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ON-ORBIT ASSEMBLY STRATEGIES FOR NEXT-GENERATION SPACE EXPLORATION

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ABSTRACT

As the world looks ahead to the next generation of space exploration programs, we must focus on designing architectures for both sustainability and affordability. By viewing exploration programs as a "system-of-systems," we can focus on reducing costs through the use of flexible, reusable infrastructures to support various aspects of manned and unmanned spaceflight. This paper addresses one key aspect of affordable exploration programs by tackling the issue of high costs for access to space. While launch vehicle trades for exploration programs are relatively well understood, on-orbit assembly has been given much less attention, but is an equally important component of the infrastructure enabling human access to space. This paper explores a number of on-orbit assembly methods for modular spacecraft, in order to understand the potential value of a reusable assembly support infrastructure. Four separate assembly strategies involving module self-assembly, tug-based assembly, and in-space refueling are modeled and compared in terms of mass-to-orbit requirements for various on-orbit assembly tasks. Results show that the assembly strategy has a significant impact on overall launch mass, and reusable space tugs with in-space refueling can significantly reduce the required launch mass for on-orbit assembly.

INTRODUCTION

In recent years, human space exploration programs such as the Shuttle and the International Space Station have been plagued by political and technical problems as well as soaring costs. In order to avoid such difficulties, next-generation human space exploration programs should be designed for both sustainability and affordability. By viewing exploration programs as "systems-of-systems", we can focus on reducing costs through the use of flexible, reusable infrastructures to support various aspects of manned spaceflight.

One of the most difficult pieces of this system-of-systems architecture is the issue of access to space. Current evolved expendable launch vehicles (EELV's) can loft only about 25 metric tons into low Earth orbit (LEO); however, major human exploration ventures such as lunar or Mars exploration will require spacecraft many times that size. Prior work on launch vehicle sizing explored the launch vehicle tradespace, concluding that "best" launcher choices can be found for a given transportation architecture, based on size and cost. For long-duration lunar missions, as many as 11 launches may be required using EELV's, reduced only to 4 or 5 using heavy-lifters with capacities between 80 and 115 metric tons [1]. Any such mission will therefore require significant on-orbit assembly.

While the launch vehicle sizing trade is relatively well understood, this other key piece of the puzzle has been given much less attention. On-orbit assembly of separately launched spacecraft modules is an equally important component of the infrastructure enabling human access to space. This paper addresses this deficiency by examining the modular spacecraft assembly tradespace, with the goal of understanding how various on-orbit assembly strategies can enhance the sustainability and affordability of human space exploration.

Background & Literature Review

In studying on-orbit assembly, we can draw upon a significant history of operational experience and technology development. This section provides an overview of the history of on-orbit assembly, and discusses the issues researchers have dealt with during the development of assembly technologies.

History. On-orbit assembly has been a key part of space exploration since the dawn of the space age, when the Apollo program chose a lunar orbit rendezvous architecture, requiring the command module and lunar module to rendezvous and dock, or assemble, in lunar orbit. The essential component technologies for on-orbit assembly were developed during this time. Zimpfer [2] describes the limited on-orbit assembly performed during the Apollo and Shuttle programs.

The only major ongoing effort involving on-orbit assembly is the construction of the international space station, the one million pound spacecraft being built by sixteen partner nations. Its assembly is an extremely complex process requiring an extraordinary amount of ground testing, personnel training, and detailed planning [3, 4, 5]. ISS construction has been plagued by scheduling delays and spiraling costs, at least in part due to the task's scale and complexity.

Other attempts at operational assembly have been few and far between. The DART mission [6, 7] tested autonomous rendezvous (a key technology for future on-orbit assembly), with mixed success [8]. Orbital Express aims at on-orbit servicing [9, 10]. Finally, the Japanese ETS-VII mission demonstrated autonomous rendezvous [11].

Assembly Methods. Throughout history, the trend in on-orbit assembly methods has tilted overwhelmingly toward assembly by astronauts of large, complex (non-modular) structures. Several studies weigh the benefits of astronaut-assisted assembly against robotic assembly [12, 13, 14], while many others simply assume humans are required because the structures to be assembled are quite complex [15, 16, 17].

A related set of literature investigates the idea of on-orbit servicing, a key component of which is assembly. A good literature review can be found in [18], but we highlight one idea from this literature because of its potential uses for assembly: the space tug. Space tugs are multi-use spacecraft that attach to and propel other spacecraft, modifying their orbits. Tugs have the potential to support a wide variety of space mission types, such as retiring geostationary communications satellites or cleaning up space debris [18]. In this case, we focus on their potential applications to on-orbit assembly tasks.

Most literature focuses on specific technical issues, rather than looking at the 'big picture'. Still, a decade-old body of work examines assembly from the systems perspective [19,20]. Because of NASA's renewed interest in lunar/Mars exploration, researchers are beginning to revisit this type of study, but few results have yet been published [21].

Summary. In summary, the existing on-orbit assembly literature generally focuses on the assembly of large, complex structures, requiring extensive astronaut and/or ground participation. Also, most of the literature focuses on specific technical issues; only a few papers view the problem from a systems perspective. Over the past several decades, assembly has clearly proven to be a complex and challenging technical problem, and operationally, assembly missions have met with mixed success and, significantly, have generally incurred high costs.

What then makes it possible *today* to improve on-orbit assembly? New technologies and architecture concepts have been developed that make robotic and autonomous assembly more feasible than in the past. Specifically, modular spacecraft design is a key enabling concept for robotic on-orbit assembly, because it reduces the complexity of the assembly task. Assembling separate modules by docking them together is much simpler than attaching trusses and solar panels, or assembling large mirrors in space. We recognize that the advent of modular spacecraft designs could allow new on-orbit assembly strategies, and in this paper we seek to investigate the potential benefits of various modular spacecraft assembly techniques.

On-Orbit Assembly Strategies

Human exploration of the Moon and Mars will clearly require the on-orbit assembly of large spacecraft. In order for any such exploration program to be sustainable, it must avoid the difficulties encountered by the ISS and other past programs, and develop a more affordable assembly strategy. Astronaut participation and extensive, unique planning for each mission cannot be the norm for next-generation on-orbit assembly. The life cycle costs of assembly could be reduced through the development of a flexible, reusable infrastructure to assist in the assembly task.

The question remains: what form should this reusable infrastructure take? In this paper, we look to the future of on-orbit assembly and study the options that have not been extensively proven operationally: assembly by robots with limited human involvement. Within this realm, many options remain. We distill the space of assembly options into the following technological choices: a module can be self-assembling or passive (requiring a robot assembler), and the robot assembler can be either single-use, or reusable. A reusable assembler either must carry all the fuel for all its missions, or it must be capable of refueling on-orbit. These basic options allow us to study whether it is in fact valuable to create a reusable assembly infrastructure in space.

