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STRATEGIES FOR ON-ORBIT ASSEMBLY OF MODULAR SPACECRAFT

ERICA L. GRALLA* AND OLIVIER L. DE WECK
Department of Aeronautics and Astronautics, Massachusetts Institute of Technology,
77 Massachusetts Ave., 33-410, Cambridge, MA 02139, USA.
Email: egralla@mit.edu*

Next-generation space exploration will most likely 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 past programs by focusing on affordability. The advent of modular spacecraft potentially enables a variety of new, more affordable assembly techniques. 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 refuelling are modelled and compared in terms of mass-to-orbit requirements for various on-orbit assembly tasks. Results show that reusable space tugs with in-space refuelling can reduce the required launch mass for on-orbit assembly between 5% and 41% (compared to self-assembly) for certain types of assembly tasks.

Keywords: Assembly, modular spacecraft, space tugs, in-space refuelling

1. INTRODUCTION

In recent years, human space exploration programs such as the Space 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", costs can be reduced 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. 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 (see, for example, [1]), 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.

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Symbols/Nomenclature

m_v	Overhead mass (for assembly)
m_{tank}	Fuel tank mass
m_p	Propellant mass
m_{pld}	Payload mass
m_{eng}	Engine mass
m_{str}	Structure mass
m_{dry}	Dry mass
f_p	Propellant mass fraction
f_{str}	Structure mass fraction
M/T	Modules assembled per tug or tank

New technologies and architecture concepts have been developed that make robotic and autonomous assembly more feasible *today* 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 individual trusses and solar panels, or assembling large mirrors in space. Recognizing that the advent of modular spacecraft designs could allow new on-orbit assembly strategies, this paper investigates the potential benefits of various modular spacecraft assembly techniques.

1.1 Background and Literature Review

There is a significant history of operational experience and technology development in on-orbit assembly, which can be drawn upon for this study. Zimpfer *et. al.* [2] describes the limited on-orbit assembly performed during the Apollo and Shuttle programs. The only major ongoing assembly operation is the construction of the International Space Station (see, for example, [3,4,5]). 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].

In the past, 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 needed because the complexity of the structures to be assembled requires it [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 one idea from this literature should be highlighted here 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; thus, they can be used for in-space assembly.

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].

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.

1.2 On-Orbit Assembly Strategies

Having made the case for investigating new techniques for on-orbit assembly, the question remains: what form should this new assembly infrastructure take? This paper studies options available only recently, with the advent of modular spacecraft: assembly by robots with limited human involvement. Within this realm, many options remain. The space of assembly options is distilled 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 refuelling on-orbit.

In order to quantify the benefits of each of these technologies, they must be refined 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 Refuelling:** A single tug performs all assembly operations, but is refuelled after a certain number of transfers (new propellant tanks are launched or the tug is refuelled from an orbiting depot).

The operations concepts for each of these strategies are illustrated in Fig. 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 new tug after a certain number of modules have been assembled. The in-space refuelling option (4) also addresses this difficulty, this time by allowing the launch of fresh propellant tanks (as modelled 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 (3) and (4).

2. 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. It is expected that some on-orbit assembly tasks are more easily or cheaply accomplished with the support of a reusable space tug, but it remains to be determined which tasks are best accomplished by each assembly strategy.

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). The goal of this study is to understand how changes in the assembly strategy (among the four listed above) impact the overall launch mass for various types of assembly tasks. 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, a trade study is performed that compares the 'cost' (defined later) of each of the assembly strategies listed above, for various assembly tasks.

2.1 Assembly Model Overview

A model has been developed to enable trades between the four assembly strategies described above. A diagram of the model inputs and outputs is given in Fig. 2.

The inputs are grouped into three categories. The assembly strategy indicates the type of strategy being evaluated (see

