Space Architecture Design for Commercial Suitability: A Case Study in In-Situ Resource Utilization Systems

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Abstract

Space Agencies are increasingly interested in stimulating non-traditional players to participate more broadly in the space enterprise. Historically, high barriers to entry in the space market have included challenges of working with the government customer and high technical and financial risks associated with the complexity of space exploration. More recently, agencies have used inducements (e.g., new contracting mechanisms, access to testing facilities) to mitigate these barriers. While these efforts mainly focused on reducing barriers to participation in existing exploration architectures, this paper explores the viability of an alternative strategy. Instead of providing inducements, which essentially subsidize participation, we propose a new strategy for space agencies to treat "commercial suitability" as another "-ility" and make it an explicit criterion of the initial architecture selection. This can be an effective option when multiple equivalent architectures (as evaluated against traditional cost, schedule, and performance measures) differ on their "commercial suitability." As a proof-of-concept for this strategy, we develop a case study with lunar in-situ resource utilization plant systems as a basis for comparing the architectures with dedicated mass-wise optimal design (selected using traditional architecting strategies) vs. standardized mass-produced modular ISRU (selected using commercially-suitable strategies). The results show that architecture selection that considers commercial suitability upfront can achieve increased commercial participation without compromising cost performance compared with the baseline architecture. This serves as an existence proof for the potential value of this new strategy.

1. Introduction

For decades, it has been the policy of the National Aeronautics and Space Administration (NASA) to involve the commercial sector in space exploration. Around the start of the shuttle era (1981 – 2011), efforts to involve the commercial sector became more emphasized and eventually took two approaches. The first approach focused on encouraging the development of capabilities that are only possible due to the space program, applying capabilities developed in the space program to terrestrial use, and fostering markets for those capabilities. The second approach focused on promoting and maintaining the industrial base for space transportation by committing NASA to be an anchor tenant (core customer) of companies developing unique capabilities.

To lower barriers associated with the federal acquisition process, which affect all commercial interactions, NASA has also explored alternative contracting mechanisms that reduce the burden of working with the government. For example, in 2005, NASA developed the Commercial Orbital Transportation Services (COTS) program, which evolved into the Commercial Resupply Services and the Commercial Crew Program. Based on the success of these programs, NASA established the Commercial Lunar Payload Services (CLPS) in 2019. Both programs rely on NASA remaining an anchor tenant of the services.

To date, NASA's efforts to induce more commercial participation in space system development have focused on reducing barriers to entry. These are important and have resulted in successes to some extent including enabling acquisition of core capabilities like a lunar lander through commercial acquisition methods. However, these efforts focus on reducing barriers to, and motivating participation in, existing exploration architectures.

In this paper, we offer an alternative, complementary, approach to inducing commercial participation that relies on increasing the inherent value of participation. If a government agency (e.g., NASA) explicitly considers commercial capabilities and interests during the systems architecting process, and it chooses architectures that create opportunities for commercial involvement, then commercial participation should increase, independent of explicit inducements. We call this strategy architecting for "Commercial suitability," as a nod to other "-ilities" (e.g., flexibility [1-3], survivability [4-5]) which are an active area of systems architecture research more broadly. Commercial suitability can be an important criterion for initial architecture selection. It is particularly effective when there exist multiple, otherwise equivalent, "best" architectures (as evaluated against traditional cost, schedule, and performance measures) that differ on their "commercial suitability." The key question would be: among the "best" options, are there differences in commercial suitability that can be exploited?

As a proof of concept demonstration that this approach can be valuable, this paper performs a case study comparing architecting strategies for the In-Situ Resource Utilization (ISRU) systems for space exploration. We compare a baseline scenario – wherein the ISRU plant is sized optimally for the given mission, as is typically done – to one that is formulated with a commercial suitability perspective – where priority is given to fixing the unit size (i.e., standardization) and modularizing the system to enable more commercial contributions through a simpler interface and by stimulating mass production. As a result, we find that the impacts of the learning curve effects enabled by standardization in the commercially-suitable architecture can potentially outweigh the inefficiencies from the (mass-wise) suboptimal sizes of the modules. In fact, depending on the assumptions about the learning curve effects, the standardized modular architecture can even reduce overall mission costs from the baseline one, besides providing other system-level benefits such as redundancy. Thus, this case study demonstrates the existence of the architectures that endogenously motivate commercial participation, without compromising on other traditional cost metrics for the agency.