In order to quantify the benefits of each of these technologies, we must distill them into well-defined assembly strategies, including vehicle designs and an operations concept. The following four basic strategies are considered:

1. **Self-Assembly:** Each module performs its own rendezvous and docking operations.
2. **Single Tug:** A dedicated, reusable space tug performs all assembly operations.
3. **Multiple Tugs:** Each tug performs only a portion of the assembly transfers; therefore, multiple tugs are required to complete the assembly task.
4. **In-Space Refueling:** A single tug performs all assembly operations, but is refueled after a certain number of transfers (new propellant tanks are launched or the tug is refueled from an orbiting depot).

The operations concepts for each of these strategies are illustrated in Figure 1.

The sequence of events in the self-assembly case (1) is straightforward: each module is launched into a parking orbit, then transfers under its own power and propellant to an assembly orbit to rendezvous and dock with the other modules. The major disadvantage here is that a propulsion and guidance system must be present on each module. In the tug case (2), each module is launched into a parking orbit. At that point, the tug docks with the module and transfers it to the assembly orbit to rendezvous and dock with the pre-assembled stack. The tug then separates from the module stack and returns to the parking orbit to retrieve the next module. Both processes repeat until assembly is complete.

The latter strategy (2) has the disadvantage that the tug must carry all the propellant for assembling all modules back and forth many times. While only one module needs a full propulsion system (the space tug itself), some inefficiency is incurred by having to shuttle propellant back and forth. The use of multiple tugs (3) alleviates this difficulty, by launching a

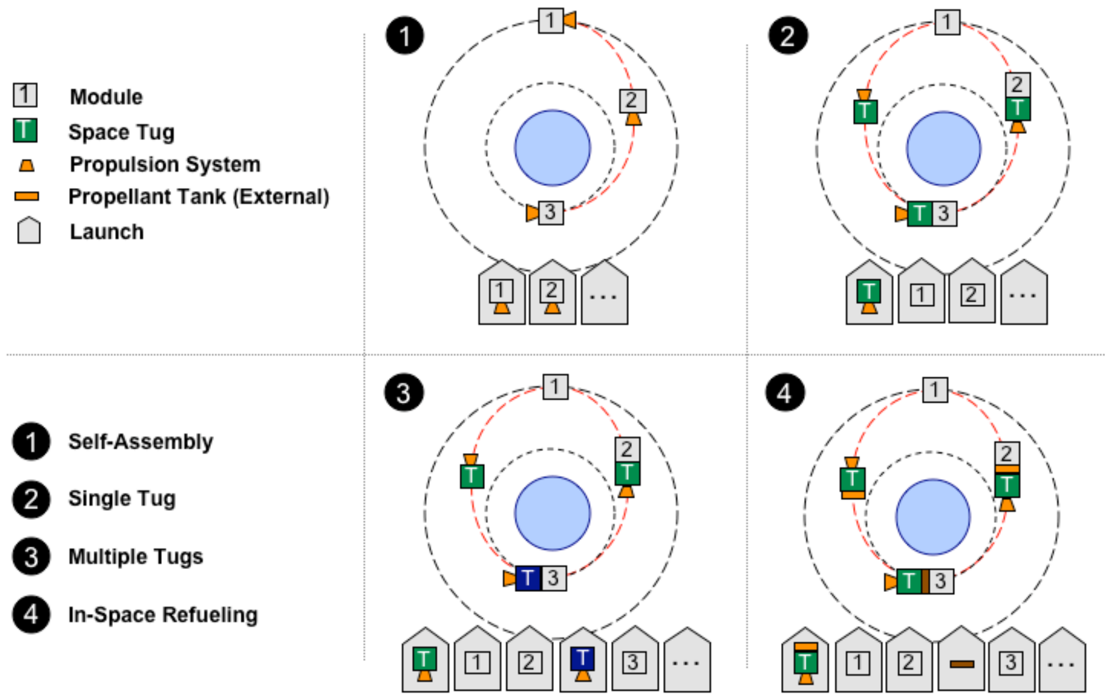

Figure 1: *The four assembly strategies are illustrated. The inner circular orbit is the parking orbit, while the outer is the assembly orbit. Red dashed lines indicate the outbound and return transfers. Launch manifests and schedules are shown.*

new tug after a certain number of modules have been assembled. The in-space refueling option (4) also addresses this difficulty, this time by allowing the launch of fresh propellant tanks (as modeled here) after a certain number of modules have been assembled. The choice of the number of modules per tug spacecraft (or fresh tank) drives the performance of both strategies.

The launch and assembly sequences as illustrated in Figure 1 are modeled in some detail; the mathematics is described later in this paper.

ASSEMBLY TRADES MODEL

In evaluating the potential of these strategies, the key question is whether the benefits of space tug deployment outweigh the costs of designing, launching, and operating an entirely separate spacecraft to provide propulsion. We expect that some on-orbit assembly tasks are more easily or cheaply accomplished with the support of a reusable space tug.

An *assembly task* can be characterized by a set of attributes: the vehicle design (e.g. number and mass of modules to be assembled, tug mass, etc.), and the orbit design (e.g. altitude and inclination of parking and assembly orbits). In order to investigate the benefits of the space tug assembly infrastructure, we must understand what kinds of assembly tasks are best accomplished using a space tug.

We must therefore understand how changes in the assembly strategy (among the four listed above) impact the overall launch mass. By tracking this metric as both the assembly strategy and assembly task are varied, the circumstances under which space tugs are valuable can be determined. To that end, we perform a trade study that compares the 'cost' (defined later) of tug-based on-orbit assembly strategies to that of the same tasks accomplished without the aid of a tug.

The next section describes how assembly tasks and strategies are modeled, while the final section provides the results of a trade study based on this model.

Assembly Model Overview

A Matlab-based model has been developed to enable trades between the four assembly strategies described above. In addition, the model provides a determination of the kinds of assembly tasks for which a tug is useful. A diagram of the model inputs and outputs is given in Figure 2.

The inputs are grouped into three categories. The assembly strategy indicates the type of strategy being evaluated; the orbit design captures information on the parking and assembly orbits; and the vehicle scenario captures information on the vehicles themselves, such as mass properties, the number of modules to be assembled, the engine specific impulse, etc. The outputs include standard metrics such as ΔV and propellant required, along with a comparative metric called 'mass overhead'. In Figure 2, input parameters in bold-face type are variables in the study; those in plain type are fixed parameters (sensitivity analysis is performed on the most important of these fixed parameters).

The rationale for this model is that it enables comparisons between assembly strategies and allows investigation of the sensitivity of the results to variations in the input scenario, such as changes in the number and size (mass) of modules. The obvious metric is the total launch mass, but this quantity needs to be carefully defined before comparisons can be made; this is the reason for the introduction of the mass overhead output, which captures the *extra mass required for on-orbit assembly* beyond the mass of the modules themselves. The various on-orbit assembly strategies can thereby be directly compared. (A detailed description of this metric can be found later in this paper.)

