty regarding assumptions and SME knowledge decreases, or the scope and fidelity of analyses and modeling increases.

At the current level of the study, the results are still capable of informing areas of targeted studies for dependent maturing technologies, determining showstoppers—critical disadvantages, insurmountable capability gaps, performance shortfalls—for the various manufacturing techniques, and allow for an initial understanding of the trade space sensitivities. The outcomes of this study are the framework approach and initial findings based on the assumptions, information, and SME knowledge available at the time.

The level of assessment and analysis for this study is rationalized by two main points. Firstly, the extant technology for the advanced manufacturing techniques has not been demonstrated on-premises and at-scale for the expected use case. As such, exact metrics that characterize or analytical models that simulate these processes are not available for comparison. However, SMEs have enough knowledge of these processes and their state of the art to give qualitative evaluations, which were converted to quantitative comparisons via the Analytical Hierarchy Process (AHP) technique. Secondly, capturing launch savings as a meaningful metric of comparison is not straightforward; several intermediate analyses or estimates need to be linked to reach some measure related to launch.

More parameters need to be included within the scope of the trade study for the purpose of defining the nominal use cases to which to size the lunar storage tanks, such that these sized tanks are used to quantify differences between launching whole tanks versus tank materials and components in various form factors, based on launch vehicle volume and mass constraints for a mixed fleet. The set of parameters that enumerate the trade space are a mix of categorical and numerical options, with some of the categorical parameters indirectly defining numerical properties that affect tank sizing. By acknowledging these separate sections of the trade space and intentionally structuring the approach to combine both quantitative and qualitative results in a flexible and systematic manner, the results are a holistic comparison of various advanced manufacturing techniques using the multi-criteria decision analysis method of Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS).

Initial findings evaluated Earth-based, in-space welding, in-space additive manufacturing (ISAM), and in-situ resource utilization (ISRU) for ISAM methods based on the following figures of merit (FoMs) as evaluation criteria: size of tanks launched per launch vehicle, size of any required infrastructure, the infrastructure lunar power demands, degree of manufacturing risk, manufacturing process complexity, intricacy of equipment deployment, rate of production, reliance on low technology readiness level (TRL) capabilities, and size limit of a given process. These FoMs are a set of distinguishing, if not orthogonal, characteristics that describe expected

launch savings, process complexity, and capability maturity of each alternative. The current FoMs and their scoring show that, overall, the in-space welding options offer the best balance of launch savings versus maturation and setup difficulty. Weighing the launch FoM as the metric of focus shows that the Earth-based and in-space welding options are the most sensitive to that FoM; it is possible that once super-heavy lift launch vehicles are precluded from the trade space that other manufacturing methods will become more attractive due to their invariance in scoring with respect to launch savings.

Overall, the initial findings are based on scoring from a small group of SMEs and estimates based on broad literature review. Changing sections of the approach—be it the analyses, estimations, scores, or trade space definition itself—will have varied levels of impact on the current results. Relative scoring of each alternative may shift with polling a larger group of SMEs or using their knowledge to revise the set of distinguishing FoMs. Formulating a more detailed tank sizing and payload packing analysis will provide an adjusted scaling of the launch savings FoM with respect to the other criteria but is not expected to drastically shift the scoring. Future iterations of this trade study can redefine the trade space to include more granularity representing ISAM and ISRU techniques, as well as additional tank use cases; the additional trade space parameters and evaluation criteria can be readily adapted into the current approach for the study.

Study Approach and Results

Trade Space Definition

The trade study defines the main alternatives being compared—and down selecting other parameters and features—as options that can be meaningfully represented with the current level of analysis and subject matter expert opinion, which is encompassed by the trade space. The main alternatives are the different manufacturing processes, categorized as Earth-based versus in-space manufacturing locations, and within in-space techniques there are the possibilities of welding, in-space additive manufacturing (ISAM), and inclusion of in-situ resource utilization (ISRU) (prospecting, mining, and processing) to obtain material for ISAM. Categories of conceptual options were established such their combinations can uniquely represent a specific scenario of manufacturing lunar storage tanks. Nested categories can be defined for the specificity of a particular manufacturing process, depending on the available level of detail for each category; e.g., decomposing in-space welding into the subcategories of high-energy, wire arc, and solid-state methods; e.g., only separating the additive manufacturing category into the options to make tank panels or a monolithic tank. The ISRU option remains generically defined due to lack of consultation with the relevant SMEs, though the structuring of the trade space will allow for a future iteration to further decompose the alternatives in an orderly fashion.

A meaningful comparison between manufacturing techniques regarding launch savings requires having quantified differences, be it order of magnitude estimations or analytical values.
To do so, the trade space needs expand its definition to include parameters that dictate the use case of the lunar storage tanks, which allows for notional sizing of the tank. Tank sizing yields dimension and mass metrics that can be used with various launch vehicle payload constraints as a quantitative comparison between the form factors with respect to each manufacturing technique alternative.

The exact type of storage tank—depot, drop, reaction control system (RCS), etc.—determines the nominal design and size of the tank. Due to the conceptual disparity between these tank types with their expected sizes and concept of operations (CONOPs) for deployment, the current study limits the alternatives to the use case of depot tanks on the lunar surface. Future iterations of the study can re-examine the inclusion of other tanks with adjusted or additional evaluation criteria. Other categorical parameters necessary for sizing include the tank material type, tank fluid, and target tank capacity.

Tank material type is limited to metals that can both be used for manufacturing on Earth and mine from lunar regolith; at the level of analysis performed for this study, the material properties did not yield meaningful differences in scoring between Aluminum 2219, Aluminum 6061, and steel. Revisions to the sizing analysis and trade space scoring can consider the exclusion of some materials based on source (non-ISRU versus ISRU options), and the evaluation criteria can be expanded to capture qualitative benefits and drawbacks of these different materials as well. For now, the study uses Aluminum 2219 to establish the methodology process.

The fluid being stored in the tank will determine the necessary thickness of the tank and other attached components and accessories to stay at a set, nominal thermodynamic state for its use case during sizing. For the lunar surface, liquid hydrogen (LH2), liquid oxygen (LOX), and water were determined to be the most sensible fluids for storage. The scope of this study does not include investigation and detail on obtaining these fluids and assumes propellant ISRU processes will be extant to justify lunar surface depot tanks as a use case.

Tank capacity is the final parameter to be included for tank sizing, and it differs from the previous parameters in being numerical rather than categorical, and continuous as well. The range of target tank capacity for sizing depends on the type of tank, which is the main factor of why each tank type results in vast conceptual disparity for sizing. In the case of a depot tank on the lunar surface, it can be assumed that the purpose of the tank is to refuel various lunar landers. Another assumption that follows is that, for this study, these depots are meant to refuel a representative lander with the capacity analogous to current industry standards (referred to throughout this paper simply as a “lander”).

Tank type, material, fluid, and capacity dictate a nominal size for the depot tank; afterwards, a packing analysis can be performed based on a given launch vehicle and its payload capacity. Thus, various launch vehicles are another category of parameter that expands the trade space. The number of tanks to be manufactured can also be another numerical, albeit discrete, parameter that affects packing and number of a given launch vehicle needed to deploy all tanks to their service destination; it was found that for the level of analysis in this study, the number of tanks was not a meaningful trade parameter.

The final trade space definition for this study can be separated based whether a given parameter feeds into the qualitative scoring by SMEs or the quantitative launch savings analysis. The quantitative analysis can be further separated into the tank sizing analysis and launch vehicle packing analysis. In this manner, the trade space alternatives can be delineated to allow for modularity of the various subanalyses and methods within the overall trade study approach, and further expansion of the trade space will not require drastic restructuring of the approach or invalidate previous findings (previous findings can instead be updated). The figure below depicts the trade space definition and its delineation as described.

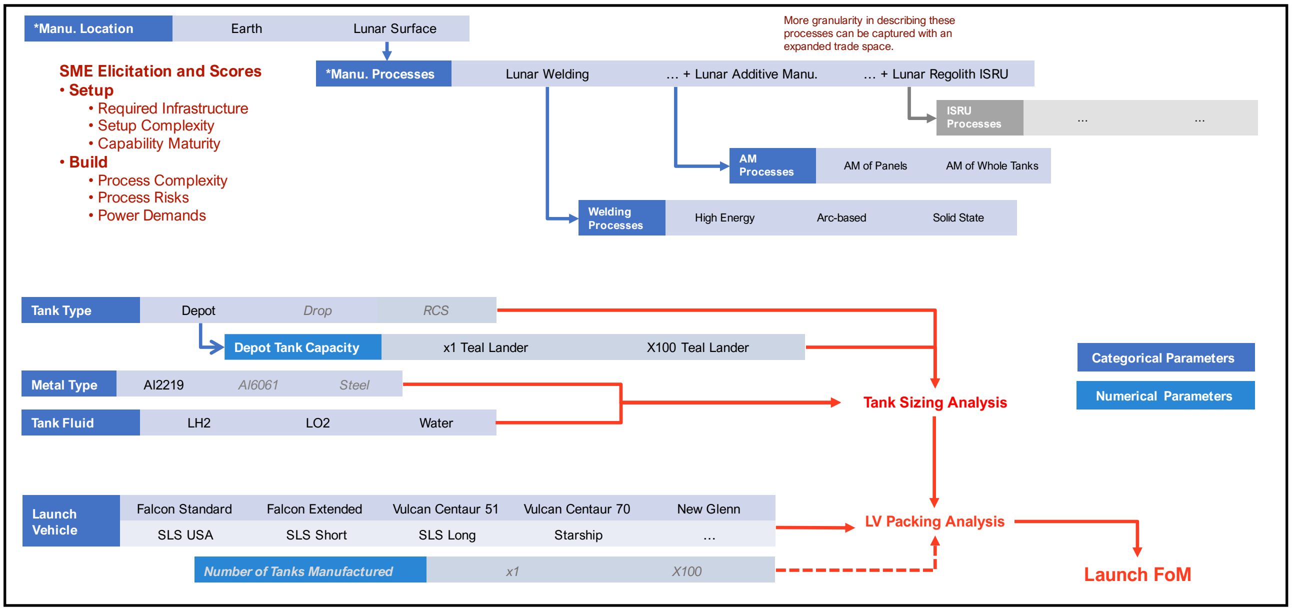


Figure 1. Trade space definition

List of Assumptions

Assumptions were made that the in-space manufacturing processes would occur on the lunar surface, and that the tanks would be deployed into service on the surface as well. The following list captures all working assumptions for this analysis:

- Assume that LVs are the only volume/mass constraint, that the lander is sized to the payload (in actuality, the lander availability would further constrain the payload)
- Assume that everything is made on the lunar surface → set up and launch destination
- Assume that the tanks are made for the lunar surface as fluid depots → fluid type down-selection, assumptions of nominal thermal subsystems
- Assume that tanks are launched unfilled for the purposes of simplifying comparisons, do not have the appropriate launch stress analysis and this helps simplify
- Assume that welding options require the launching of the same tank divided into barrel and gore panels (from SMEs)
- Assume that the AM options require launching the same tank material amount in the form of metal wire, spooled and vacuum-packed into barrels (from SMEs)

Concept of Operations

Use Case

For this trade study, it is important to understand the four options that are being traded. The first step in this process was to piece out the concept of operations for each option. Each option involved an Earth-Launched aspect, a landing aspect, and a lunar surface deployment aspect.

Earth-Launched Depot Tank

The Earth-launched depot tank involves manufacturing the tank on Earth, using traditional methods. This depot tank would include the tank structure, any propellant management devices necessary, MLI and cryocoolers, the stand, and other miscellaneous internal components and accessories. All of those would be built into the tank and loaded onto the launch vehicle.

Once launched into orbit, the tank would rendezvous with the lander and get delivered onto the lunar surface. From there, it would be offloaded and deployed into the service environment via robotics from the existing lunar infrastructure.

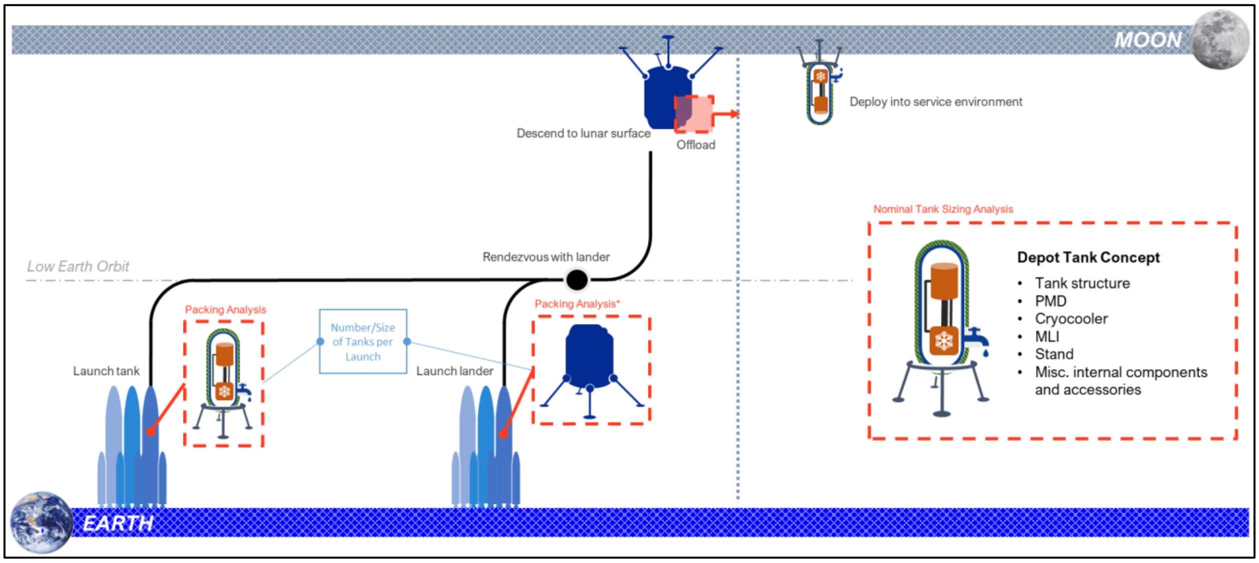


Figure 2. Earth-Launched Depot Tank ConOps (see Appendix A for enlarged graphic)

In-Space Welded Panels

The panel-welded depot tank involves manufacturing the panels on Earth using traditional methods. These pieces would presumably consist of the tank material along with any MLI that is reasonable to apply while on still on Earth. (This would result in gaps in the MLI, which would be necessary in order to have a weldable area on the lunar surface. This would significantly reduce the thermal insulation ability of the MLI and would have to be traded versus the lack of ability to apply MLI on the lunar surface. This is a significant deep dive that should be looked into in a future trade study.)