We believe the proposed new space mission strategy can introduce a paradigm shift from identifying the role of commercial players in a given space architecture to designing a commercially-suitable space architecture where commercial players can be leveraged optimally and thus stimulate future space commercialization.

The remainder of the paper is organized as follows. In Section 2, we review NASA's space commercialization strategy. In Section 3, we discuss the proposed concept of commercial suitability and its associated strategy. Section 4 introduces a proof-of-concept of the proposed strategy in the context of lunar ISRU. Finally, we conclude this paper in Section 5 with a discussion of the proposed framework and future work.

2. Review of NASA's Space Commercialization Strategy

Before introducing our concept of space architecture design for commercial suitability, we review the history of NASA's space commercialization strategies.

2.1 Brief History of NASA's Commercial Engagement

Around the start of the Space Shuttle era (1981 – 2011), efforts to involve the commercial sector became more emphasized and eventually took two approaches: 1) directly investing in capabilities intended solely for use in space and 2) maintaining the health of the space industrial base. Both approaches have required substantial subsidies on the part of NASA. The emphasis was not on the incorporation of commercial capabilities into space exploration endeavors beyond the defense-type contracting mechanisms already in place [6].

The first approach focused on encouraging the development of capabilities only possible because of the space program, applying capabilities developed in the space program for terrestrial use, and fostering markets for those capabilities. In 1979, NASA issued the "NASA Guidelines Regarding Early Usage of Space for Industrial Purposes" [6]. As indicated by the title, the emphasis of these guidelines was to encourage companies to use NASA resources. Specifically, the guidelines outlined three incentives for companies: "Providing flight time on the Space Shuttle; Providing technical advice, consultation, data, equipment, and facilities; and Entering into joint research and demonstration programs with NASA and the private sector partner funding their own efforts" [6]. These guidelines formed the basis of the 1984 National Policy on the Commercial Use of Space, introduced under the Reagan administration. The emphasis of the 1984 National Policy was on technology transfer – encouraging companies to find terrestrial applications for technologies originally developed for the space program [6]. This commercial use of space policy emphasized a flow of capabilities from those developed for space to companies that sold them on Earth; therefore, it promoted the development of new capabilities only possible because of access to the space environment.

The second approach focused on promoting and maintaining the industrial base for space transportation by committing NASA to be an anchor tenant of companies developing unique capabilities. Just before the shuttle era ended in 2011, the current 14-page National Space Policy was published with a full-page section on commercial space guidelines. The first bullet of the guidelines emphasizes that the government shall "purchase and use commercial space capabilities and services to the maximum practical extent" [7]. The space policy goes on to direct the government to refrain from competing with the private sector [7]. As stated in the pricing policy for the International Space Station (ISS) commercialization, "NASA is restricted from competing with the U.S. private sector; therefore, if, at any point, a U.S. Entity is available to provide any of these resources, NASA shall, to the best of its ability, migrate the provision of such services to the non-U.S. government provider" [8]. The National Space Policy "sets forth the goal of energizing and enhancing a competitive U.S. domestic space industrial base" [9]. The existence of a marketplace for the space industrial base is simply assumed in the 2010 National Space Policy.

2.2 Incentivizing Commercial Participation by Lowering Barriers

Federal acquisition regulations are notoriously difficult to work with to the point that companies create segregated portions of their business in order to work with the government. A 1992 paper on Department of Defense acquisitions of commercially available aircraft and airframes [10] reveals that acquisition methods that include the following discourage companies from selling to the government even when they produce and sell the capability in the commercial market:

- requirements peculiar to the government
- excruciatingly detailed product descriptions
- accounting requirements imposed by the government
- layers of bureaucracy and oversight
- lack of uniformity in contracts
- existence of onerous clauses in the contracts

If they do sell to the government, companies often will create a segregated portion of their business to protect against the costs of doing business with the government affecting the commercial side of their business [10].