The following sections provide detailed descriptions of the implementation of the model sketched out above. We describe the vehicle models, orbital mechanics model, overhead mass metric, and baseline parameters.

Spacecraft Models

Two different vehicles must be modeled (module and tug), along with several variations on each of these vehicles. Because we are drawing comparisons between tug- and self-assembly strategies, it is essential that the schemes used for modeling both vehicles be *consistent* with each other. We cannot model one in great detail and oversimplify the other; the levels of fidelity and the underlying assumptions must match, in order to ensure an accurate comparison.

In this conceptual exploration of the assembly tradespace, it is not necessary to model the vehicles extremely accurately. We therefore simplify the models to the essential elements

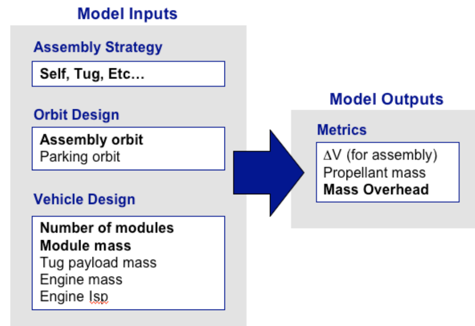

Figure 2: *Assembly trade model inputs and outputs.*

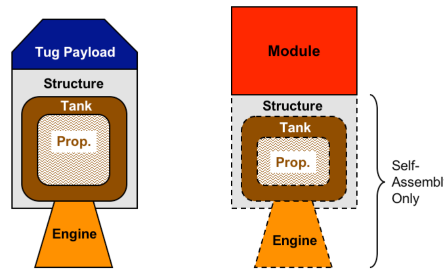

Figure 3: *Notional vehicle models of the space tug (left) and self-assembled module (right).*

affected by the on-orbit assembly strategy: payload, propulsion system, and support structure. We assume that the remainder of the spacecraft mass would be similar between the various assembly strategies and can therefore be ignored (at this level of detail). This modeling approach is depicted in Figure 3.

Figure 3 shows a notional model for both vehicles: the space tug (left) and a self-assembly module (right). A module assembled by a tug would consist simply of the red 'module' box on the right-side vehicle, with no extra structure, tank, propellant, or engines. Each vehicle is modeled as a payload (the module, in the self-assembly case), with associated propulsion system and structure. The propulsion system is made up of an engine, a propellant tank, and the propellant itself.

We estimate the mass of each of these components based on simple rule-of-thumb relationships, described in the following paragraphs. The baseline values for the design parameters are provided in a later section. The tank mass m_{tank} depends on the amount of propellant required for the trip, but the engine mass m_{eng} is fixed so that it is the same in both tugs and self-assembled modules, regardless of assembly task. The tug payload m_{pld} (docking port, grappling arm, etc.) is an estimate of the mass of a docking port or grappling arm, and the structure mass m_{str} depends on the mass of the payload and propulsion system combined. The propellant tank and structure masses are calculated based on the mass fractions f_p and f_{str}, respectively. The factors used in this model are shown in Table 1.

With this framework, the mass of each vehicle can be calculated based on a given engine mass, payload mass, and propellant requirement. In the tug case, the payload mass is simply the tug payload mass m_{pld}. In the self-assembly case, the payload mass is the mass of the module to be assembled m_{mod}. The method for calculating the mass of each vehicle component is given below. For the space tug, the calculations are given in Eqs. 1 below.

$$\begin{aligned} m_{tank} &= f_p \cdot m_p \\ m_{str} &= f_{str}(m_p + m_{tank} + m_{pld} + m_{eng}) \\ m_{dry} &= m_{pld} + m_{tank} + m_{str} + m_{eng} \end{aligned} \quad (1)$$

For the self-propelled module, the calculations are given in Eqs. 2. Note that the structure mass of the self-propelled module does not depend on the module mass; we assume that the module mass already accounts for its structure. Likewise, the module's docking ports are already accounted for in the module mass.

$$\begin{aligned} m_{tank} &= f_p + m_p \\ m_{str} &= f_{str}(m_p + m_{tank} + m_{eng}) \\ m_{dry} &= m_{mod} + m_{tank} + m_{str} + m_{eng} \end{aligned} \quad (2)$$

With this framework, we can model the space tug and self-propelled module spacecraft at a reasonable degree of accuracy. The mass depends on the size of the required propellant tanks, but a fixed mass 'penalty' is also incurred because the engine mass is fixed. Thus we can capture the idea that it is more expensive to outfit many small modules with their own propulsion systems. The assumed values for engine mass and payload masses are shown in Table 1.

Propellant Requirements Model

The model calculates propellant requirements by modeling the orbital maneuvers required to perform rendezvous operations for all modules. Docking operations are not modeled (and are not expected to be a major contributor to propellant requirements).

Several simplifications are assumed for clarity. First, phasing operations are not implemented. Phasing should contribute very little 'cost' in terms of propellant requirements, and since time is not considered as a metric, phasing can be ignored for the purposes of this study. Second, only simple inclination changes and Hohmann transfers are modeled; combined plane changes and altitude changes are not implemented. (These combined maneuvers would affect most strategies equally, so they would not affect this comparative study).

For each transfer from parking to assembly orbit, the payload is calculated based on either the module mass or the mass of the combined tug/module stack. The inclination change is performed first (if necessary), according to

$$v = \sqrt{\frac{\mu}{r}} \quad (3)$$

$$\Delta V_i = 2v\sin\tfrac{\theta}{2} \quad (4)$$

In Eqs. 3 and 4, v represents the circular orbit velocity, r is the orbit radius, μ is the mass parameter (gravitational constant) of the central body (Earth in this case), and θ is the required inclination change. A Hohmann transfer from the parking orbit to the assembly orbit is then performed, and the ΔV is found from Eq. 5, where r_1 represents the initial orbit radius, and r_2 is the radius of the final orbit.

$$\begin{aligned} \Delta V_1 &= \left[\mu\left(\frac{2}{r_1} - \frac{2}{r_1 + r_2}\right)\right]^{1/2} - \left[\mu\left(\frac{1}{r_1}\right)\right]^{1/2} \\ \Delta V_2 &= \left[\mu\left(\frac{2}{r_2} - \frac{2}{r_1 + r_2}\right)\right]^{1/2} - \left[\mu\left(\frac{1}{r_2}\right)\right]^{1/2} \\ \Delta V_H &= \Delta V_1 + \Delta V_2 \end{aligned} \quad (5)$$

Finally, the propellant required to provide the ΔV for each of these maneuvers can be found from the rocket equation, given in two forms in Eq. 6.

$$m_p = m_f\left(e^{\frac{\Delta V}{I_{sp}g}} - 1\right) = m_o\left(1 - e^{\frac{-\Delta V}{I_{sp}g}}\right) \quad (6)$$

The propellant mass m_p can be found based on either the initial mass m_o or the final mass m_f of the spacecraft. The propellant mass for each module in the self-assembly case is found by a straightforward calculation using the final mass of the module, but the tug cases are more complex. The single tug, for example, carries enough propellant to transport *all* modules to the assembly orbit, so it pushes its own propellant as payload for many of the transfers. Therefore, the tug propellant mass must be calculated iteratively. Based on an estimate of the tug propellant mass, a value for m_p is found and compared to the initial value. If not within a small tolerance value, the process is repeated, using the calculated m_p as the new guess. In this manner, an accurate value for the tug propellant mass for the entire mission can be calculated. For the other tug-based assembly cases, more complex iteration loops are used to calculate the propellant required for each of multiple tugs, and each tank in the refueling case.