These panels would be packed and loaded onto the launch vehicle, along with any components to be added to the tank during in-space assembly. This includes (but is not limited to): any propellant management devices necessary, MLI and cryocoolers, the stand, and other miscellaneous internal components and accessories. These would be packed in a container so that the lander can deliver them to the lunar surface.

Once launched into orbit, the tank container would rendezvous with the lander and get delivered onto the lunar surface. From there, it would be offloaded. The lunar infrastructure would be capable of handling the tank panels, inserting the internal hardware, and welding the panels together into a complete depot tank. Several different welding methods were evaluated in this trade study and further detailed descriptions can be found in the “Manufacturing Techniques” section.

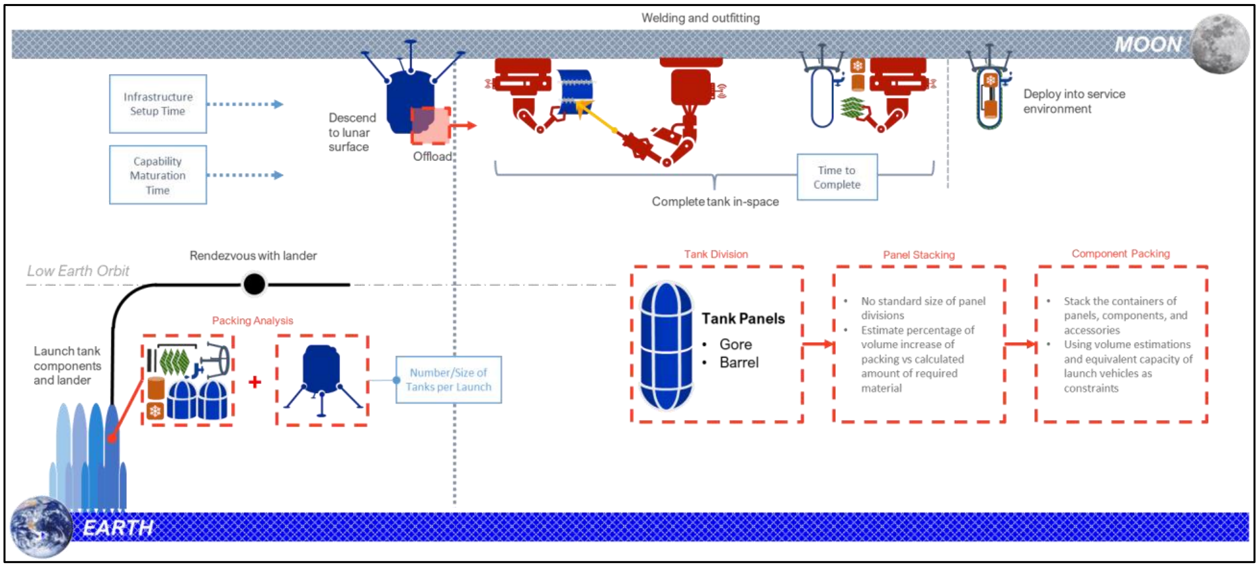


Figure 3. In-Space Welded Panel Depot Tank ConOps (see Appendix A for enlarged graphic)

In-Space Additive Manufacturing (ISAM)

The in-space AM tanks involve launching only the internal tank components and the metal wire necessary for the lunar infrastructure to print the depot tanks on the lunar surface. As such, the Earth-based operations are much simpler. The metal wires would be vacuum sealed into large barrels and loaded onto the launch vehicle along with the internal tank components: any propellant management devices necessary, MLI and cryocoolers, the stand, and other miscellaneous internal components and accessories. These would be packed in a container so that the lander can deliver them to the lunar surface.

Once launched into orbit, the tank container would rendezvous with the lander and get delivered onto the lunar surface. From there, it would be offloaded. The lunar infrastructure would be capable of handling the barrels of wire, loading the wire, printing panels, inserting the internal hardware, and welding the panels together into a complete depot tank. Several different welding and AM methods were evaluated in this trade study and further detailed descriptions can be found in the “Manufacturing Techniques” section. This includes both printing panels and then welding them together (similar to the in-space welding method above), versus using a newer method to fully additively manufacture the tank from the ground up.

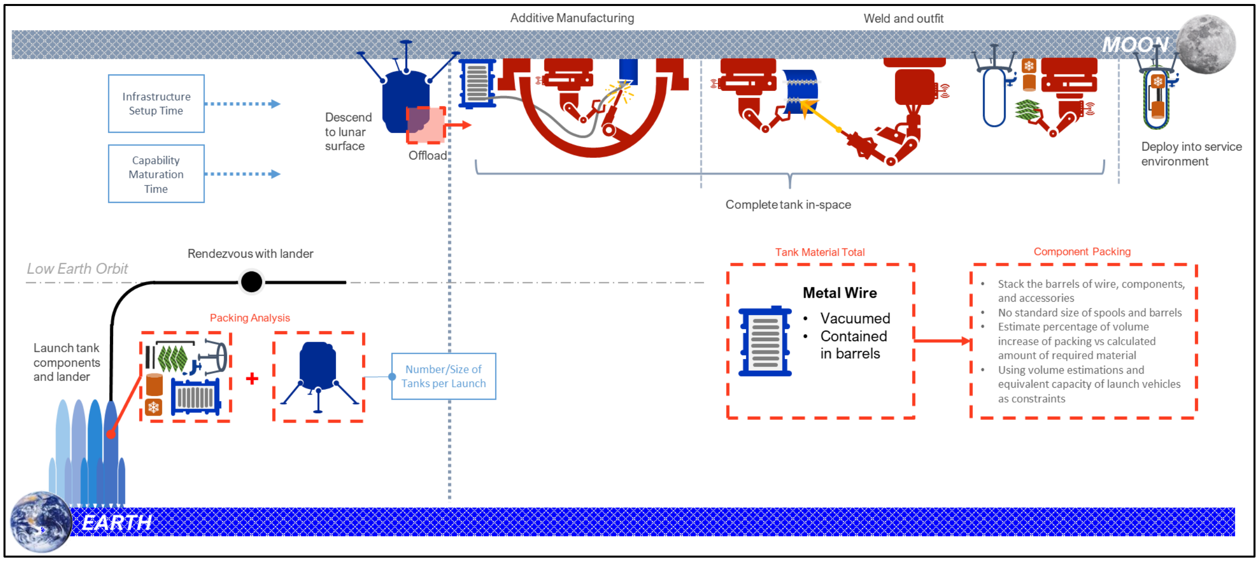


Figure 4. ISAM Depot Tank ConOps (see Appendix A for enlarged graphic)

ISAM Tanks Using In-Space Resource Utilization Materials (ISRU)

The ISRU AM tanks require the least Earth-based interaction, but the most lunar infrastructure development. Unfortunately, there would still be internal tank components that would need to be launched from Earth. These would be packed in a container so that the lander can deliver them to the lunar surface.

Simultaneously, the lunar regolith would be mined and processed on the lunar surface. The lunar infrastructure would be capable of mining, processing, and extracting aluminum from the regolith. This whole cycle would take considerable time and energy but would result in the raw material needed for the depot tanks. We assume that it is reasonable to turn this material into a metal wire form similar to the wire from the “in-space additive manufacturing” case. From there, the process is nearly identical.

Once launched into orbit, the container holding the components would rendezvous with the lander and get delivered onto the lunar surface. From there, it would be offloaded. The lunar infrastructure would be capable of handling and loading the regolith-derived wire, printing panels, inserting the internal hardware, and welding the panels together into a complete depot tank. Several different welding and AM methods were evaluated in this trade study and further detailed descriptions can be found in the “Manufacturing Techniques” section. This includes both printing panels and then welding them together (similar to the in-space welding method above), versus using a newer method to fully additively manufacture the tank from the ground up. The various methods of ISRU were not within scope of this short trade study but would be a top choice for a deeper dive in a follow-up study.

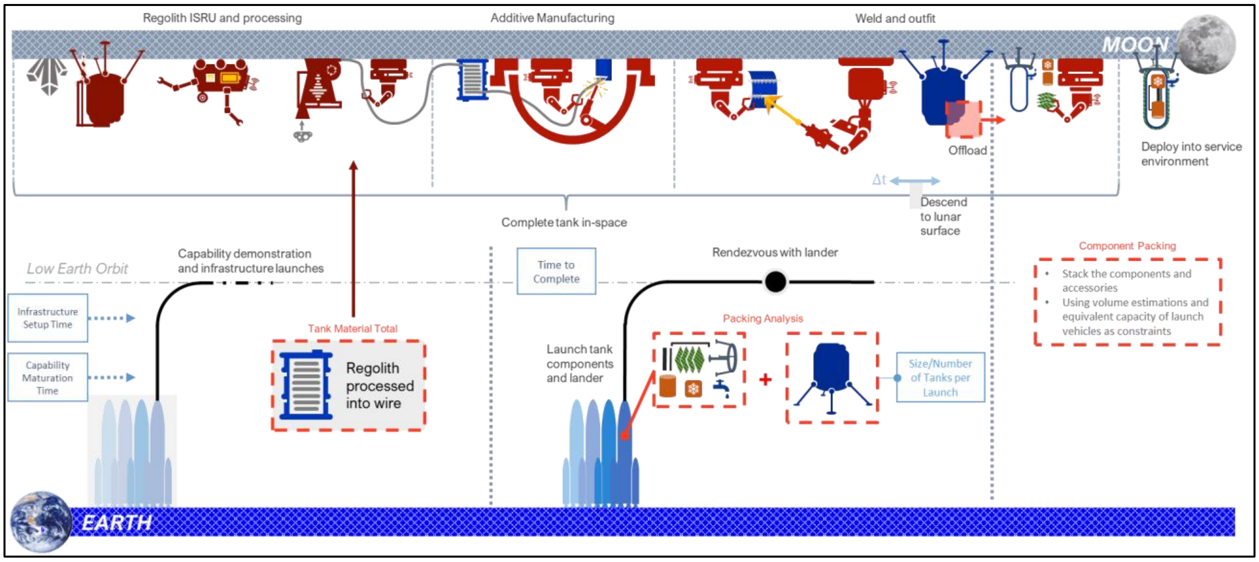


Figure 5. ISRU-Derived ISAM Depot Tank ConOps (see Appendix A for enlarged graphic)

Manufacturing Techniques

As mentioned in the previous section, there are four different Con-Ops that will be explored. However, there are multiple ways to accomplish these different con-ops. These different techniques are explored in Table 1 and explained in detail in this section.

Table 1. Manufacturing Processes Trade

Methodology	**Manufacturing Techniques**			
Earth-based	**1.** Earth-based			
Panels launched and welded in space	**2.** HE Welding	**3.** AB Welding	**4.** SS Welding	
In Space Additive Manufacturing	**5.** Panel AM + HE Welding	**6.** Panel AM + AB Welding	**7.** Panel AM + SS Welding	**8.** Whole AM
In Space Resource Utilization	**9.** ISRU + Panel AM + HE Welding	**10.** ISRU + Panel AM + AB Welding	**11.** ISRU + Panel AM + SS Welding	**12.** ISRU + Whole AM

Earth-based (Technique 1)

Earth-based tanks would be manufactured on-Earth using current manufacturing processes. Metallic tanks can be produced with precision machined barrels and spherical or elliptical domes. These would be machined and welded together using typical to state of the art manufacturing processes. Isogrids and other mass-saving features can be machined out of the finished tank. Tanks could also be made via additive manufacturing similar to Relativity Space's AM tanks or out of composite material used in composite overwrap pressure vessels (COPV) (Space, 2020). For the study, like metal tanks were considered and compared. While the tanks are launched from

Earth, the tanks need to be sized to take into account random vibration loads alongside launch loads resulting in thicker structure. Tanks can also be outfitted with additional hardware that would not be printable in space with things such as fill/drain valves, active cooling, pumps, etc. on the tanks. Earth-based tanks are the highest TRL of all the proposed manufacturing technology techniques. Earth-based tanks are also more easily verifiable than in space manufactured alternatives. Earth-based tanks do have volume efficiency issues compared to other in-space manufacturing techniques.

Panels launched from Earth (Techniques 2 – 4)

Panels would be precision machined on Earth—with additional machining used along the edges for weld interfacing requirements—and packaged efficiently to be launched within a given launch vehicle. Once delivered in space, the panels would be positioned and then welded together. Astronaut welders, astronaut operators, robotic arms, fully autonomous robotic welding, or some combination would be used for performing the welding operation. With Earth-launched panels, verification of panel microstructure quality could be done on Earth. In-space welding would require additional verification processes to ensure proper joining. The TRL for in-space welding is lower than that of Earth-based welding. The technologies for in-space welding are also a similar TRL to that of ISAM. However, due to the panels being produced on Earth, the TRL of panels launched from Earth and welded in space is higher than that of panels being ISAM.