The regulatory and policy requirements of the federal acquisition regulations create a barrier to entry that increases the cost of doing business with the government [10]. The government is then put in the position of compensating for that barrier by paying more for an otherwise commercially available capability and/or by providing incentives to companies to sell to the government.

The 1992 paper, as well as others throughout the years, have argued that the government should use a commercial-style acquisition process for commercially available capabilities [10]. Such an acquisition process would be free of the onerous requirements and overhead typical of the federal acquisition regulations, thus lowering the barrier to entry for companies seeking to sell to the government and lowering the cost for the government to acquire commercially available capabilities [10].

In an effort to lower barriers associated with the federal acquisition process and reduce the financial burden on the government, NASA developed the Commercial Orbital Transportation Services (COTS) program in 2005 [11]. The success of these programs has prompted a similar approach for the lunar exploration plans. Named the Commercial Lunar Payload Services (CLPS), it calls for the contractor to "provide all activities necessary to safely integrate, accommodate, transport, and operate NASA payloads using contractor-provided assets, including launch vehicles, lunar lander spacecraft, lunar surface systems, Earth re-entry vehicles, and associated resources" [9]. The request leaves the means quite open so that the contractor is free to choose how to develop or purchase the sub-capabilities. Similar to COTS and Commercial

Crew at their starts, CLPS is fostering capabilities that have not yet been proven but that likely can be in the near term. In 2015, some of the NASA employees who had developed the COTS idea proposed what essentially became CLPS in a conference paper [11]. Calling the concept Lunar COTS or LCOTS, they highlighted the similarity it had to COTS and the benefits it could bring. As with COTS and as is likely to be true of CLPS, the assumption was that NASA would be an anchor tenant of the technologies developed [11].

3. New Concept: Architecting for Commercial Suitability

To date, NASA's efforts to induce more commercial participation in space system development have focused on reducing barriers to entry. This paper proposes an alternative, complementary approach that relies on increasing the inherent value of participation through architecture selection. We contend that if NASA explicitly considers commercial capabilities and interests during the systems architecting process and chooses architectures that create opportunities for commercial involvement, participation will increase, independent of explicit inducements. We call this strategy architecting for "Commercial suitability," as a nod to other "-ilities" (e.g., flexibility, survivability) which are an active area of systems architecture research more broadly.

It may sound counterintuitive that systems' architects would choose to constrain their own design space, but it is not as radical as it seems. On the high complexity end of the spectrum, system designers are keenly aware of available launch envelopes and design their systems within those constraints. On the low complexity end of the spectrum, there is clear guidance on which COTS electronics are suitable for use in space systems based on their qualification and quality control procedures [12]. The reason for constraining designs can be different: for example, in the launch vehicle case, it would be prohibitively expensive to customize launch services for each mission, so the relatively few available volumes are taken as fixed; in the context of the electronic parts, the space sector is a relatively small customer and does not have the market power to request specialized components. Thus, either space organizations can work with what is available commercially or can take on the substantial cost of developing a unique space electronics market – the result is the same: designers take the available options as given, and architect around them.

With a strategy of architecting for commercial suitability, we suggest that this approach be applied to a larger set of design decisions. Examples of such a commercialization strategy include picking a specific size for a module (e.g., power system) that is common to multiple missions and or has the same interface characteristics as existing terrestrial applications. This is a way to leverage the broader terrestrial market and enable economies of scale in the space market.

Commercial suitability can be an important criterion for initial architecture selection and a particularly effective option when multiple equivalent architectures differ only on their "commercial suitability." Thus, a commercially-suitable architecture is only chosen if the cost of the constraint (i.e., the impact of choosing to design around a fixed standardized size or interface on performance) is balanced by the potential benefit of the constraint (i.e., either the social value of increased commercial participation, or the future benefits of reduced costs and or risk reduction). We believe that there are many potential instances where the future gain is sufficient to justify the choice on the basis of traditional performance measures. As an existence proof of this concept, this paper selects an example – ISRU systems – and demonstrates that with moderate learning effects, the choice to fix (i.e., standardize) ISRU sizing can both create a commercial market and deliver value to a government customer.