With this model, accurate propellant requirements for on-orbit assembly can be generated, based on the assumptions given initially.

Overhead Mass Metric

The model output is technically the total propellant mass required for assembly, but this is only part of the comparison between the assembly strategies. The true metric of comparison is cost, but this is difficult to model at this early conceptual stage of the study. One widely used surrogate metric is launch mass, of which the required propellant mass forms a significant part. We adapt this surrogate metric to capture the comparison between the various strategies.

The comparison between the two basic strategies is driven by the respective advantages of each: the tug case allows for lighter modules without propulsion and navigation capabilities, while the self-assembly case does not require return transfers from assembly to parking orbits, nor transfer of excess propellant between the parking and assembly orbits (because the tug must carry propellant for its entire mission). To capture the true differences between the strategies, we introduce the overhead mass metric m_v. The overhead mass is the total weight of all extra fittings, including propellant, that are required for on-orbit assembly. It is calculated differently for each strategy: details are given in Eqs. 7 below.

Self:
$m_v = n_{mod}(m_{str} + m_{tank} + m_p + m_{eng})$
Single Tug:
$m_v = m_p + m_{tug}$
Multiple Tugs: (3.7)
$m_v = n_{tug}(m_{p,tug} + m_{tug})$
In-Space Refueling:
$m_v = n_{tanks}(m_{p,tank} + m_{tank}) + m_{tug} - m_{tank}$

For the self-assembly case, m_v depends on the mass of propellant for each module, plus the mass of all the additional fittings required – engine, propellant tank, and supporting structure. For the single tug scenario, m_v depends only on the mass of the tug propellant m_p and the tug itself m_{tug}. For multiple tugs, the mass of the tug and the propellant carried by each tug ($m_{p,tug}$) is simply multiplied by the number of tugs $n_{tug},$ assuming all tugs are of identical design. The in-space refueling case, as modeled here, assumes that new tanks of propellant are launched for each tug refueling (rather than in-space propellant transfer from a depot to previously used tanks). Thus, the overhead mass depends on the mass of each tank m_{tank} and the propellant in each tank $m_{p,tank}$, multiplied by the number of tanks required n_{tanks}. The mass of the tug spacecraft must also be taken into account, but the mass of its included propellant tank has already been accounted for within the first term of the equation, so it is subtracted here.

With this overhead mass metric, all four scenarios can be weighed against one another based on the output from the model.

Baseline Parameters & Assumptions

Baseline values are selected for the variables and parameters based on literature searches and the requirements generated by a study for NASA [22]. Initial research helped to refine these values, shown in Table 1.

The rationale varies for the selection of each of these baseline values. The parking orbit is baselined at a standard parking orbit for launch from Kennedy Space Center (KSC). The assembly orbit's altitude and inclination are varied using the parking orbit parameters as minimum values because drag perturbations make orbits lower than 200 km infeasible, and inclination changes have the same ΔV 'cost' whether they increase or decrease inclination; therefore, for the purposes of this study, the direction of inclination change is irrelevant.

The baseline module dry mass was chosen to fit on current launch vehicles (~ 27 mt) while reserving a reasonable amount of launch mass for propellant (in the self-assembly case), and varied from the lowest feasible size (based on [22]) to 30 mt. Note that both the upper limit on module dry mass and the range for the number of modules to be assembled is on the low end of the possible requirements spectrum (Gralla [1] showed up to 27 modules may be required, and module masses may reach 100 mt). Modeling higher values for each of these parameters does not add any value to the study, because the results are simply a continuation of the same trends shown at the ranges modeled here.

The engine Isp is a standard value for bi-propellant engines [23], and the phasing strategy is the logical choice (lowest ΔV for this type of mission) among several standard methods (double Hohmann transfer, elliptical phasing loops, sub- and super-orbital drift). (Recall that phasing is not explicitly accounted for; this phasing method was initially modeled to ensure that propellant usage for phasing would be negligible.)

The engine mass estimate is intended to capture all the fixed components of the propulsion system, including the engine and all other system hardware, attitude control, etc.. Wertz [23] shows that liquid propellant engines weigh on the order of 100 kg; We double this number to account for the extra fittings. This is obviously a rough estimate but we perform extensive sensitivity analysis to understand how changing this value affects the results. In addition, we ensure that the resulting tug dry mass estimates match those found in the literature: McManus [24] models a bi-propellant GEO tug at 1100-1300 kg, and Galabova [18] describes a LEO tug weighing in at around 650 kg. With an engine mass of about 200 kg, the tugs weigh in on the low end of this range of values.

The tug payload refers to the docking/berthing equipment carried by the tug; this could take the form of a docking port, a robot arm, or something related. The baseline value was estimated based on the mass of modern docking systems and values in the space tug literature. The latest NASA docking port design – the Advanced Docking and Berthing System – weighs in at about 300 kg [25]. In addition, McManus [24] estimates a reasonable tug payload could weigh about the same amount, based on typical sizes and masses of industrial robots. Again, sensitivity analysis shows the impact of varying this estimate.

Finally, the propellant and structures mass fractions are based on relationships given in McManus [24], Lamassoure [26], and Wertz [23].

TRADE STUDY RESULTS

With the model described in the preceding section, a comprehensive trade study can be carried out to investigate the relative value of the four assembly strategies: self-assembly, single tug, multiple tugs, and in-space refueling. As mentioned above, the on-orbit assembly model is used to explore the design space and to understand the effects of varying several parameters on the overhead mass m_v and on the comparison between the various strategies. We reiterate that the end goal is to understand which assembly strategy is better for various kinds of scenarios.

The study follows a basic structure in which a parameter (or two) is varied within a specific range while the others are held constant at their baseline values. (Recall that the ranges and baselines are summarized in Table 1). First, the vehicle scenario parameters are varied, then the orbit design variables; thus an exploration of the tradespace is completed. Finally, sensitivity analysis is conducted to understand the impact of some of the assumed and baseline values.

Vehicle Scenario Parameters

The vehicle scenario is described by both the number of modules and the mass of each module that must be assembled. For clarity it is assumed that all modules are identical.