In Space Additive Manufacturing (ISAM) (Techniques 5 – 8)

With ISAM, panels would be manufactured in-space or the entire tank would be manufactured in space under a single operation. The wire spool used for the AM process would be launched within a launch vehicle. Robotics or an astronaut would maneuver the wire spool into the AM machine. This ISAM techniques would be like arc-based welding. A wire feed would provide the material that the electrode would melt and form into the part shape. This would include ISAM for just producing panels to then be welded, alongside full tank ISAM. Powder-based techniques (and especially powder bed techniques) were not highly rated by the SMEs for use in large scale tank designs. Additional machining may be required post-ISAM and prior to welding panels together in order to have joints that could be properly joined together with the various joining processes. From a verification standpoint, ISAM would require both verifying the panel/tank microstructure in addition to the welded joints. As a result of inconsistencies, greater tank thicknesses may be required for ISAM techniques compared to in-space welded panels.

In Space Resource Utilization (Techniques 9 – 12)

ISRU would involve using material from the lunar regolith to then ISAM into panels or full tanks. ISRU would not only require the machines to perform the ISAM and the welding, but also the infrastructure to properly take in the lunar regolith and generate sufficient raw material to be then converted into storage tanks. Infrastructure would include techniques for collecting the lunar regolith, techniques for sorting out the usable materials from the lunar regolith, and techniques for turning that usable material into usable wire or powder for ISAM. Lunar regolith is composed of up to 24% aluminum by weight, which is of particular interest for ISAM storage tank material. ISRU techniques expect to yield about 19% aluminum by mass from processed lunar regolith (Archive.org, n.d.). The ISRU methodology is at the lowest TRL and is still in development. Research is being done on ways to extract various usable metals like aluminum-2219 (Ferguson & Shafirovich, 2018). Verification processes would be similar to that of ISAM in that both the material of the manufactured tank and the welded joints would need to be inspected and verified.

High Energy (HE) Density Welding (Techniques 2, 5, 9)

High energy density welding processes focus a high energy beam as the welding process across a joint. The two main processes are laser beam welding (LBW) and electron beam welding (EBW). EBW has been demonstrated in space from 1969 through 1988 aboard the Soyuz-6, Skylab, in-space outside Salyut-7, and aboard the Mir space station. (Strelko, 2021) (Poorman, 1975) (Sowards, Cordero, & Courtright, 2021) LBW has been demonstrated via parabolic flight tests. Advantages for HE welding include being the most power efficient and most capable for thicker section materials. HE welding also does not require consumables thereby eliminating the mass needed. Disadvantages include concerns from the emission of x-rays from EBW to ensure proper shielding. For LBW concerns regarding heat radiation and dissipation (Nance & Jones, Welding in Space and Low-Gravity Environments, 1993). HE welding processes have the tightest fit requirements. HE welding techniques is also the fastest welding process for welding operations. When used with a wire filament for ISAM, HE welds have a more similar travel speed to that of cold metal transfer techniques. HE welds have been demonstrated alongside six-axis control machines in both welding and AM applications.

Arc Based (AB) Welding (Techniques 3, 6, 10)

Arc based techniques consist of an electrode connected to a power source and the workpiece. When the power supply is active, current flows through the electrode and through the plasma arc to the workpiece. Since the arc consists of superheated plasma, it is important to shield the weld from atmospheric contaminants by providing an inert. In theory, due to the vacuum of space, limited shielding would be needed and only some gas would be required to maintain the arc. Advantages include AB welding being a simpler and less expensive equipment. Further, due to the nature of the arc, it is nearly impossible to have the arc jump to an unwanted piece of hardware, operator, or spacecraft. AB welding require a steady gas supply that can result in the need for additional gas supply and storage for said gas supply. Further, the arc requires more energy compared to HE density welds when applied to thicker joints (Nance & Jones, Welding in Space and Low-Gravity Environments, 1993). Arc based welding has been demonstrated in space-like environments (airborne-based high-vacuum reduced-gravity experiments (Sowards, Cordero, & Courtright, 2021). Theory shows that arc-based welds should work in space but have yet to be conclusively demonstrated. Concerns mainly occur from space's low-pressure environment rather than the microgravity. Proposed uses of hollowed tungsten electrodes for space welding to provide a trace amount of argon gas to allow for the arc to be maintained (Suita, Y, T, & K, 1994) (Luchinsky, Hafiychuk, Wheeler, Roberts, & Hanson, 2021). Through modeling efforts, concerns remain relating to porosity due to trapped gas bubbles in the melt from low gravity and difficulties with maintaining the weld beam in space (Luchinsky, Vasyl, Wheeler, Roberts, & Hanson, 2021).

Solid State (SS) Welding (Techniques 4, 7, 11)

Solid state welding, primarily demonstrated via friction stir welding (FSW) have an inner pin and thus do not require as tight a joint fit as the other welding processes. SS welding require an additional anvil that is required to work against alongside high-power requirements and a torque motor. Cold metal transfer (CMT) welding has the largest weld head of the considered techniques. They have been demonstrated in vacuum but not in space. A six-axis control machine would be most challenging to create for a SS welding machine due to the need for the inner pin and additional anvil across the weld joint.

Whole AM (Techniques 8 and 12)

With proper lunar infrastructure development, robotics or astronaut assisted machines could be developed to build an entire tank in one pass using AM like Relativity Space's terrestrial applications (see Reference for Relativity Space). Additional analysis would need to be done to look into concerns regarding structural integrity of the fully ISAM structure as temperature fluctuation from the AM process alongside holding a very large tank could induce loads into the material that would need to be checked. This technique would cut the additional need for welding verification, and would instead rely on verifying the printed material of the tank in its entirety.

Evaluation Methodology

As stated at the end of the trade space definition section, the study methodology is separated into qualitative and quantitative portions to evaluate the main alternatives. Once the trade space is defined, down selected, and partitioned, the qualitative and quantitative subanalyses can be performed asynchronously before combining the results for a final evaluation. Broadly, the steps for this methodology are as follows:

1. Establish the representative criteria and scope of trade study.
2. Enumerate the alternatives and sort into quantitative and qualitative portions of the trade space.
3. Connect the alternatives to the evaluation criteria as FoMs.
    - Qualitative scoring with AHP
    - Tank sizing and launch vehicle constraint estimations
4. Combine the qualitative and quantitative results using TOPSIS for a final scoring.

The first two steps were covered in the trade space definition and concept of operations sections. The following subsections will first focus on the qualitative evaluation and its specific FoMs, and then the quantitative evaluation related to launch performance.

Qualitative Analysis

Qualitative assessments use SME elicitation to evaluate trade space alternatives that are uncertain and immature concepts, which otherwise lack exact metrics characterizing or analytical models to simulate their performance for their expected use case. The characteristics of each advanced manufacturing technique being compared are abstracted into the evaluation criteria meant to distinguish each alternative. These criteria are then redefined as FoMs that have ordinality in that each alternative may be ranked against each other.

Analytical Hierarchy Process

The AHP technique—although typically used to capture individual preferences between various options to find the overall preferred option—is used to capture these rankings and transform them into a quantitative representation of the qualitative evaluation. This technique performs pairwise comparisons between each alternative, represented by a ratio scale, for a particular FoM. The pairwise comparison ratios are collated into a matrix that is normalized, such that the overall ranking of each option is yielded through individual comparisons. For the level of knowledge available for these advanced manufacturing techniques, this method provides an appropriate balance of detail versus certainty of evaluation; once set up, it can easily intake new rankings to provide updated rankings. This study's use of AHP is adapted from the approach detailed in the paper by Prasadh et al, modified to accommodate the current trade space definition (Prasadh, et al., 2014).

For this study, the total number n of qualitative trade space alternatives that must be compared is 12, based on the trade space definition of conceptual options and compatibilities (these alternatives are detailed in the subsection on manufacturing techniques). Let each alternative be denoted i or j where $i, j = 1, \ldots, n$ for its corresponding index, and a FoM is denoted a with the element a_{ij} representing the pairwise comparison of alternative i versus alternative j. The comparison uses a numerical ratio scale, 1 through 9, to estimate a multiplicative factor between alternatives; any scale may be used, although literature has found that larger values may create numerical difficulties and consistency errors during comprehensive scoring.

If the alternatives being compared are identical (i.e., $i = j$), the element $a_{ij} = 1$. For $i \neq j$, if alternative i is considered larger or more than alternative j in some manner, then $a_{ij} > 1$. For the opposite consideration, then $a_{ji} > 1$ and $a_{ij} = 1/a_{ji}$. The entire AHP matrix comprising all entries a_{ij} for FoM a yields a pattern where the diagonal elements are 1, and the upper triangular entries should be reciprocal values of the lower triangular entries. In practice, only half of the entries for a_{ij} need to be obtained through SME elicitation as either a small-scale discussion or a large-scale poll.

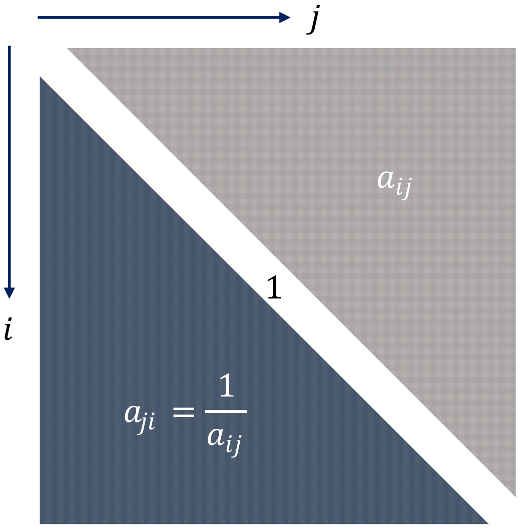


Figure 6. Example AHP Matrix

Once the AHP matrix has been obtained, the sum of each column is calculated and used to normalize the entries a_{ij} for a comprehensive comparison of all alternatives. The normalized AHP matrix is represented by entries $\bar{a}_{ij} = a_{ij}/\sum_{i}^{n=12} a_{ij}$. The vector of scores for the alternatives is typically referred to as the priority vector with the largest number being the most preferred alternative due to the typical use case of AHP; here, this vector denotes the ranking of the alternative in which preferred directionality is contingent on a given FoM definition. The priority vector is calculated by averaging the rows of the normalized AHP matrix; the scores for alternative i with respect to FoM a is denoted $A_i = \sum_{j}^{n=12} \bar{a}_{ij}/n$.

A priority vector per FoM can be generated, and a final score for each alternative i can be calculated by summing the priority vectors together. If there are FoMs $a, b, c,$ then the final AHP score of the alternative i is given as $S_i = A_i + B_i + C_i$. However, this scoring consolidation assumes that the direction of preference is towards the larger score and only captures the qualitative portion of the trade space; for this study, another method of ranking the alternatives is used in combination with the quantitative analysis.

Qualitative Figures of Merit for Evaluation

The FoMs listed in this section were informally downselected through discussions with SMEs; formal downselection would be conducted through a workshop for the specific purpose of establishing and defining FoMs. Regardless, the main goals for the FoMs are to capture noted differentiating characteristics of the manufacturing techniques and ensure a consistent description for SMEs to use as a precept when ranking the alternatives. The same AHP technique can be used to score any number of alternatives with a different set of FoMs. The FoMs are listed below in Figure 7.

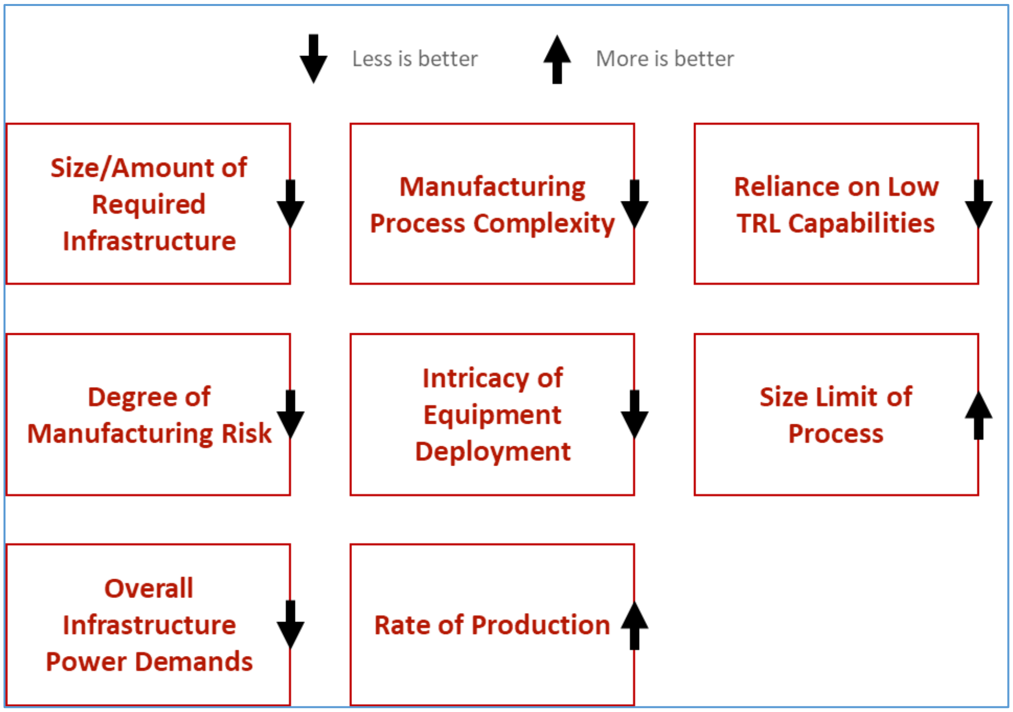


Figure 7. Qualitative Figures of Merit

Some FoMs have overlapping characteristics by nature of their subjective definition, which can be revised in iterative studies upon examining the results of the current study. An alternative can be valuated differently for the FoMs based on the SME's assumption of the future state of the art—e.g., one assumption might rate an alternative's deployment as simpler but with a lower technological readiness to ruggedize the equipment for the environment, or leveraging current terrestrial capabilities will require more infrastructure to set up the necessary operating environment.

As stated previously—the benchmark alternative of Earth-based manufacturing assumes that some lunar infrastructure will be present due to projected lunar surface activities. There is necessary infrastructure present to assist in offloading the storage tanks from a lander, and then deploy those tanks into their operating environment. Estimating the impact of lunar manufacturing capabilities and infrastructure for each FoM will consider the assumption of having the supporting infrastructure for deploying Earth-made tanks.