4. Proof-of-Concept Case Study: Lunar ISRU

As a proof of concept for the proposed space commercialization strategy, we consider the case of lunar ISRU systems for exploration. ISRU is chosen because it is a representative example of highly specialized technology that is typically optimally customized for each mission; our goal is to explore the value of standardization in this relatively conservative context.

Lunar ISRU has been considered as a promising technology for lunar and Mars exploration, and past studies have evaluated the value of ISRU [13-16]. Many such studies assumed that we can optimally choose the ISRU size dedicated to the mission.

However, the strategy of designing dedicated, one-time-only, ISRU systems for each mission may not be the preferred strategy from the commercial-suitability perspective. Rather, commercially-suitable architectures would give priority to fixing the unit size (i.e., standardization) to simplify commercial contributions. The standardized mass-producible ISRU units (i.e., also referred to as modules in this paper) can drive down the cost, stimulating the commercialization of the technologies for future missions beyond the particular mission of interest. For example, the proposed architecture enables future companies to purchase standard ISRU units and use it for their own missions, just like how CubeSats have become a new standard in the satellite development industry.

Despite the benefit of commercially-suitable standardization, the government agency would only choose this strategy when its benefit outweighs its cost. In this case study, we show that the commercially-suitable standardization can, in fact, potentially achieve a similar or lower cost compared with the traditional baseline architecture, leveraging the cost reduction due to mass production, which we model as learning curve effects.

4.1. Overview of the Case Study

We consider designing a lunar ISRU system to meet an annual demand of oxygen production: D [kg per year]. This value is considered to be 50,000 kg/year in this study, which falls under the range of the propellant demand in cislunar space for Mars space exploration [17]. We compare the following two approaches to achieve this demand:

(i) the dedicated optimally sized ISRU systems, which represent the traditional design approach (i.e., baseline): note that this solution is mass-wise optimal;

(ii) the standardized modular ISRU systems, which represent the commercially-suitable approach (i.e., new approach).

The metric for comparison is the cost. The cost and ISRU performance models are discussed in the following.

4.1.1. ISRU Cost Model

As discussed above, the ISRU cost model is based on a linear model. Since the nonrecurring cost for the ISRU plant applies to both cases equally, we do not consider that in our comparison. Nonlinear cost models can be considered for a more realistic analysis, which is beyond the scope of this paper.

For Case (i) evaluated with optimized ISRU, the specific cost is defined as α [$/kg].

For Case (ii) with modular ISRU systems, the learning curve effects are incorporated to represent the cost reduction caused by mass production [18]. Here, a standardized ISRU module mass is chosen and used in common for all missions to generate the given demand. The module cost p [$/unit ISRU] is constructed using the theoretical first unit specific cost α [$/kg] (i.e., the baseline specific cost), the mass m of the standardized ISRU module [kg], the learning rate r, and the number n of ISRU modules in the following way:

$$p = \alpha\, m\, n^{\log_2(r)}\,. \tag{1}$$

The total cost c of the batch of produced COTS ISRU systems is then obtained by multiplying the production cost rate by the number of produced ISRU systems:

$$c = p\, n = \alpha\, m\, n^{\log_2(r)+1}. \tag{2}$$

In the considered case study, the theoretical first unit specific cost $\alpha = \$40{,}000$/kg is used, and the module mass size m is varied. This value of α is consistent with Ref. [19], which gives the range of the first unit specific cost α of launch vehicles to be between $3,600/kg and $10,700/kg and that of manned spacecraft to be between $13,000/kg and $90,000/kg.

Fig. 1 illustrates the specific cost of ISRU modules (p/m) vs. the number of ISRU modules (n) at the theoretical first unit specific cost of α =$40,000/kg with different production learning rate r. An important observation from Fig. 1 is that savings in production cost are the most significant for the first few produced ISRU and for a lower production learning rate.