Table 1: *Assembly Model Baseline Values and Ranges*

Variable	Type	Baseline	Range
Assembly strategy	Variable	-	[Self, Single-Tug, Multi-Tug, In-Space Refuel]
Assembly orbit	Variable	400 km, 28.5 deg	200 – 1000 km
Parking orbit	Fixed	185 km, 28.5 deg	-
Phasing strategy	Fixed	Wait in lower orbit	-
Module dry mass	Variable	15 mt	5 – 30 mt
Number of modules	Variable	-	1 – 15
Engine mass	Fixed	200 kg	-
Tug payload mass	Fixed	300 kg	-
Engine Isp	Fixed	310 s	-
Propellant Fraction f_{prp}	Fixed	0.12	-
Structures Fraction f_{str}	Fixed	0.15	-

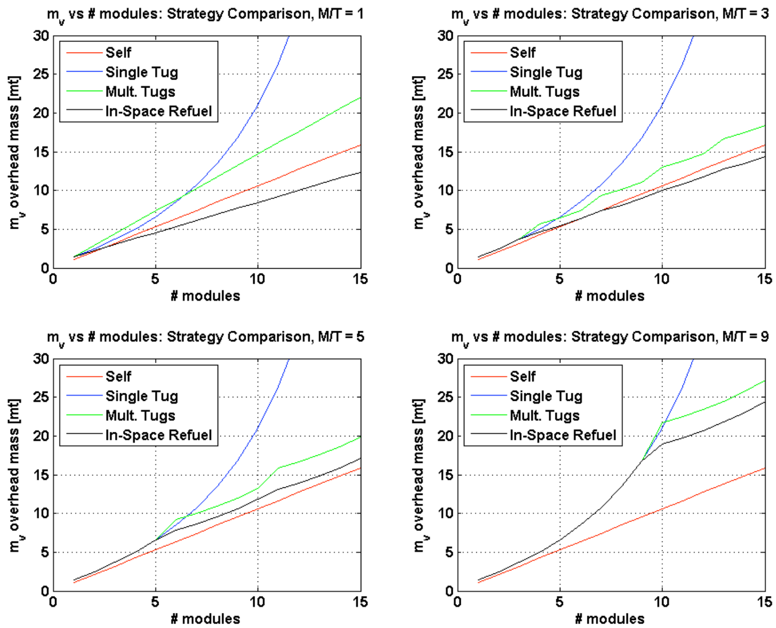

Figure 4: *Results showing the change in overhead mass as the number of modules is varied. Each plot is based on a different value of 'M/T', or modules per tug/tank.*

Number of Modules. Figure 4 shows the variation in additional mass for each of the tug strategies, as the number of modules is varied from 1 to 15. Each plot is based on a different value for 'M/T'. The 'M/T' parameter signifies either the number of modules transferred per tug or per tank (for the multiple tugs and in-space refueling scenarios, respectively. Note that, unless otherwise specified, results are calculated from the baseline values given in Table 1.

In the first graph, with M/T equal to one (one module per tug/tank), the trends are fairly clear. The self-assembly case shows an essentially linear increase in the metric m_v for increasing numbers of modules. The single tug case, on the other hand, has a lower slope at lower values on the horizontal axis, and a higher slope as the number of modules increases. The reason for this behavior is that in this scenario, the tug is required to begin its life carrying all the propellant required to assemble *all* modules. Therefore, it must push a large amount of propellant back and forth between the parking and assembly orbits in cases with a high number of modules. Thus, the single tug strategy is useful *only* at lower numbers of modules.

The multiple tugs and refueling strategies appear to advantage over the single tug. In this case, with M/T equal to one, the multiple tugs case performs rather poorly, with a higher additional mass metric than all other strategies (except single tug at high *x*-values). This is due to the requirement for a new tug spacecraft for every module transfer. The multi-tug strategy with a ratio of M/T=1 performs worse than self-assembly because tugs have a higher mass overhead than modules with an integrated propulsion system. The use of space tugs for on-orbit assembly appears to make sense only when tugs are reused for more than one module. The in-space refueling scenario, on the other hand, performs consistently better than any others, showing a linear increase with number of modules at a lower slope than self-assembly (because it requires only a new propellant tank for each module and not an entire propulsion system).

The other three graphs, with M/T values of 3, 5, and 8, also display clear trends. While the self-assembly and single tug scenarios do not change based on M/T, the multiple tugs and in-space refueling scenarios vary. The 'jagged' curves are due to uneven divisions of modules into M/T-sized chunks. For example, with an M/T of 5, both scenarios show higher m_v values for a six-module scenario, because an entire tug or tank must be launched for the one remaining module (after the first five have been transferred

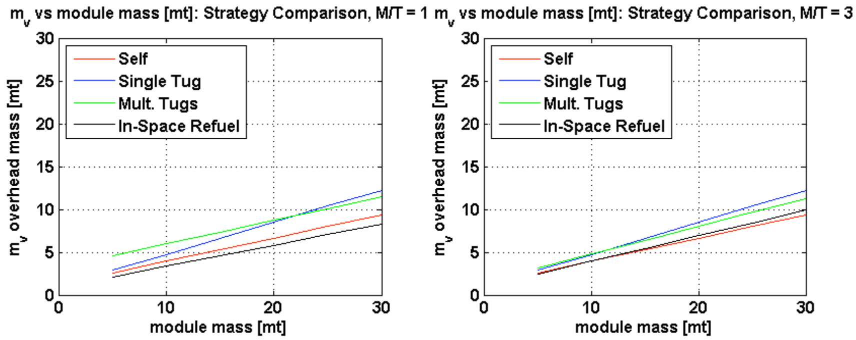

Figure 5: *Results showing the change in overhead mass as the module mass is varied. Each plot is based on a different value of 'M/T', or modules per tug/tank.*

on the first tug/tank). With an M/T of 3, in-space refueling is advantageous at higher numbers of modules; however, note that the best option (least m_v) overall remains in-space refueling *with an M/T of 1*. Based on the trends visible in this set of graphs, it is clear that while mid-level M/T values (e.g. 3, 5) improve the performance of the multiple tugs strategy (over M/T's of 1 or 9), the improvement is not sufficient to make the strategy more attractive than either self-assembly or in-space refueling at M/T=1. Clearly, high M/T values, such as 9, do not improve the situation (too many return transfers required).

Module Mass. The remaining vehicle scenario parameter is the mass of the individual modules. Results for the overhead metric as the module mass increases from 5 to 30 mt are shown in Figure 5. In this case, the number of modules is fixed at 5.

First, note that these graphs can be misleading: the y-intercept of the multiple tugs and in-space refueling lines is highly dependent on the number of modules and M/T (see Figure 4). The key point here is the slope of each line. The single tug case has the highest slope; therefore, its overhead mass increases fastest as module mass increases. Self-assembly and in-space refueling (only when M/T is 1) have the lowest slopes, so the increase in m_v as module mass increases is smaller than for the other strategies. This makes sense as the mass for propulsion and attitude control has a fixed component which is independent of module mass. Thus, as modules are increased in mass, the relative percentage of that mass due to propulsion and attitude control gets smaller.