Size and Amount of Required Infrastructure

Each technique will require infrastructure on the lunar surface; at the minimum, means to deploy the tanks or launched tank materials and components must be present to allow unmanned operations. Lunar-based alternatives will differ in the footprint of their machining and positioning equipment, and the needed enclosures for their operations for considerations such as pressurization, cleanliness, etc. This FoM does not consider the intricacy of deploying the infrastructure, nor its maturity state. The preferred directionality of this FoM is having less required infrastructure, as this will correlate to additional setup time and cost due to launch demands for the infrastructure (launch vehicle capability and a given vehicle's cadence).

Degree of Manufacturing Risk

From launch to deployment into service, there is a chance that a tank will not meet the threshold for its operational quality. Earth-made tanks may be inspected and fixed prior to launch, but the deployment process might cause damage that cannot be repaired. Each lunar surface manufacturing technique differs in number of sensitive or “high value” processes, the number and ease of inspections via remote means, predictability of faults, and possibility of repairing or reworking failed processes.

An example of comparison between solid-state alternatives and ones using fusion processes would consider that solid-state processes are easy to inspect, but defects are difficult to predict and resolve appropriate, whereas fusion processes are much easier to repair, but X-ray is required to inspect for porosity in the material and determining the end quality is difficult. Overall, this FoM characterizes the likelihood of having a failed product that cannot be recovered, and the preferred directionality is having less overall risk.

Infrastructure Lunar Power Demands

Each alternative requires some amount of power on the lunar surface for deployment equipment, and more so for additional manufacturing infrastructure. Processes within the alternatives will have different energy requirements; these differences are more granular in the case of the in-space welding options—i.e., the delineation between high energy, arc based, and solid-state welding processes in the trade space corresponds with brackets of typical energy consumption—the AM and ISRU alternatives. Satisfying the power demand of the ISAM options is not considered within scope of the size and amount of infrastructure FoM. It is assumed that the power demand will be a requirement that, alongside other lunar surface infrastructure, will drive the surface power architecture to support all operations. The preferred directionality of this FoM is needing less power.

Manufacturing Process Complexity

Manufacturing process complexity considers the number of steps and operations, and the degree of difficulty of the constituent operations of the processes rated for the environment. This characteristic is not wholly separate from the degree of manufacturing risk, in that more operations and more complex operations may have a higher chance of failure. Using AM as a counterexample—the manufacturing of a monolithic AM tank would have the least number of steps among the in-space options, but any faults during the extended process will likely not be possible to resolve. The directionality of this FoM assumes that simpler processes are preferred.

Intricacy of Equipment Deployment

Deploying the necessary equipment for each manufacturing alternative must also consider its setup on the lunar surface in addition to its launch from Earth, which launch-dependent characteristics have been abstracted in the FoM for size and amount of required infrastructure. Once the infrastructure and equipment have been landed on the lunar surface, setting it up will vary in difficulty due to positioning, wires, environmental radiation and dust, and necessity of telerobotic manipulation per alternative. Some processes may use the same manufacturing equipment but require extra positioners, e.g., welding versus AM process using same welding robot. This FoM depends on assumptions on the future state of the art, which will trade off with the FoM concerning technology readiness and uncertainty of the projected capability. It is assumed that the preferred directionality of this FoM is having the least intricate setup.

Rate of Production and Deployment

Comparing the rate of production and deployment of completed tanks requires assumptions for defining the start and finish per alternative. Each alternative in the trade space has concept of operations that are broadly grouped by manufacturing, launch, and final deployment; however, the order of manufacturing and launch are switched for the Earth-based benchmark and the lunar manufacturing alternatives. For Earth-made tanks, the start of production is when the tank panels are formed for fitup and welding, and is benchmarked against the lunar manufacturing alternatives, which start from the launch of tank materials and components. The preferred directionality of this FoM is having a higher rate of production.

Reliance on Low Technology Readiness Level Capabilities

For all manufacturing alternatives, the concept of deploying lunar storage tanks is untested, and the most advanced capability for this concept is at TRL 6. The various concept of operations are used in determining the enabling capabilities per alternative, in technological categories such as: manufacturing techniques, sensors and monitoring, robotic manipulation, resource exploration and acquisition, material refinement and preparation, preventing contamination during manufacturing, etc. Scoring for each alternative is based on its dependency for technologies that are TRL 3 and below as the current state of the art. This FoM is representative of the uncertainty of reaching a useable threshold of performance and quality for an alternative, and the preferred directionality is having a lower dependency value to represent a more mature concept.

Size Limit of Process

Due to positioning equipment, possible internal stresses, or launch constraints, each manufacturing alternative will have overall limitations for the tank capacity it can feasibly produce and deploy. For the Earth-based alternative, the size limit is dictated by launch vehicle payload constraints. For the lunar-based alternatives, it is expected that the welding and AM processes will dictate manufacturing limitations, not ISRU processes. The preferred directionality of this FoM is to have a larger size limit for a higher capacity tank.

Quantitative Analysis

Tank Sizing Analysis

The depot tank sizes for all four options were sized based on the amount of LH2 and LOX needed to refuel a representative, industry-standard lander. The size of the water tank concept was based on the tank volume of the LOX, simply to keep things consistent even though the H2O tank is not relevant to a lander. After the fluid volumes were determined, a residual and reserve propellant volume were assumed and added onto the fluid volume. The fuel depots were sized to fit the sum-total of the fluid volume while remaining structurally sound to a safety factor of 1.5.

These assumptions were used for the Tank Sizing Analysis:

- LH2: 60 m3, 20 K, 13.2 psi
- LOX: 20 m3, 95 K, 23.7 psi
- H2O: 20 m3, 283 K, 13.2 psi
- Minimum tank thickness .01 inches
- Residual propellant: 3%
- Reserve propellant: 25%
- Tank material: Al-2219

Once the initial tank sizing was complete, the next step was to factor in multiple tank capacities to determine if size played a factor in the final scoring. This was achieved by scaling up the capacity of each tank to be capable of refueling a minimum of one lander to a maximum of 100 landers. The analysis was run parametrically to achieve a new volume for each case. The choice of the numbers 1-100 was arbitrary and can be changed upon request. The goal of these tank capacity sweeps was to understand the sensitivity of tank size on the overall trade study, especially when factoring in the fixed volumes of the launch vehicle payload capacities. Knowing if certain options trade better at larger or smaller tank volumes is useful.

Packing Analysis

To estimate the tank panel and metal wire packing, a packing efficiency methodology was selected. The packing efficiency for the tank panels was estimated via computer aided design (CAD) modeling. Afterwards, these tank panel counts were compared to the tank capacities calculated above for the Earth-launched fuel depots. That comparison yielded a packing efficiency percentage, which was used to scale the tank panel option later in the analysis.

The CAD analysis was performed to determine tank sizes for full-sized, Earth-launch tanks and Earth-launch, lunar-manufactured tank panels. Due to scope limitations, a detailed packing optimization was not performed. Instead, the CAD for the tank panels was packaged within payload fairings and filled within the barrel section of the fairing to fill the payload volume.

A gap of 100 mm was placed between each panel to account for the housing that would be required to hold the panels in place alongside any additional packaging that would prevent any untoward vibrations from damaging the panels. Two payload fairings were analyzed: Falcon 9 for a baseline smallest configuration and SLS 1B for a largest configuration. Other payload fairings could have been analyzed, but this provided packing efficiency data across multiple payload fairings to identify relative efficiencies for the panel welded method.

A 3 m inner diameter tank was sized for the 60 m^3 lander LH2 tank. The barrel length was then broken into five barrels. A 20 m^3 lander LOX or H2O tank would take one barrel length alongside the barrel domes. The barrel and gore were then split into six segments based on inputs from in-space welding SMEs. A 60 m^3 lander LH2 is shown in Figure 8.

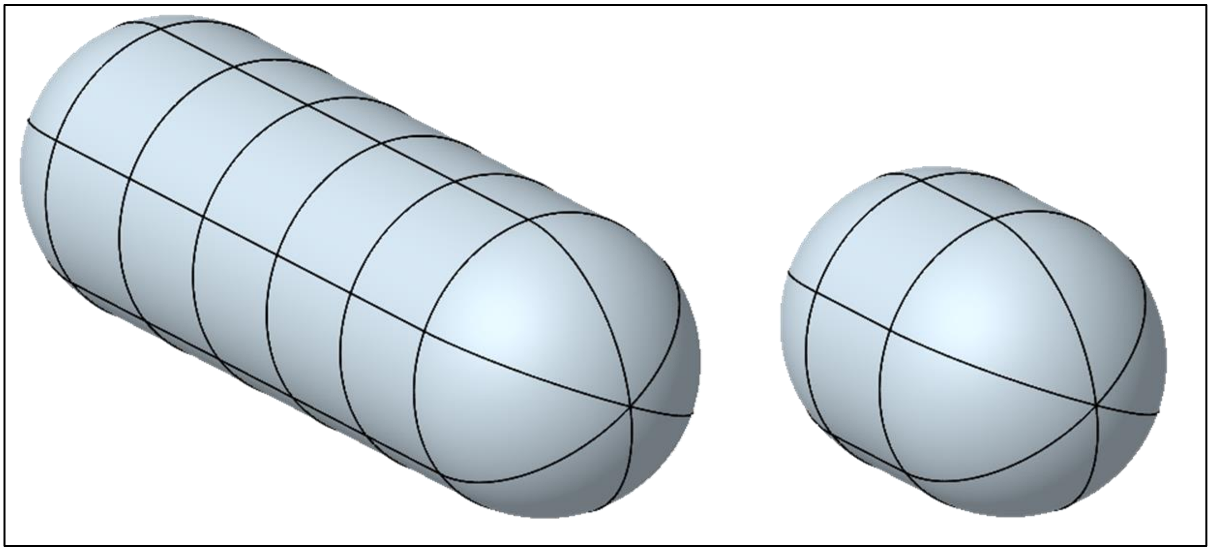


Figure 8. 60 m^3 LH2 tank made from six-segment panels with five-cylinder segments and two domes (left). 20 m^3 LOX or H20 tank made from six segment panels with one cylinder segment and two domes (right).

This all led to a barrel to gore ratio of 5:2 for the lander LH2 tank, which was the configuration primarily sized in the packaging analysis. However, a 5:2 barrel to gore ratio was not always possible in the various configuration when keeping columns of panels to be the same panel type (gore vs barrel). As a result, different barrel to gore ratios were explored to determine both overall number of producible lander tanks and maximum tank volume as shown in Figure 9 and Figure 10.

Table 2. 4:2 barrel to gore panel ratio for Falcon 9 standard fairing.

Barrel Panels per Row	4
Gore Panels per Row	2
Number of Rows	66
Number of Total Barrel Sections	8
Number of Gore Pairs	11
Number of Lander Tanks	8
Lander Tank Volume	473.1 m^3
Maximum Tank Volume (use all gore pairs and full barrels)	552.5 m^3

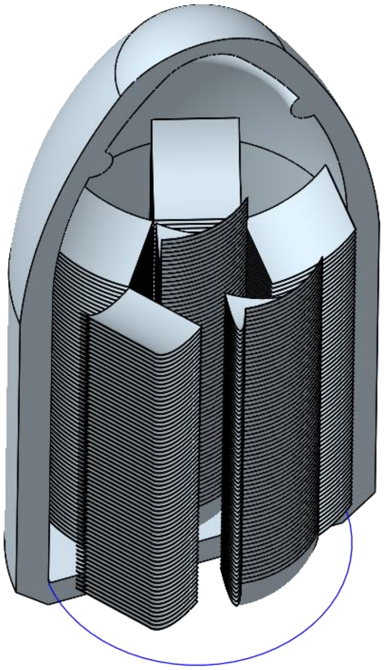


Figure 9. Falcon 9 standard fairing with a 4:2 barrel to gore ratio for a maximum number of lander LH2 tanks.

Table 3. 5:1 barrel to gore panel ratio for Falcon 9 standard fairing.

Barrel Panels per Row	5
Gore Panels per Row	1
Number of Rows	66
Number of Total Barrel Sections	11
Number of Gore Pairs	5
Number of Lander Tanks	5
Lander Tank Volume	295.7 m^3
Maximum Tank Volume (use all gore pairs and full barrels)	568.2 m^3

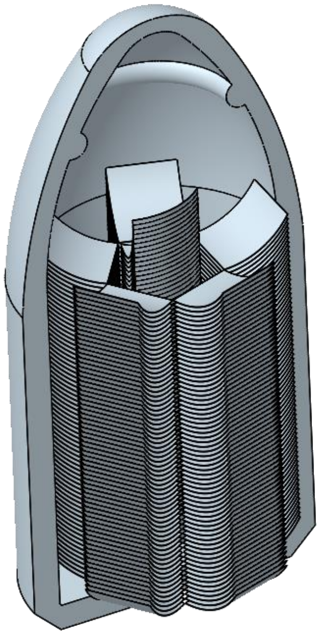


Figure 10. Falcon 9 standard fairing with a 5:1 barrel to gore ratio for a maximum volume of tanks.

A sensitivity analysis was performed to determine maximum available volume by seeking a maximum number of barrel length tank. In this case, the overall producible volume was looked into by only having a single column of gore panels. While the overall number of lander tanks decreased, the overall maximum available volume increased as shown in Figure 10. Note additional optimization could be performed on tank sizing and panel distribution.

These steps were repeated for the maximum size configuration for a SLS Block 1B 8.4m Short payload fairing as seen in Figure 11.

Table 4. 3:1 barrel to gore panel ratio for SLS Block 1B 8.4m short payload fairing.