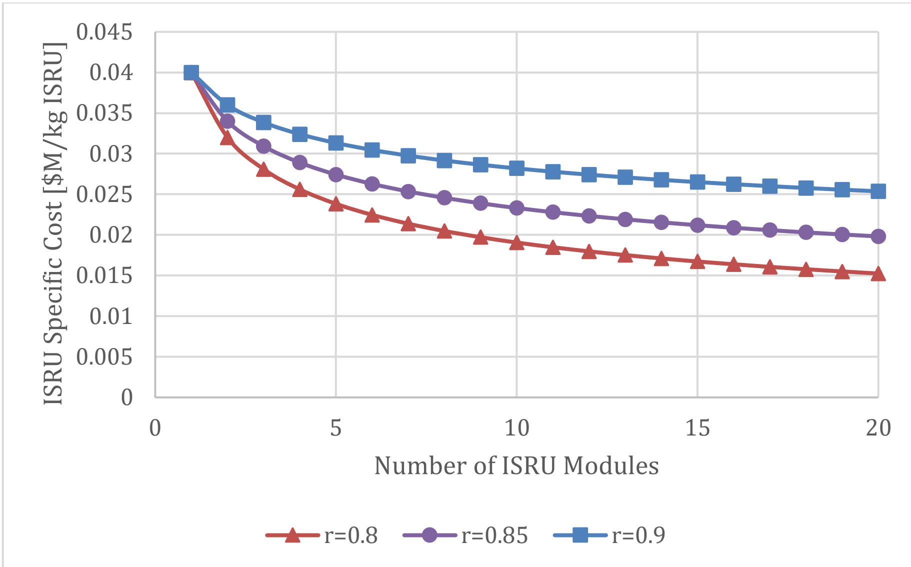

Fig. 1. Learning-curve-based cost model for ISRU modules at the theoretical first unit specific cost of α =$40,000/kg

4.1.2. ISRU Performance Model

The ISRU oxygen production model is modeled using a non-linear model derived in Ref. [20] from Ref. [21]. This model is created based on subsystem-level design models for lunar ISRU plant systems, including not only the chemical reactor but also the excavator, hopper/feed system, storage, and power subsystems. The assumed chemical process is the molten regolith electrolysis method.

The model represents the annual mass-specific oxygen production g [kg O2/year/kg ISRU] as a function of the ISRU mass m. This function $g(m)$ is as follows:

If $m \in [0,400)$

$$g(m) = 0.$$

If $m \in [400,10000]$ (3)

$$g(m) = -0.438 + 6.9623\left(1 - \exp\left(-\frac{m}{812.1563}\right)\right) + 2.0173\left(1 - \exp\left(-\frac{m}{3967.2644}\right)\right).$$

This function is represented in Fig. 2. Note the monotonically-increasing nature of this curve, which induces an increase in oxygen production efficiency as the ISRU gets larger in size.

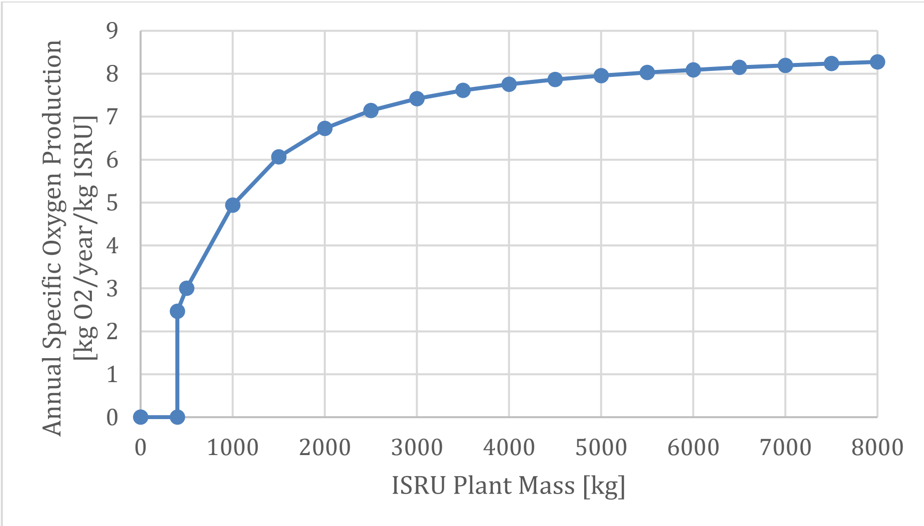

Fig. 2. Non-linear ISRU oxygen production model

4.1.3. Integrating Cost and Performance Models

Using the aforementioned cost and performance models, we can analyze Cases (i) and (ii) in the following way:

For Case (i), we need to find the ISRU plant size to satisfy the demand D optimally in terms of the mass. Therefore, we need to solve the following optimization problem:

$$\min m \quad \text{s.t.} \quad m \cdot g(m) \geq D. \tag{4}$$

Note that $m \cdot g(m)$ is a monotonically increasing function; thus, the solution of this optimization is also the solution of

$$m \cdot g(m) = D.$$

With this m and $n = 1$, we can compute the cost using the aforementioned cost model.