The obvious conclusion here is that in-space refueling provides the best option at an M/T of 1; self-assembly is a close second-best. Note that these results are consistent with the conclusions drawn based on Figure 4.

Orbit Design Parameters

Figures 6a and 6b show plots comparing the four assembly strategies as the orbit altitude is varied. The assembly orbit altitude is plotted along the x-axis. In this case, the number of modules in Figure 6a is fixed at 2, and in 6b at 5. In these plots, no inclination changes are required (based on our analysis, the addition of inclination change simply exacerbates the trends shown here). The required ΔV cost for each scenario is therefore based on the difference between the assembly orbit parameters and the parking orbit, at 185 km.

Based on Figures 6a and 6b, it is clear that increasing the altitude of the assembly orbit increases the overhead mass for all strategies; again, the slope of the lines indicates the rate at which overhead mass goes up as altitude is increased. The results differ based on the number of modules. In Figure 6a, with a 2-module assembly task, the self-assembly strategy is consistently favored, for all orbit altitudes. On the other hand, in Figure 6b (5 modules), the self-assembly task has a higher m_v value than in-space refueling when M/T = 1. As found in the previous section, self-assembly has the advantage for small numbers of modules.

Interestingly, these plots show the first assembly scenario in which the single tug strategy shows significant advantages. In all cases, for very low assembly orbits (near 200-300 km), the single tug strategy has the lowest overhead mass (along with other strategies). At 400 km, our baseline assembly orbit, the strategy's overhead mass is significantly higher than most of the others, explaining why the

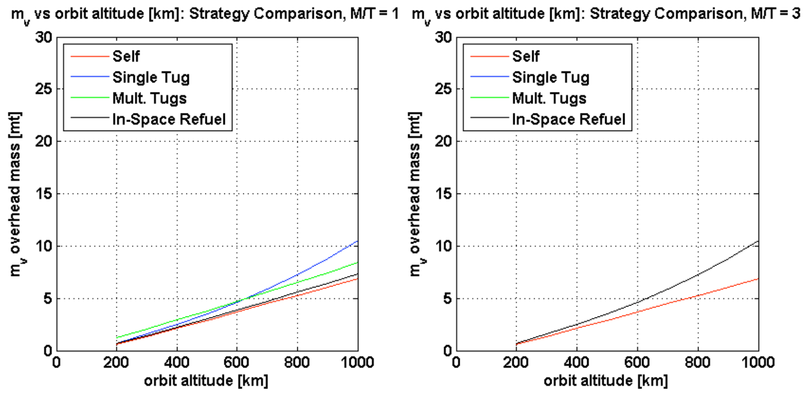

Figure 6a: *Results for varying assembly orbit altitude, <u>with 2 modules</u>.*

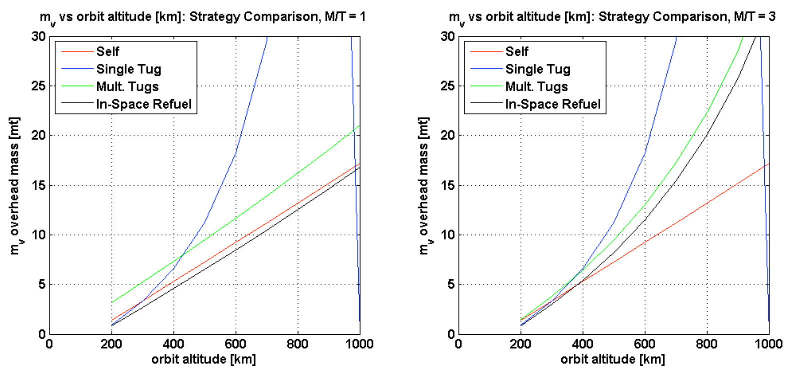

Figure 6b: *Results for varying assembly orbit altitude, <u>with 5 modules</u>.*

single-tug case always appears to poor advantage in the rest of the study.

Similar plots can be generated for changes in orbit inclination, but due to their higher ΔV cost, the trends for these maneuvers are similar but even more pronounced.

Tradespace Exploration

Finally, the results obtained above are combined to create a general idea of the tradespace. With the baseline values for the vehicle and orbit design parameters set (Table 1), the overhead mass is plotted as a function of both the module mass and number of modules. Because the lowest overhead mass in Figures 4, 5, and 6 was obtained for M/T =1, we look only at that case here. The surface in Figure 7 shows the minimum additional mass possible at each point in the *x-y* plane; the color coding shows which strategy provides the minimum mass at that point. (See Figure 6 for legend).

For very low numbers of modules, the self-assembly strategy is superior, but the in-space refueling case wins out as the number of modules increases beyond very low values. As the mass increases, in-space refueling becomes valuable at lower numbers of modules. The plot makes a very clear case for in-space refueled space tugs as an assembly strategy.

Sensitivity Analysis

The assembly trades model is based on a number of estimates and assumptions (necessary at this conceptual stage of the study). It is therefore important to understand the sensitivity of the results to changes in these assumptions.

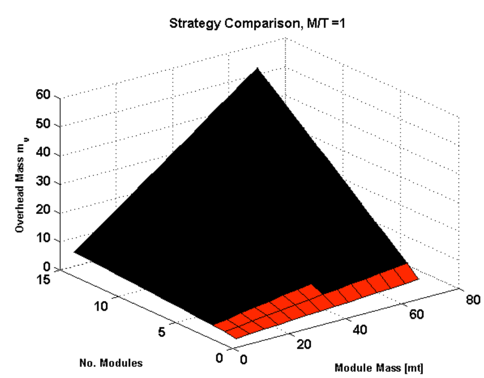

Figure 7: *Minimum overhead mass as a function of module mass and number of modules. See previous figures for legend.*

The most important assumptions are the fixed engine mass m_{eng}, the tug payload mass m_{pld} and Isp, and the propellant and structures fractions f_{prp} and f_{str}. Recall that the baseline values are given in Table 3.1. In this section, we describe our sensitivity analysis, in which each of these parameters is varied from the baseline, and the results are analyzed to determine the direction and extent of the ensuing change in the results.

We first investigate the sensitivity to the engine mass m_{eng}. Figures 8a, 8b, and 8c show a comparison of all four strategies as the number of modules increases, as in Figure 4 above. In this case, however, 8a shows the results when the engine mass is 200 kg (the baseline), 8b shows the results for an increased mass of 500 kg, and 8c shows the results for a decreased mass of 100 kg. We can thereby examine the sensitivity of the results to changes in the engine mass.

In the baseline case (Figure 8a), the in-space refueling strategy has the lowest overhead mass in all cases except the one-module and two-module tasks; self-assembly is a close second. Interestingly, neither of the tug strategies appears at all useful due to high overhead mass as the number of modules increases. In the low-mass case (Figure 8c), the results change slightly but, significantly, the sorting order of the strategies does not change, indicating that results are relatively insensitive to decreasing engine mass.