Barrel Panels per Row	12
Gore Panels per Row	4
Number of Rows	97
Number of Total Barrel Sections	38
Number of Gore Pairs	32
Number of Lander Tanks	32
Lander Tank Volume	1892.2 m^3
Maximum Tank Volume (use all gore pairs and full barrels)	2205.1 m^3

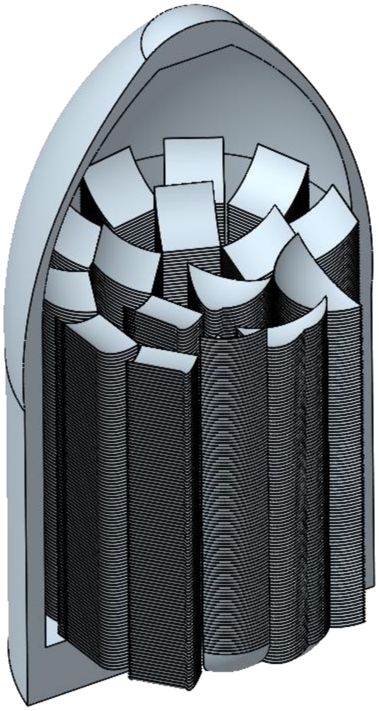


Figure 11. SLS Block 1B 8.4m short payload fairing with a 3:1 barrel to gore panel ratio for a maximum number of lander LH2 tanks.

Additional work would include optimizing packaging within given fairing volumes alongside sizing of the tank panels themselves. Future work into tank sizing for overall volume efficiency could also be performed. Future work into understanding how the panels would be held within the volume would also inform packing efficiency.

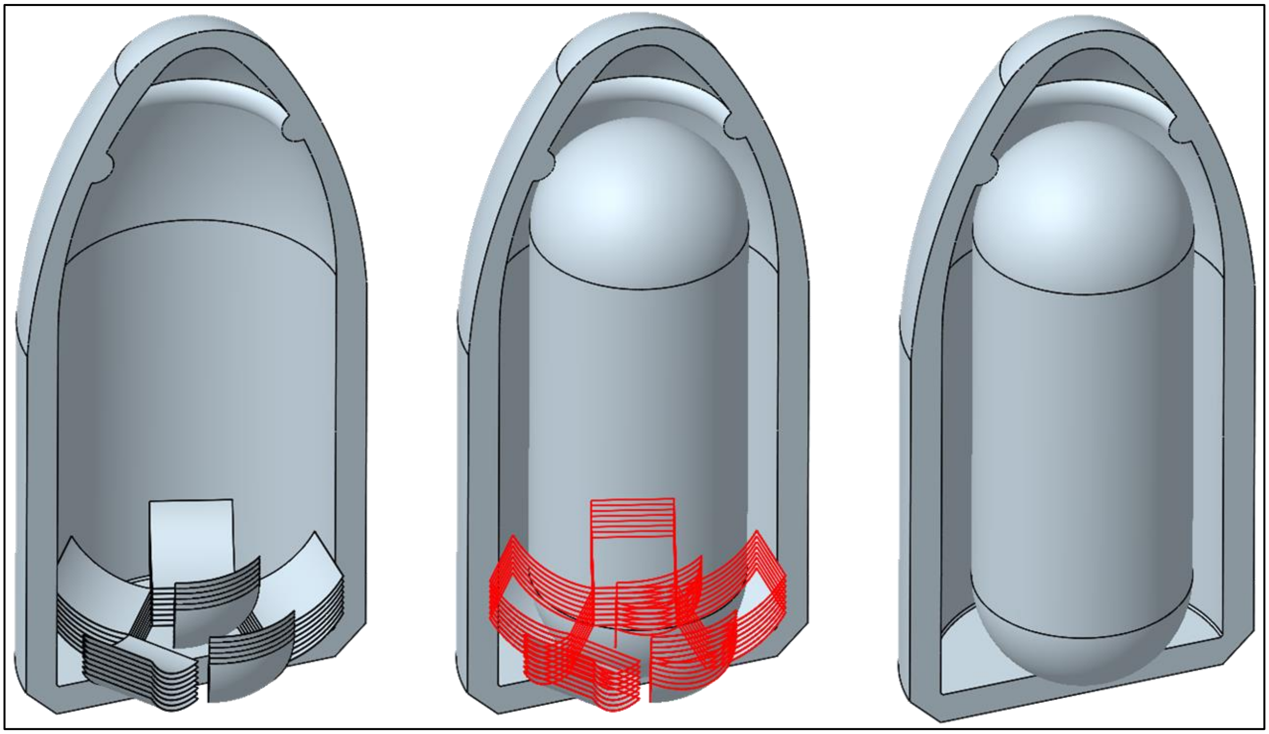


Figure 12. Comparison of same sized tank stowed as a set of panels (left); superimposed (middle); as a launched tank (right)

The packing efficiency was determined by comparing the amount of full volume Earth-launched tanks that fit into the launch vehicle versus the amount of completed tanks' worth of tank panels fit into the launch vehicle. Both tanks hold a volume suitable to refill one lander. For example, the Falcon 9 standard fits one Earth-launched LH2 tank but fits 30 barrel-segment panels and 12 gore-segment panels. This resulted in a roughly 24% packing efficiency, as shown in Figure 12. A similar analysis was performed for the much larger SLS Short payload fairing.

The packing efficiency for the metal wire was estimated using a visual estimation of an industrial wire spool and the physical properties of the material. This was due to time constraint and lack of knowledge of the state of the art. Metal wire spools on Earth are packed based on ease of use and industry standard. For a maximized, space-launched case it would make sense to forgo the spools and pack the metal wire into vacuum-sealed barrels in order to maximize the volume savings. We prioritized our qualitative analysis evaluations for our time with the subject matter experts, so unfortunately a detailed look into the limitations of this methodology did not happen for this phase of the trade study. Fortunately, in the future, a new packing efficiency can be determined and easily applied to the methodology with ease.

The packing efficiency volume percentages used were:

- Earth-Launched: 100%
- Tank Panels: 24%
- Metal Wire: 0.10%

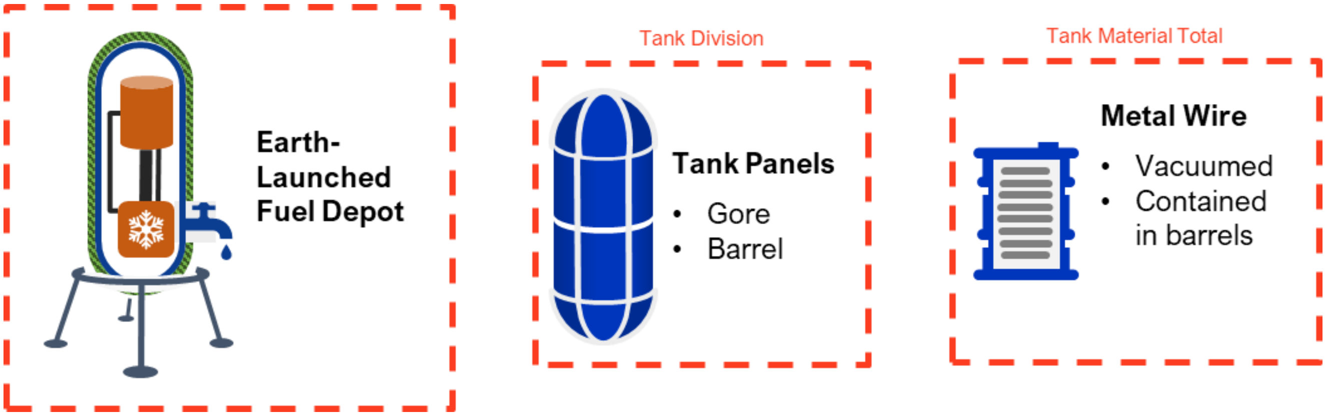


Figure 13. Visualization of the different launched Depot Tank options

In order to understand how the tanks and tank components would fit into the launch vehicles, we used the “Cargo Transfer Bag Equivalent” (CTBE) method. 3D packing and volume constraints of items is not a trivial problem to model and analyze, so we needed a zeroth-order approximation to stand in for further analysis. The CTBE method came from “Logistics Rates and Assumptions for Future Human Spaceflight Missions Beyond LEO”.

Table 5. CTB Mass and Volume Parameters

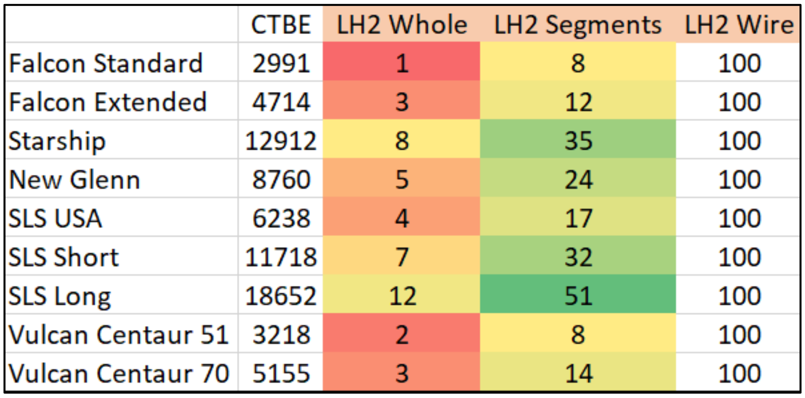
Item	Rate	Units
CTBE Mass	0.83	kg
CTBE Liner Mass	0.10	kg
CTBE Cargo Mass Limit	26.81	kg
CTBE Cargo Volume Limit	0.049 (1)	m^3 (CTBE)
CTBE External Volume	0.053	m^3

Table 6. Payload Cargo Transfer Bag Equivalent for traded launch vehicles.

Launch Vehicle	Payload Volume [m^3]	Payload CTBE
Falcon Standard	158.5562	2,991.63
Vulcan Centaur 51 ft	170.56392	3,218.19
Falcon Extended	249.84439	4,714.04
Vulcan Centaur 70 ft	273.25149	5,155.69
SLS USA 8.4 m	330.62272	6,238.16
New Glenn	464.282	8,760.04
SLS Short 8.4 m	621.082	11,718.53
Starship	684.345	12,912.17
SLS Long 8.4 m	988.570	18,652.26

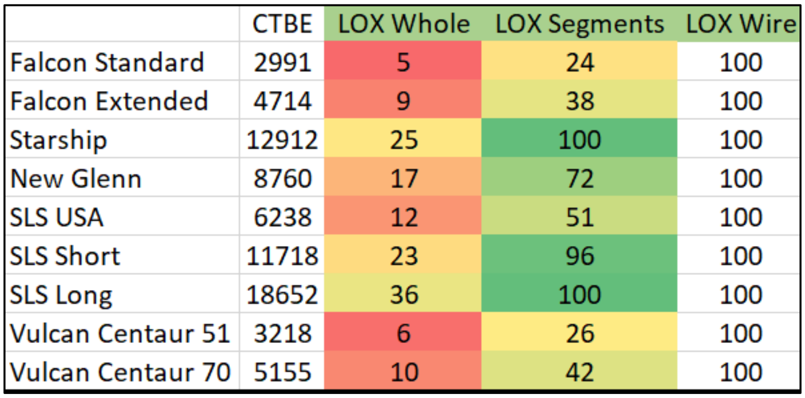
Now it is time to combine all the elements of the previous sections. The tank capacity sweeps were rerun with the CTBE convention and the packing efficiency assumptions for the tank segments and wire spools. This was compared to the CTBE capacity of each launch vehicle in order to show the largest tank capacity (measured in number of total lander refills) that could fit onboard each launch vehicle. For example, this shows that a single tank that is large enough to refill eight landers with LH2 could fit in the Starship (as shown in row three of LH2 Max Tank Capacity per Launch Vehicle for each packing method, Table 7).

Table 7: LH2 Max Tank Capacity per Launch Vehicle for each packing method



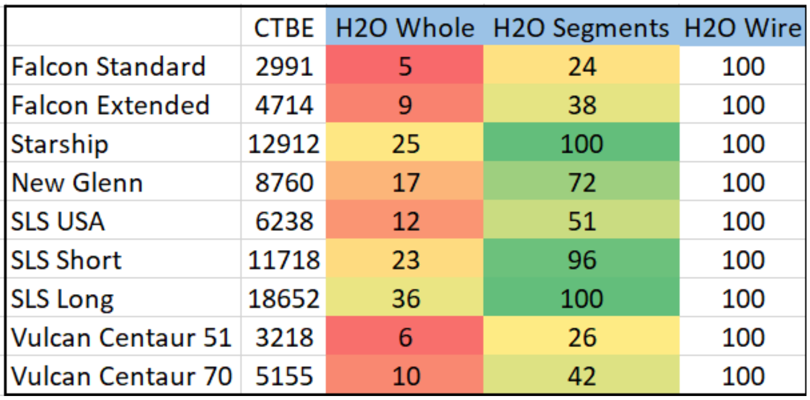
	CTBE	LH2 Whole	LH2 Segments	LH2 Wire
Falcon Standard	2991	1	8	100
Falcon Extended	4714	3	12	100
Starship	12912	8	35	100
New Glenn	8760	5	24	100
SLS USA	6238	4	17	100
SLS Short	11718	7	32	100
SLS Long	18652	12	51	100
Vulcan Centaur 51	3218	2	8	100
Vulcan Centaur 70	5155	3	14	100

Table 8: LOX Max Tank Capacity per Launch Vehicle for each packing method



	CTBE	LOX Whole	LOX Segments	LOX Wire
Falcon Standard	2991	5	24	100
Falcon Extended	4714	9	38	100
Starship	12912	25	100	100
New Glenn	8760	17	72	100
SLS USA	6238	12	51	100
SLS Short	11718	23	96	100
SLS Long	18652	36	100	100
Vulcan Centaur 51	3218	6	26	100
Vulcan Centaur 70	5155	10	42	100

Table 9: H2O Max Tank Capacity per Launch Vehicle for each packing method



	CTBE	H2O Whole	H2O Segments	H2O Wire
Falcon Standard	2991	5	24	100
Falcon Extended	4714	9	38	100
Starship	12912	25	100	100
New Glenn	8760	17	72	100
SLS USA	6238	12	51	100
SLS Short	11718	23	96	100
SLS Long	18652	36	100	100
Vulcan Centaur 51	3218	6	26	100
Vulcan Centaur 70	5155	10	42	100

Looking at the results, we can see that the segments have a significant packing advantage over the fully Earth-launched tanks. Even further, the wire spools were never constrained volumetrically. The maximum volume capacity of the analysis was 100x and the wire spools far exceed that by a large margin. The mass limits for all three options will be explored in future work, due to time and budget constraints.