For Case (ii), we want to analyze the cost given the ISRU plant size m, thus we need to compute the number of needed ISRU plants n to satisfy the demand D. This can be found in the following equation:

$$n = \left\lceil \frac{D}{m \cdot g(m)} \right\rceil. \tag{5}$$

where $\lceil \cdot \rceil$ is a ceiling function. Given this value of n, we can evaluate the cost using the cost model given the ISRU plant size m. Additionally, we can vary the value of m further to find the optimal ISRU plant size m^*.

4.2. Case Study Results

This subsection discusses the case study results. In the case study, we vary the standardized ISRU plant module size (i.e., mass) m for Case (ii), i.e., the commercially-suitable standardization strategy, and compare its cost with the baseline Case (i).

Fig. 3 shows the main results: the relationship between the ISRU cost and the ISRU plant module mass for Case (ii) for three different learning rates (0.8, 0.85, 0.9). The baseline cost for Case (i) is also shown for comparison. The optimal solution for Case (i) is \$246.6M with an ISRU plant of 6,164.08 [kg]. We have a few findings from these results.

First, we can find the optimal ISRU plant module size m^* given a learning rate r for Case (ii). For example, for $r = 0.8$, this optimal ISRU plant module size is around 1,000 kg. This can be explained as follows. On the one hand, when the ISRU plant module is too large, we would have unnecessary extra ISRU capability, and thus the cost will be larger. On the other hand, when the ISRU plant module is too small, each ISRU module can be inefficient as can be seen in the monotonically-increasing ISRU performance model with respect to the module mass (i.e., larger ISRU modules experience higher performance). An additional important factor that impacts this tradeoff is the learning curve effects, which prefers to have more small ISRU modules than fewer large modules. Given these above factors, we would expect a convex curve to have an optimal ISRU plant mass size m^*. The reason why the curves in Fig. 3 are not precisely convex is because of the integer number of ISRU modules. For example, there are jumps in the cost curve when the ISRU plant module mass is around 3,000 [kg] and around 6,000 [kg], which corresponds to when the number of needed modules dropped from 3 to 2 and from 2 to 1, respectively. Also, note that, beyond this pure analytically optimal ISRU plant size, the actual standard size can also be determined with consideration of existing similar technologies (e.g., mining technologies) so that these existing commercial players can naturally be incentivized to participate in the mission; this analysis is left for future work.[1]

A more important finding is that the proposed standardization can achieve a similar or even lower cost than the mass-wise optimal solution. For example, Case (ii) achieves a lower cost than Case (i) when the ISRU plant size is 2,000 [kg] at the learning rate of 0.85 or 0.8. This is because the impacts of the learning curve effects outweigh the inefficiencies due to the mass-wise suboptimal modular size, resulting in a reduced cost. In this case, the system has four ISRU plant modules, each being 2,000 [kg], rather than one large plant; the learning curve effects due to producing four modules outweigh the extra cost of modularization, besides providing other system-level benefits such as redundancy. This cost reduction is expected to promote further mass production and thus stimulate commercial participation in this enterprise. For example, the companies can leverage this reduced cost of the standardized ISRU units for other government or privately-funded lunar, Mars, and even asteroid missions beyond this particular mission.

This case study demonstrates the feasibility of our strategy to achieve commercially-suitable architectures with little or no sacrifice in cost. By choosing such architectures with standardization and thus explicitly creating opportunities for commercial involvement, the space agency can attract commercial players to participate in the enterprise. Note that we do not claim that the obtained ISRU designs from this simple case study are the optimal architecture to pursue (e.g., modularizing only part of the subsystems may be more effective); rather, our goal is to provide a proof-of-concept to show the promising nature of the concept of commercial suitability.