In the high-mass case (Figure 8b), on the other hand, the results do change somewhat. In-space refueling appears even more valuable as it gains a greater advantage over the other three strategies. However, the single-tug strategy, which looked bad in the baseline case, is slightly better than self-assembly for smaller assembly tasks. More significantly, the multiple tugs case

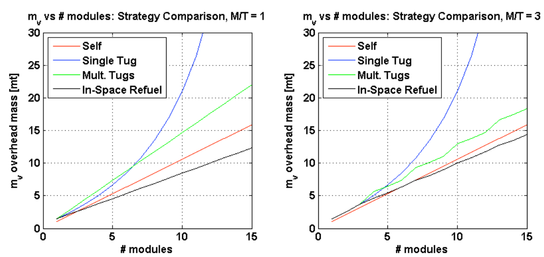

Figure 8a: *Number of modules comparison,* *<u>with 200 kg engine mass</u>.*

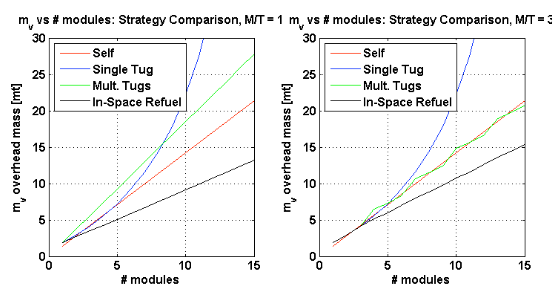

Figure 8b: *Number of modules comparison,* *<u>with 500 kg engine mass</u>.*

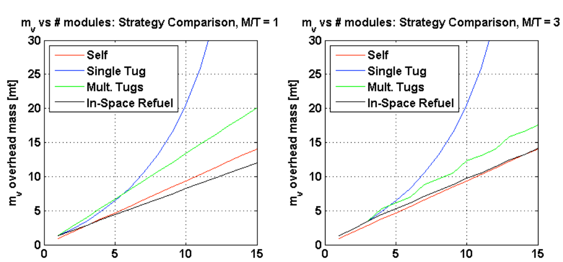

Figure 8c: *Number of modules comparison,* *<u>with 100 kg engine mass</u>.*

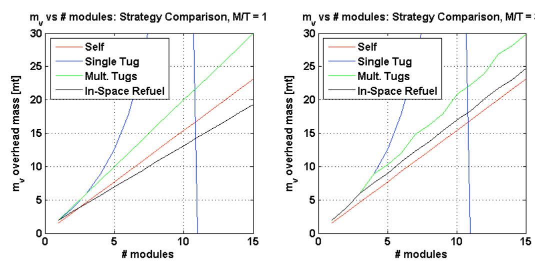

Figure 9a: *Number of modules comparison,* *<u>with 200 s Isp</u>.*

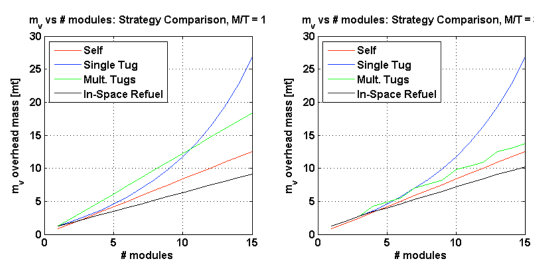

Figure 9b: *Number of modules comparison,* *<u>with 420 s Isp</u>.*

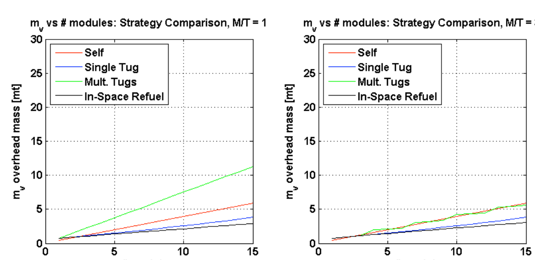

Figure 9c: *Number of modules comparison,* *<u>with 1500 s Isp</u>.*

for M/T=3 is an improvement over self-assembly for most assembly tasks (assuming M/T can be adjusted to the task, to remove the 'jumps' in m_v). Therefore, we can conclude that the results are indeed sensitive to the engine mass: increasing the fixed engine mass makes the tug cases more attractive, and decreases the relative value of self-assembly.

This sensitivity makes sense because the fixed component of the engine mass is what drives the advantage of space tug-based assembly scenarios. Including this fixed engine mass on every module makes self-assembly less attractive when the engine mass is large.

We expect the choice of propellant type, or Isp, for the space tug to have a similarly significant effect on the results. Recall that the baseline value was 310 s, corresponding to the range of standard bi-propellant propulsion systems. Figures 9a, 9b, and 9c show the results for three other types of propellant: a 200 s Isp for monopropellant, a 420 s Isp for H2/LOx, and a 1500 s Isp for electric propulsion, respectively. These figures can be compared to Figure 4 (310 s Isp). Based on 8a, we can conclude that lowering the Isp makes all four strategies perform less well in terms of overhead mass, but affects them all more or less equally. Raising the Isp slightly to 420 s increases the performance of the single tug strategy slightly, but not enough to surpass in-space refueling or self-assembly. However, giving the Isp a large boost to 1500 s does indeed change the results significantly. Most notably, the single-tug strategy shows very good performance, showing a consistently lower overhead mass than self-assembly. Only the in-space refueling strategy can provide better performance. All four strategies show better performance from the higher Isp, but the single tug strategy is the most sensitive to changes in this parameter. Thus, we can conclude that the results presented in this chapter are only slightly sensitive to small changes in Isp (e.g. from bi-propellant to H2/LOx); however, the use of electrical propulsion – or some other high-Isp propellant – could change the study results significantly, making the use of space tugs more attractive.

The same type of study was performed to investigate sensitivity to the tug payload mass. The baseline tug payload mass of 300 kg was both increased and decreased and the results were inspected for changes from the baseline. In this case, however, the results were relatively insensitive to changes in this parameter. Reducing the payload mass gives tug-based strategies a slight improvement in overhead mass, but does not change the sorting order of the results; increasing the payload mass slightly increases the overhead mass but, again, does not change the results.

The remaining two parameters – the propellant fraction f_{prp} and the structures fraction f_{str} – were investigated similarly. Reducing f_{prp} from the baseline value 0.12 to 0.05 produced no change in the results; an increase to 0.3 gave only a slight advantage to self-assembly at low numbers of modules. This is to be expected because it increases the impact of the excess propellant that must be carried by the tugs for their return trips. Still, the sensitivity is small. Changes in f_{str} produced virtually no changes in the results. The baseline value of 0.15 was increased to 0.3 and decreased to 0.05 with no effect, probably because this parameter affects both the self-assembly and tug cases nearly equally.