Combining the Qualitative and Quantitative Analyses

Aggregating the qualitative and quantitative results requires a method to normalize the metrics calculated from the sizing and packing analysis with the AHP scores. From the quantitative analysis, the capacity of the storage tank (tracked by how many landers it can refuel) per launch is the representative FoM that captures differences due the tank material form factor, as constrained by the fleet of launch vehicles in the trade space.

The final trade space for the overall evaluation is defined by:

- Manufacturing Technique
- Tank Fluid Type
- Launch Vehicle

The final set of FoMs used in evaluation are:

- Size and Amount of Required Infrastructure
- Degree of Manufacturing Risk
- Infrastructure Lunar Power Demands
- Manufacturing Process Complexity
- Intricacy of Equipment Deployment
- Rate of Production and Deployment
- Reliance on Low TRL Capabilities
- Size Limit of Process
- Size of Tank per Launch

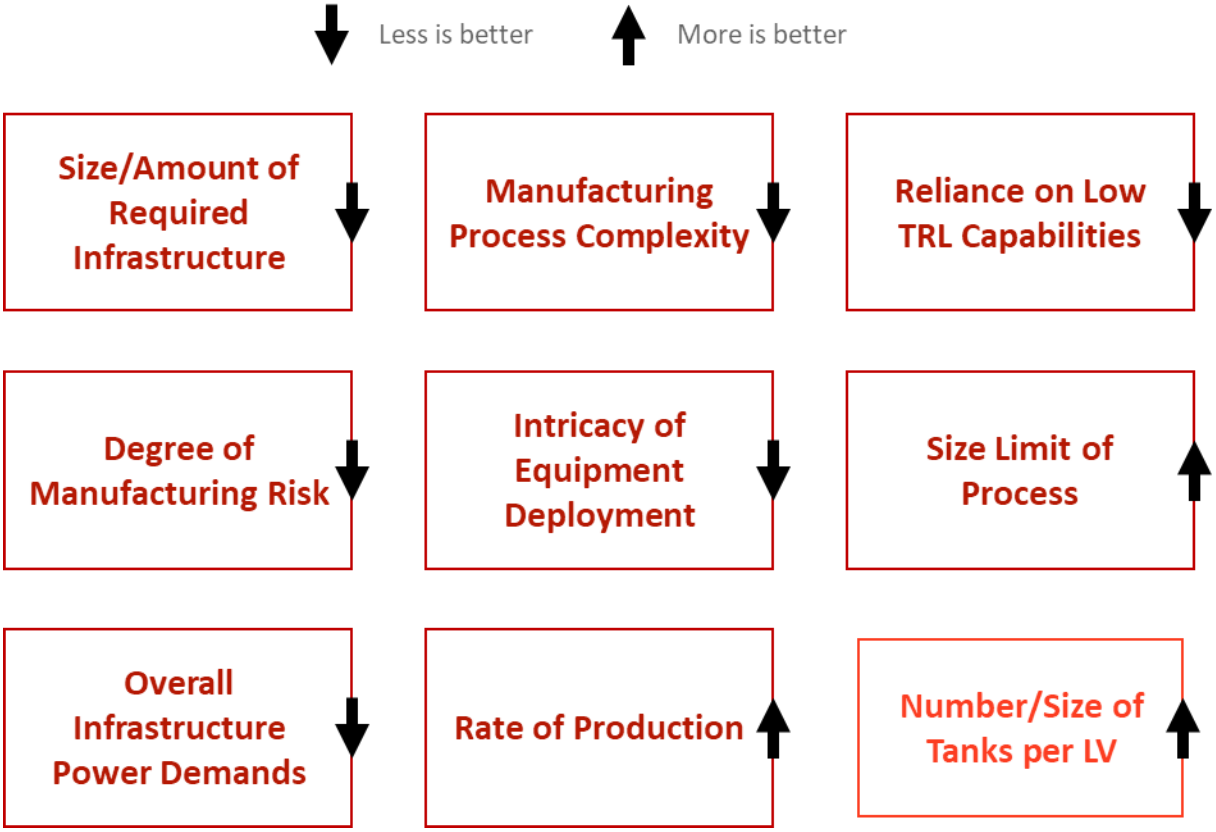


Figure 14. Full Trade Space Figures of Merit

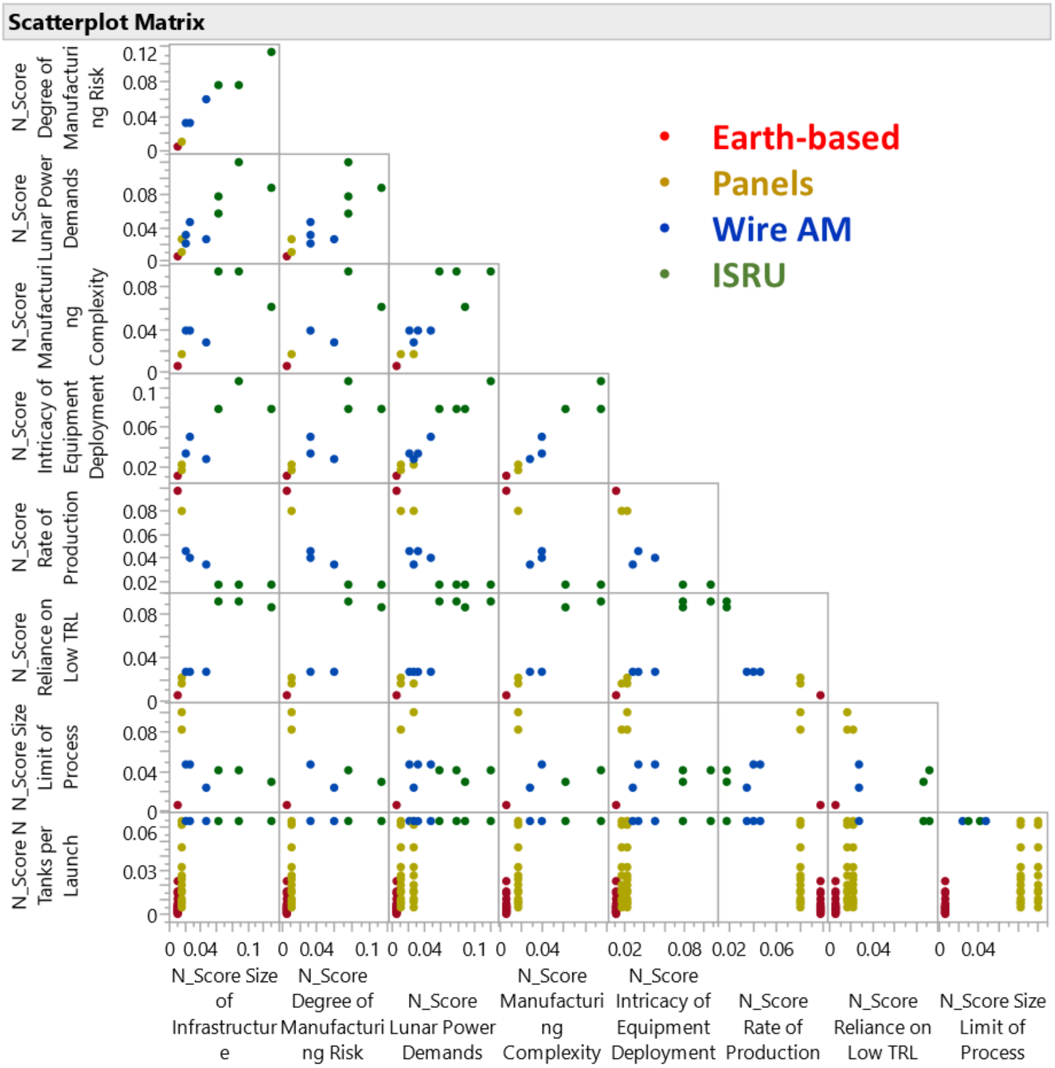


Figure 15. Scatterplot matrix depicting different figures of merit against one another.

The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is a multi-criteria decision analysis method, used to aggregate and evaluate the alternatives as documented in the paper by Prasahd et al (Prasadh, et al., 2014). This method allows for a parametric and compensatory tradeoff of alternatives, rather than a flattened score that does not consider how each FoM may be valued differently depending on real-world context influencing a decision-maker. For example, the cost of different launch vehicles might render the size of the tanks per launch dominating metric; otherwise, the desire to have lunar manufacturing as quickly as possible might weigh the reliance on Low TRL capabilities, Intricacy of Equipment Deployment, and Size and Amount of Required Infrastructure FoMs highly instead. TOPSIS combines the values for all relevant FoMs, normalizes them as a score, adjusts the scores with weights denoting priorities or preferences, before ranking each option based on a geometric proximity to an ideal solution formed from the dataset.

Firstly, the trade space combinations for evaluation are enumerated for sweeping through the qualitative and quantitative analyses, resulting in 324 combinations. For this trade study, the qualitative results are only affected by the selection of manufacturing technique, so the AHP results can be recorded separately in the overall data table. Each FoM requires 66 pairwise comparisons for all the alternatives, resulting in 528 total pairwise comparisons to calculate the 96 entries of AHP score. As for the tank size at launch FoM—this metric depends on the tank form factor for the manufacturing technique (three options if not including the ISRU option), tank fluid (three options), and the selected launch vehicle (nine options), resulting in running 91 cases for the quantitative analysis.

The combinations and FoMs create a decision matrix D, with size corresponding to the number of combinations multiplied by the number of FoMs. Let a given combination of alternatives—manufacturing technique, tank fluid, launch vehicle—be denoted i in the set I of trade space combinations; let j be a FoM in the set J of trade study FoMs. Each D_{ij} entry in the decision matrix is either populated by the AHP score or tank size per launch FoM. The normalized decision matrix R is calculated from D, where each entry D_{ij} is normalized by the root-square-sum of its column so that:

$$R_{ij} = \frac{D_{ij}}{\sqrt{\sum_i D_{ij}^2}}$$

For each FoM, a weight w_j is assigned to denote its priority and all the weights are collated into a weight vector w. These weights can use any value model that is desired, and their adjustments result in parametric scoring of the trade space; for this study, the values 1-3-9 were used to denote low-medium-high priority for each FoM. A weighted normalized decision matrix T uses the weight vector W to modify the normalized decision matrix R:

$$T_{ij} = \frac{w_j}{\sum_j w_j} R_{ij}$$

Each column of the weighted normalized decision matrix T is used to form two vectors representing the “best” and “worst” values of each FoM. Vectors A^b and A^w form the ideal and negative ideal solutions for the dataset, respectively. Each trade space combination i determines its positive distance and negative distance—S^+ and S^-—using T_{ij}:

$$S_i^+ = \sqrt{\sum\nolimits_j \left(T_{ij} - A_j^b\right)^2} \qquad S_i^- = \sqrt{\sum_j \left(T_{ij} - A_j^w\right)^2}$$

The relative closeness C_i to the ideal solution S^+ is determined with a combination of both the positive and negative distances:

$$C_i = \frac{S_i^-}{S_i^- + S_i^+}$$

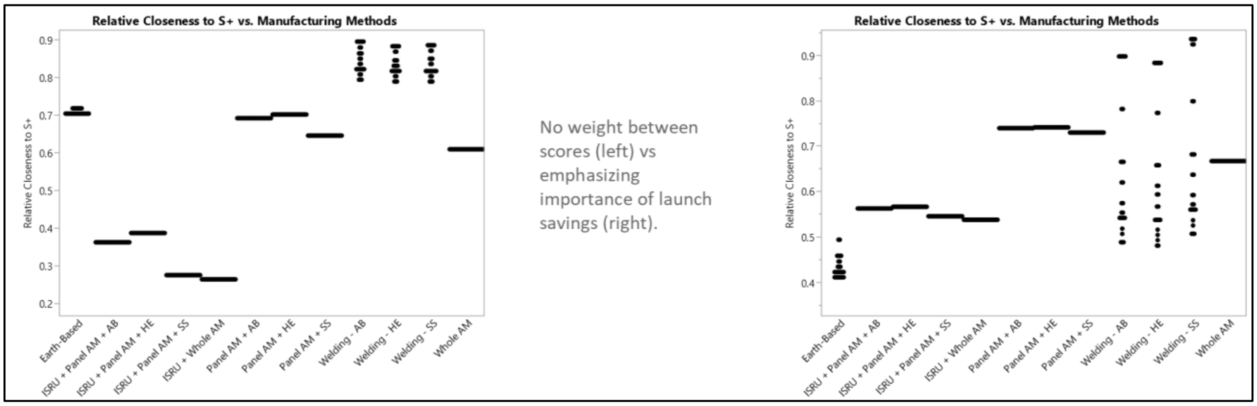
Relative closeness C_i is used as the final scoring metric in this methodology, with a higher closeness being the higher ranked alternative. In using TOPSIS, adjustments can be made to the qualitative and quantitative analysis, as well as the weight of the FoMs, for a fully parametric multi-criteria evaluation that would be reflected in the change in relative closeness as the scoring metric. It’s possible that through multiple criteria, some options may be equivalent; this methodology can generate a pareto front of alternatives as well; it is also possible that a specific dataset does not have a pareto front.

Trade Study Initial Results

As demonstrated in the methodology breakdown, this report's fully parametric multi-criteria evaluation allows for analyzing across multiple success criteria. With purely AHP based scoring, the Earth-based options would dominate based on the study's current information and FoM decomposition (FoM shown in

Figure 14 above). This is likely due to Earth-based options dominating across the current set of FoM without any weighting being applied to tip the scales. However, if launch savings was the dominant FoM, in-space AM options would dominate.