[1] The 1,000-2,000kg ISRU module size is consistent with NASA's plan on ISRU [23], and thus is a realistic module sizing.

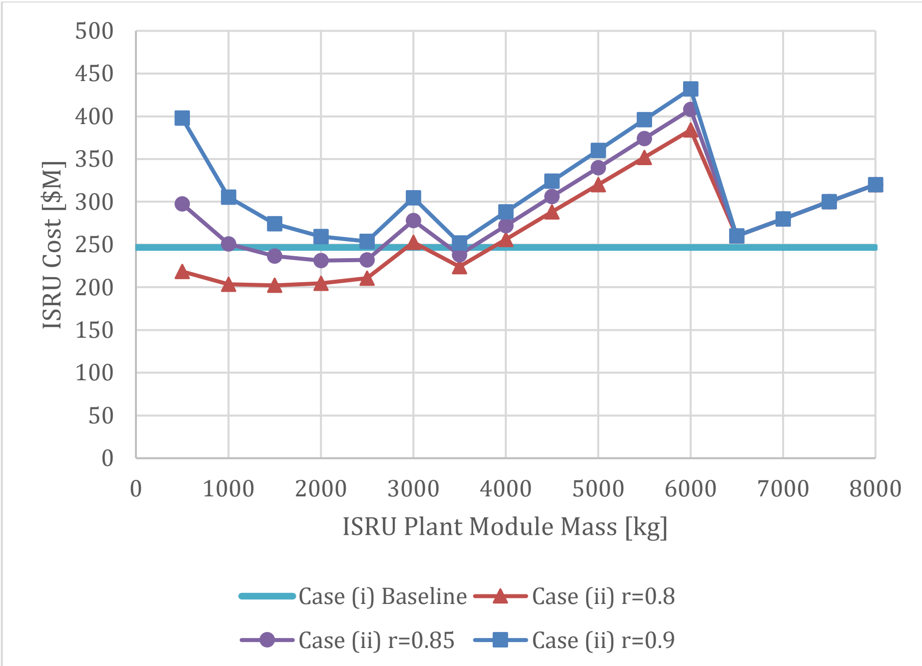

Fig. 3. ISRU Cost vs. ISRU Plant Module Mass for Case (ii). The Case (i) baseline cost is added for reference.

5. Discussion and Future Work

This paper proposes a new way to think about increasing (and broadening) commercial involvement in the space industry. Instead of encouraging participation through monetary subsidies and/or favorable contracting mechanisms, it suggests that commercial entities can be endogenously induced to participate by creating value for them through architecture selection choices. Architecting for commercial suitability is offered as a strategy to achieve this.

We illustrate the potential feasibility of this approach with a case study of ISRU systems by demonstrating an example of a commercially-suitable architecture (i.e., standardized ISRU) that can also potentially achieve a similar cost or even reduce the cost compared with the baseline architecture. Thus, we prove that there exist such architectures that induce commercial participation without negatively impacting traditional measures of effectiveness. More broadly, this style of analysis can be used to identify opportunities to apply selective constraints during the architecting process that can stimulate broader commercial participation in future missions.

Now that the viability of this approach has been demonstrated, we can address specific strategies for implementing it. Although those specifics are left for future work, our general vision is to work within existing architecting frameworks in two main ways: First, generic strategies for modularity, standardization, and commonality can be applied to generate more potentially commercially-suitable options in the tradespace. Second, scorecards can be developed to aid in the screening for commercial suitability during the analysis of alternatives. In this initial proof-of-concept, particular architectures are coded as commercially suitable or not, and then compared on standard measures (e.g., cost). A more sophisticated analysis can require a more complete assessment of the value of broader commercial participation. For example, decision-makers would want to weigh a small increase in cost against potentially stimulating secondary markets. Ref. [22] presents a potential scorecard-based approach.

Space Agencies are increasingly interested in stimulating non-traditional players to participate more broadly in the space enterprise, and a novel alternative strategy for doing so is proposed in this work. Our hope is that this framework will enable future research to explore strategies for generating commercially-suitable architectures and also valuing their advantages during the architecting process.

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