Based on this sensitivity analysis, we can garner increased confidence in this model. The only parameter that shows real sensitivity to changes in assumptions is the fixed engine mass. We expect this parameter to drive the comparison between tug-based strategies and self-assembly strategies. The remaining parameters – tug payload mass, propellant fraction and structures fraction – show relatively little sensitivity to changes in assumptions.

CONCLUSIONS

The results of this tradespace exploration indicate that both tug-based and self-assembly strategies are worthy of further study, because neither was an absolute winner in all assembly scenarios. However, the results clearly indicate that in-space refueling of tugs, as modeled here, is the best assembly strategy (based on our comparison metric) for nearly all assembly tasks. In tasks with very few modules to be assembled, on the other hand, self-assembly often has a lower overhead mass. The single-tug and multiple-tug strategies rarely have lower overhead mass values than either self-assembly or in-space refueling.

Assembly Strategy Comparison

It is somewhat surprising that both of the non-refueled tug-based strategies performed so poorly in this study. On closer examination, however, this result can be explained. The single tug strategy, as noted earlier, is at an immediate disadvantage at high numbers of modules because it must carry propellant for all its journeys to and from the assembly orbit. The overhead mass therefore increases exponentially, and the strategy is useless for large numbers of modules. The effect can be somewhat lessened by going to a higher Isp propellant (e.g. LH2/LOX in the range of ~400-400 sec) but at this point boil-off issues might start to dominate the problem. Single non-refuelable tugs for on-orbit assembly in LEO might therefore only be viable for proximity operations or once high-thrust, high-Isp electrical propulsion systems become a reality.

The multiple-tug strategy was introduced in an attempt to alleviate this problem. However, by launching multiple tugs, we encounter the same problem as in the self-assembly case: we must launch heavy propulsion, docking, and other hardware quite frequently in order to complete the assembly task. Therefore, in order to make the use of multiple tugs valuable, the right balance must be found between minimizing the number of back-and-forth trips each tug makes, and minimizing the amount of duplicate hardware launched (this balance is controlled by the selection of the M/T parameter). Even with this balance found, the self-assembly case nearly always has a lower overhead mass than the multiple tugs case because the tugs case requires launching *more* excess hardware: not only the propulsion system and propellant tanks, but also the tug payload along with excess propellant for return transfers. The multiple tugs case only appears advantageous in cases where the fixed engine mass is large (rendering the self-assembly 'mass penalty' per module very high). The conclusion therefore is that if the propulsion system hardware is rather light, the use of non-refueled tugs for assembly does not make sense. However, if the propulsion hardware is heavy, non-refueled tugs can indeed be useful.

On the other hand, *refueled* tugs are clearly shown to be the best strategy for on-orbit assembly tasks with more than two or three modules. The strategy performs best when the tug is refueled after assembling only one module. This result is reasonable because rather than launching a new propulsion system on each module (self-assembly), or launching an entirely new tug (propulsion and payload) every few modules, we launch only the required propellant and tank. The only caveat here is that we do not account for additional propellant required to retrieve each newly launched tank (just as we do not account for propellant for rendezvous with modules, and any excess hardware that may be required to provide attitude control for the tanks). Adding in this relatively small additional propellant requirement might change the results slightly. However, the propellant tanks could also be launched as piggyback payload with the modules; no increased propellant usage would then be incurred.

The self-assembly strategy performs best for tasks with a small number of modules, where other parameters are 'high-stress': large modules and/or high assembly orbits. With heavy modules, the addition of a propulsion system is a lower percentage of the total launch mass. With high assembly orbits, the self-assembled modules do not have the tug disadvantage of returning to the parking orbit. However, in most other scenarios, the refueled tug strategy has a lower overhead mass than self-assembly

A secondary result from this tradespace exploration is the relative lack of sensitivity of the results to changes in three of the most important vehicle design parameters: the tug payload mass, propellant mass fraction, and structures mass fraction. This lack of sensitivity leads to increased confidence in the results of this study (rough estimates and assumptions still probably lead to the correct conclusions).

On the other hand, the results are shown to be sensitive to changes in the engine mass parameter – the *fixed* component of the overhead mass required on each tug or self-assembled module. This result was expected, and indeed provides one of the most important conclusions from this study. When this fixed mass component is increased, the performance of the self-assembly strategy gets worse, and the tug-based assembly strategies become more attractive. As a result, we can conclude that if the propulsion system mass is high, a tug-based assembly strategy should be used. If the propulsion system mass is low, on the other hand, self-assembly should be considered as a superior alternative.

Future Work

A third result that could be found from a tradespace exploration is an idea of the optimal assembly orbit. However, the level of fidelity of this model is not high enough to capture all the necessary variables. In this study, the assembly orbit simply exacerbates already-present trends. High altitude or high inclination orbits simply increase the ΔV requirements. Future iterations of this model could incorporate relevant orbit perturbations such as drag and solar pressure, which we expect to drive the assembly orbit toward an optimal value. In that particular analysis, the drag-induced altitude losses of modules waiting in an assembly orbit for stack completion will be integrated over time. Thus, a low assembly orbit will incur significant drag losses, while a high assembly orbit is more expensive to reach initially. The optimal assembly orbit is expected to be in between, depending on the total number of modules to be assembled and the expected time interval between successive rendezvous and docking operations.

Additionally, the results of the sensitivity analysis for the Isp parameter showed that very high Isp systems, such as electric tugs, could make a space tug architecture significantly more attractive (lower overhead mass than any options with chemical propulsion). We only touched on this subject briefly, but a more extensive investigation of the potential of electric tugs as assemblers would be enlightening. Two additional elements would be needed in the model: the capability for modeling spiral trajectories and comparing results in terms of time (since electric tugs are generally slow).

Finally, real mission scenarios feature non-uniform module masses. The model could be extended to handle modules of varying masses that can be described by a vector of module masses or by a distribution function. Also, electrical tugs could be investigated if they appear to offer significant benefits. Allowing for an electrical propulsion tug (I_{sp} >1000 sec), will favor the tug, but will cause slower transfers. Non-uniform module masses were not incorporated into this model because they did not add to the objectives of this particular study: to understand the types of tasks for which each strategy is well-suited. Future iterations of the study should focus on the particular strategies and tasks shown to be advantageous and do a more detailed design study; at that point, non-uniform module masses should be incorporated into the model.

Summary of Conclusions

In summary, this assembly trade study accomplished its major objectives of exploring the design space and providing conceptual conclusions about the relative merits of self- and tug-based assembly. The results show that neither the tug case nor the self-assembly case is clearly optimal in all situations, so the trade between the two strategies is worthy of further study. The results also show that the refueled space tug, as modeled here, is a better option than self-assembly for most (but not all) assembly scenarios. The relevant parameters have been identified (vehicle design, orbit design, and assembly requirements) and their impact on the trade has been examined. Sensitivity analysis has been performed to understand the validity of the assumptions inherent in the model. It is clear from this study that a refueled space tug could be a valuable method for on-orbit assembly of various types of modular spacecraft.

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