This can be shown in further detail by considering Figure 16. As shown on the left of Figure 16 without any weights, the closeness to S+ (ideal case across all FoM) heavily favors welding panels without much disparity across the different welding techniques. However, when emphasizing launch savings as shown on the right in Figure 16, the trade-space alternatives across the various Earth-launched panels, in-space welded configurations expands. Now the specific launch vehicle and tank being manufactured does influence the results. Smaller tanks and larger launch vehicles require overall a smaller number of launches weighting those parameters to be closer to the S+ case.



No weight between scores (left) vs emphasizing importance of launch savings (right).

Figure 16. Trade study design space exploration. No weight between different scores (left) vs emphasizing importance of launch savings (right)

Leaving the launch FoM as number/size of tank launched as a means of rolling up different launch vehicle constraints based on the most limiting physical capacity (vol or mass). The value of that FoM is part of the Pareto front—in different scenarios of launch vehicle availability, or launch costs, or needed cadence. These results can be weighted and filtered in accordance to one's interpretation.

Take the TOPSIS grouped scoring shown in

Figure 17 for example. This weighting favored launch savings and less reliance on low TRL. By favoring launch savings, Earth-based launched tanks performed especially poorly. It is worth noting that the LH2 tanks were much larger volumetrically, and therefore performed even worse. Preferring less reliance on low-TRL options made ISRU less attractive as well. Instead, Earth-manufactured and launched panels performed the best when relying on the largest launch vehicles (SLS and Starship options). Whereas, if the larger launch vehicles were not available, ISAM panels welded together would be more favorable as they would both limit the number of overall launches required without relying on ISRU technologies. With this weighting method, there is not a lot of difference in scoring between AM and ISRU methods since there is not a significant difference in launch vehicle volume needs across the alternatives.

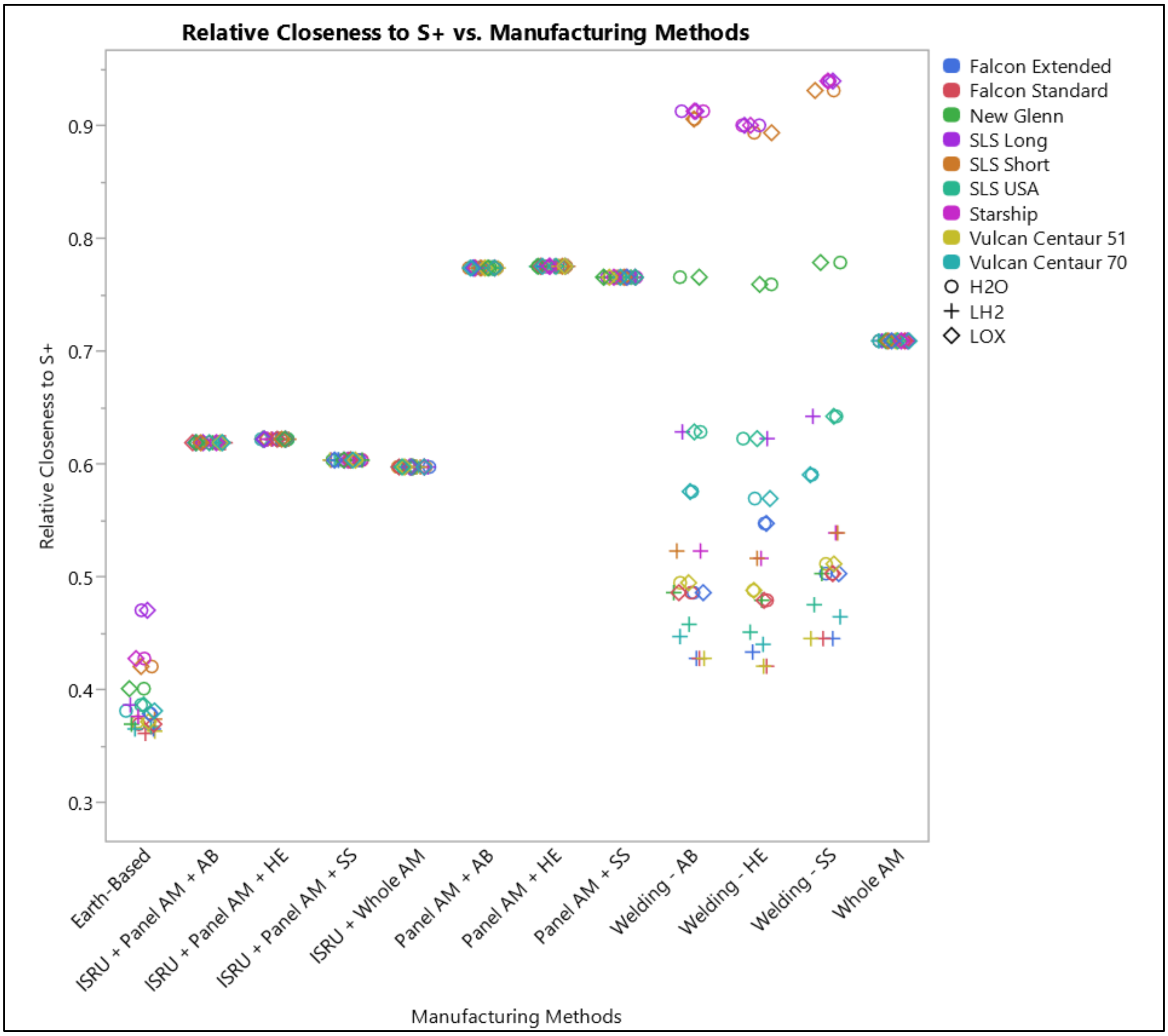


Figure 17. TOPSIS Scoring grouped by trade space related to closeness to S+ (ideal solution)

Conclusions and Recommendations

Conclusions

The goal of this trade study was to provide an initial framework and preliminary trade results for assessing a complicated and uncertain trade space with both quantitative and qualitative criteria. The trade study approach allows for revisiting the results as breakthroughs occur in advanced manufacturing capabilities. As such, the scoring can be readjusted with more polling and suggested weights. Some figures of merit can gain enough certainty to obtain quantitative results. More granular figures of merit can be defined to further understand and capture the trade space and differentiate the alternatives.

Future Work

This trade study was performed such that the inputs could be refined in the future. Many details were not dug into in depth due to time or manpower reasons. For example, a more in-depth qualitative discussion with a larger swath of EM experts (potentially including panel scoring) was desired towards the end of the trade study but was not able to be executed. This would've been beneficial due to a larger diversity of opinions and expertise.

A better understanding of wire packing efficiency would increase the fidelity of the packing analysis. What would a bundle or barrel of aluminum wire look like when packed for this mission? Is there a theoretical limit of how tight the wire can pack? Metal wire spools on Earth are packed based on ease of use and industry standard. For a maximized, space-launched case it would make sense to forgo the spools and pack the metal wire into vacuum-sealed barrels in order to maximize the volume savings. We prioritized our qualitative analysis evaluations for our time with the subject matter experts, so unfortunately a detailed look into the limitations of this methodology did not happen for this phase of the trade study. Fortunately, in the future, a new packing efficiency can be determined and easily applied to the methodology with ease.

Additional fidelity could be incorporated into the model by looking at structural concerns between the various tank manufacturing methods. This would include launch load impacts on both sizing of traditionally manufactured tanks and its impacts on Earth-launch panels. Sizing impacts could result in larger launch structures versus ISAM or ISRU ISAM tanks as launch loads may impact the sizing of the available panels. However, perhaps panel sizing would not be impacted much by launch loads compared to ISAM panels. Additional understanding of the impacts of launch loads on the sizing of the panels would be helpful in improving the fidelity of the analysis.

A more detailed understanding of thermal impacts on the tanks would also improve the study. This is especially important for stowage of cryogenic propellants and what the CONOPS would be for providing adequate thermal insulation to tanks manufactured in the space environment. Looking into multi-layer insulation (MLI) manufacturing and application methods and how they would apply to in-space applications would improve in understanding a comparison between Earth-based manufacturing processes versus in-space manufacturing.

Additional hardware integration CONOPS would need to be identified for in-space manufactured tanks. Additional hardware such as valves, active cooling, pumps, ducts, etc. along with related interfaces would need to be attached to the in-space manufactured tanks somehow. Future studies could look into how additional hardware is delivered to in space storage versus using a pre-launched tank dome with all necessary hardware already attached and then joined in space. Studies could also look into additional complications with integrating hardware essential for operating tanks.

Begin discussions with ISRU group to better understand how ISRU would factor in. Actual ISRU analysis was outside of scope and budget for this trade study. The study only factored in ISRU at a high level with respect to the in-space welding and in-space additive manufacturing methods. For instance, for the complexity FoM, the complexity of launching the tank was compared to the complexity of welding the tank segments, the complexity of performing AM to make the tank segments before welding them, and the complexity of utilizing pre-existing ISRU material into wire suitable for performing AM to make the tank segments before welding them together. In other words, the trade study factored in additional complexity needed for ISRU implementation but was unable to dig into details beyond those on the surface level.

Acknowledgements

Special thanks to the following subject matter experts who contributed to this trade study:

Ilana Lu (MSFC, EM42)
William Evans (MSFC, EM32)
Parker Shake (MSFC, EM42)

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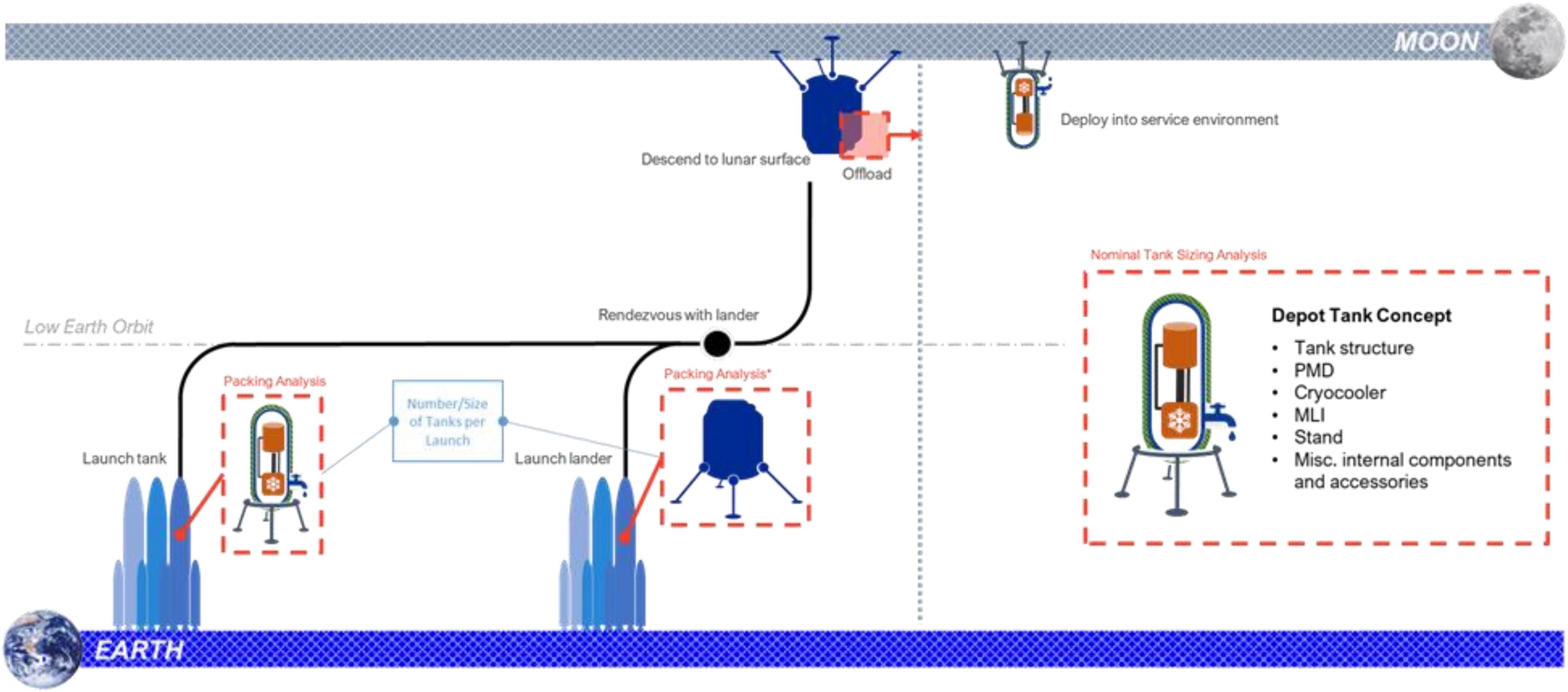
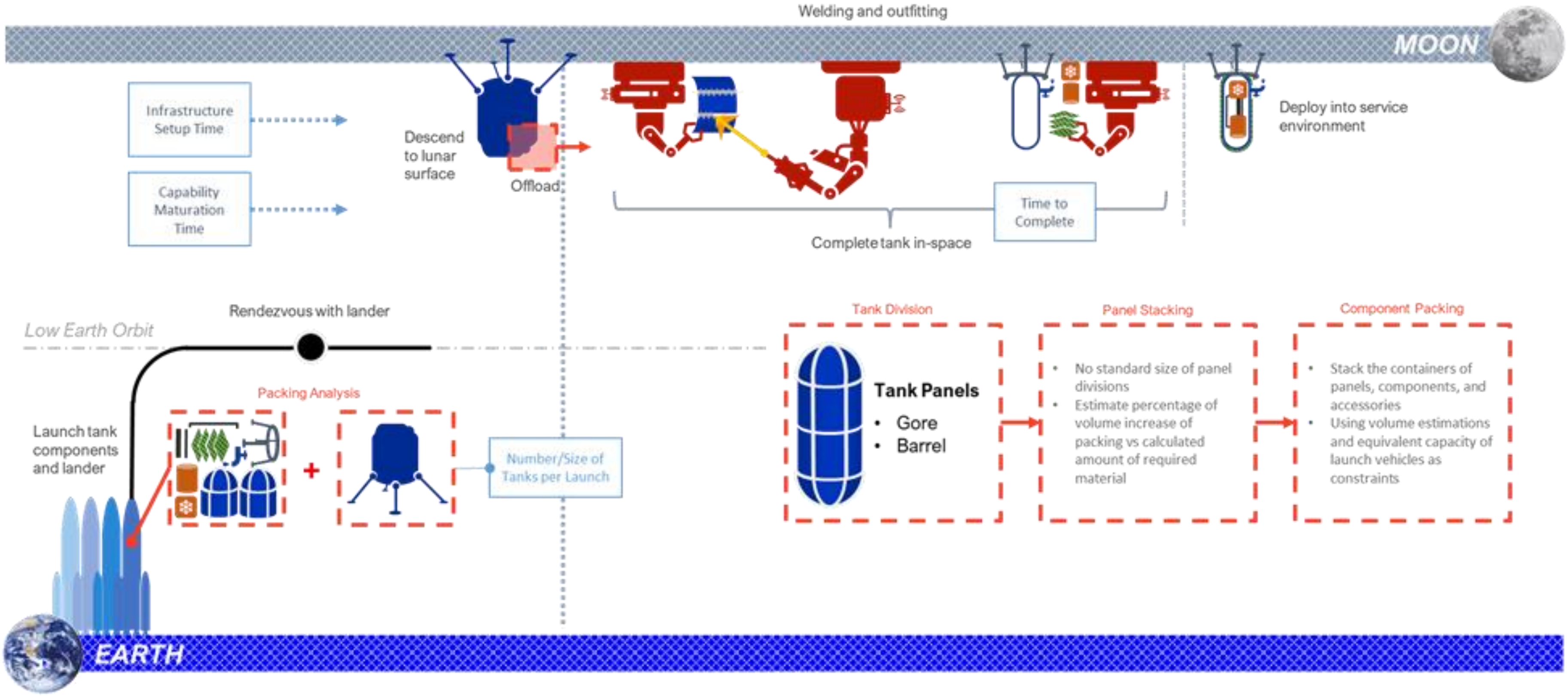
Appendix A – Enlarged Graphics



Earth-Launched Depot Tank ConOps



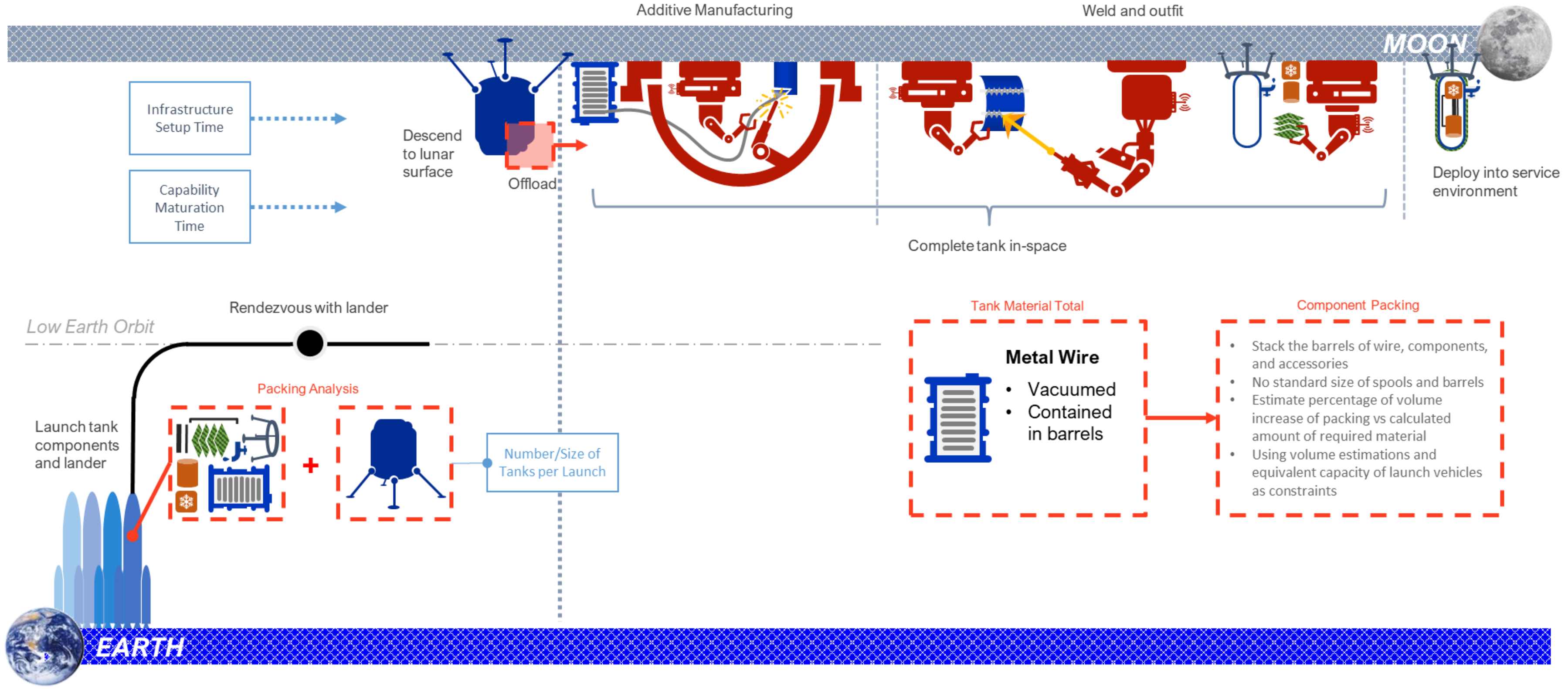
Tank Panels

- Gore
- Barrel

- No standard size of panel divisions
- Estimate percentage of volume increase of packing vs calculated amount of required material

- Stack the containers of panels, components, and accessories
- Using volume estimations and equivalent capacity of launch vehicles as constraints

In-Space Welded Panel Depot Tank ConOps



Additive Manufacturing

Weld and outfit

MOON

Infrastructure Setup Time

Capability Maturation Time

Descend to lunar surface

Offload

Deploy into service environment

Complete tank in-space

Low Earth Orbit

Rendezvous with lander

Launch tank components and lander

Packing Analysis

Number/Size of Tanks per Launch

Tank Material Total

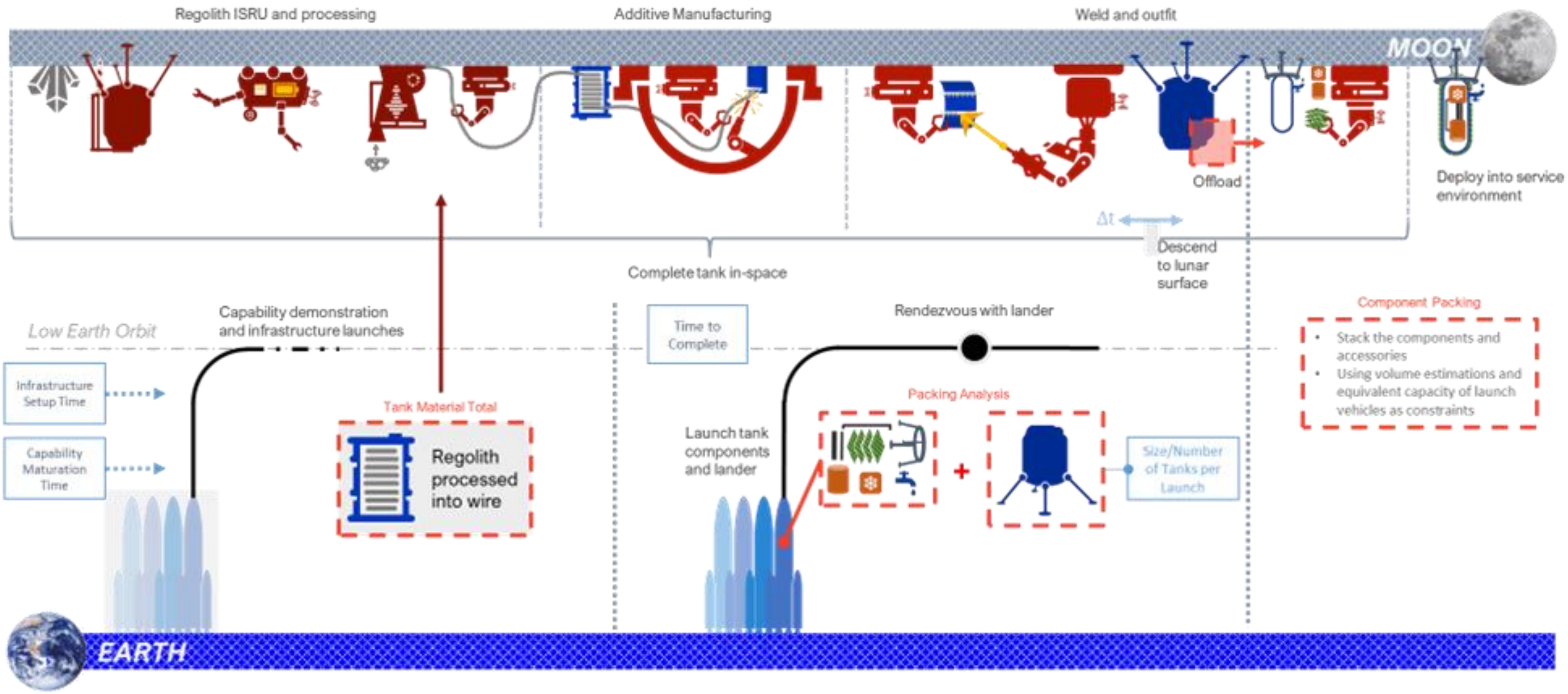
Metal Wire
- Vacuumed
- Contained in barrels

Component Packing

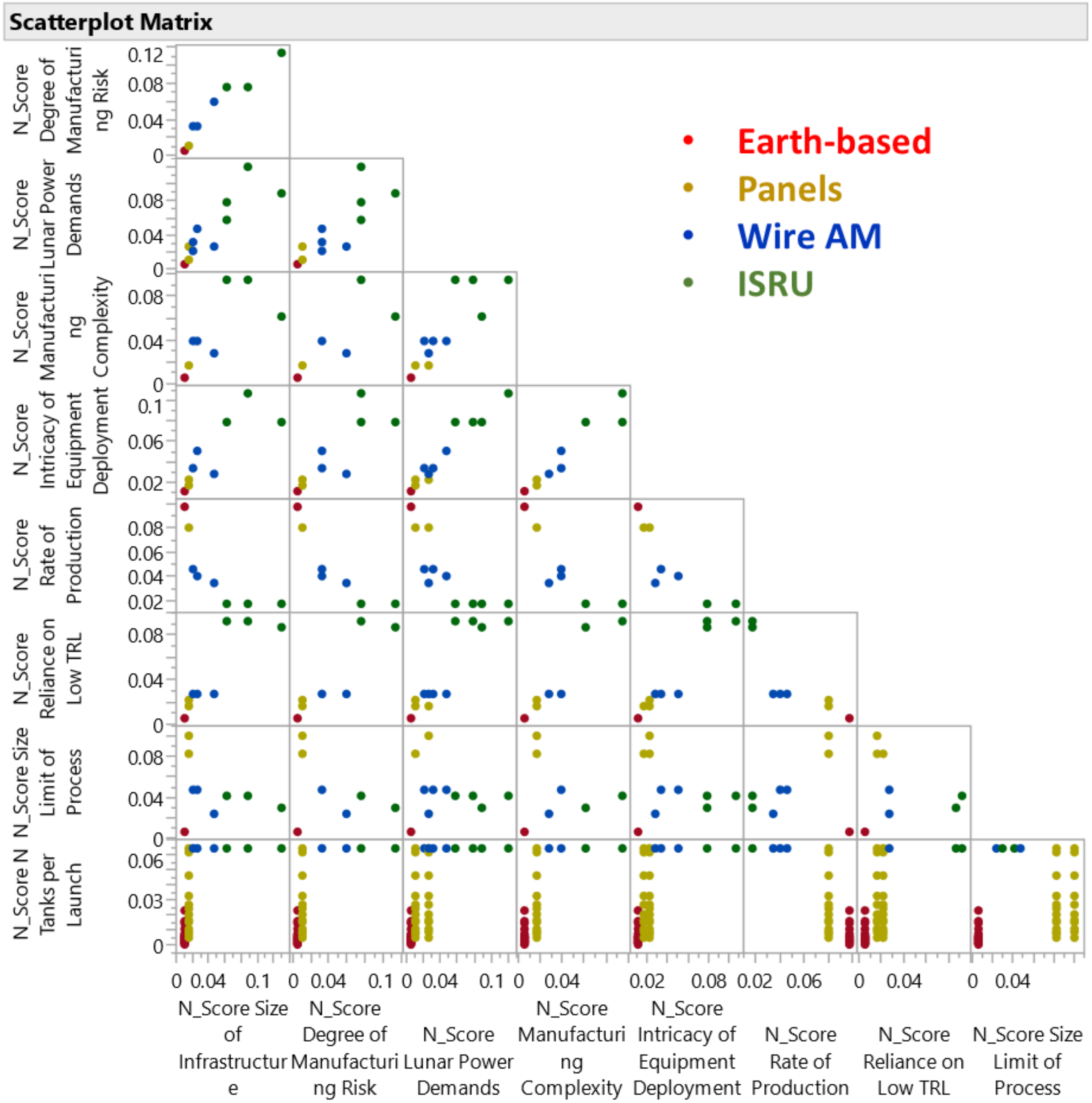
- Stack the barrels of wire, components, and accessories
- No standard size of spools and barrels
- Estimate percentage of volume increase of packing vs calculated amount of required material
- Using volume estimations and equivalent capacity of launch vehicles as constraints

EARTH

ISAM Depot Tank ConOps



ISRU-Derived ISAM Depot Tank ConOps



Scatterplot matrix depicting different figures of merit against one another