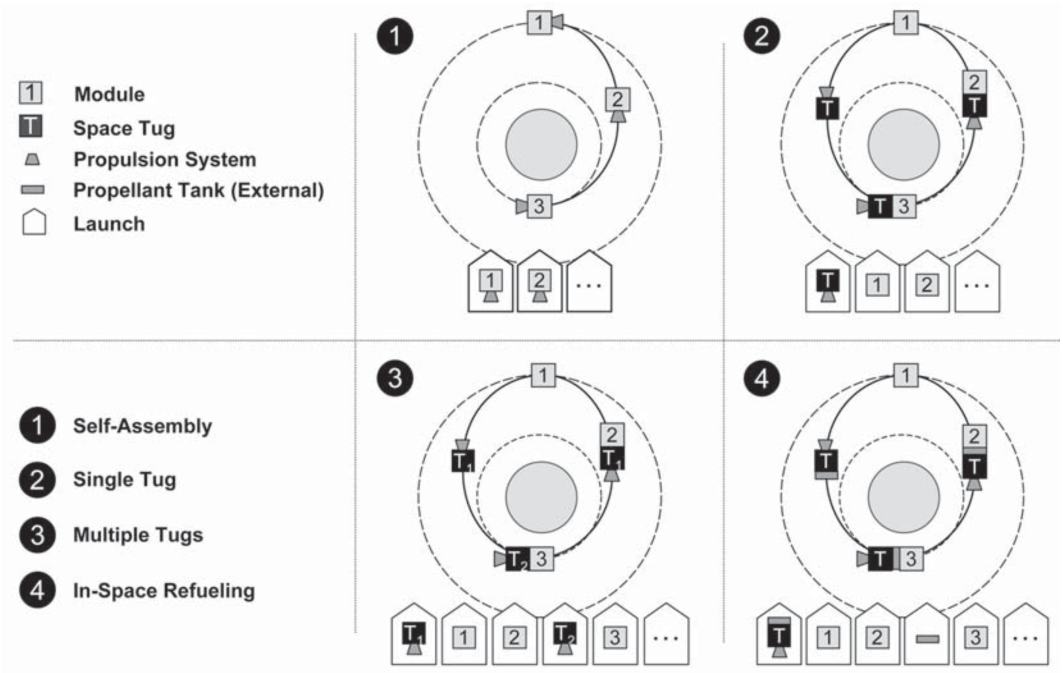


Fig. 1 Illustration of the four basic assembly strategies.

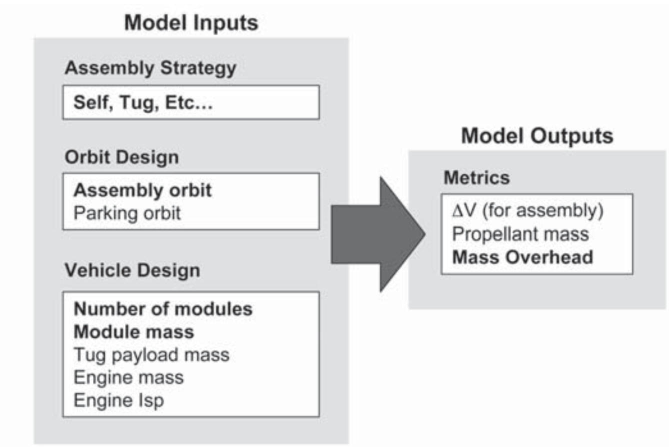


Fig. 2 Assembly model inputs and outputs.

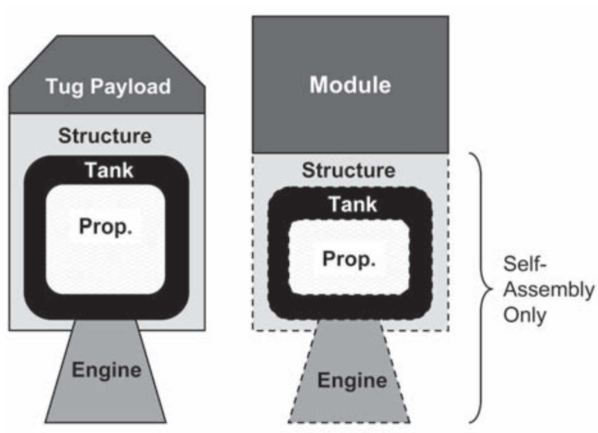


Fig. 3 Notional vehicle models of the space tug (left) and self-assembled module (right).

Fig. 1); 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 Fig. 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; see section 3.4).

The model is composed of three major elements: spacecraft models, propellant requirements, and the calculation of the overhead mass metric; these are described in the following sections.

2.2 Spacecraft Models

Two different vehicles must be modelled (module and tug), along with several variations on each of these vehicles. Figure 3 shows notional models for both vehicles: the space tug (left) and a self-assembled module (right). A module assembled by a tug would consist simply of the 'module' element, with no extra structure, tank, propellant, or engines. Each vehicle is modelled 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.

The mass of each vehicle can be calculated based on a given payload mass, engine mass, and propellant requirement (see Table 1). In the tug case, the payload mass m_{pld} is an estimate of the mass of a docking port or grappling arm. In the self-assembly case, the payload mass is the mass of the module to be assembled m_{mod}. The engine mass m_{eng} is fixed so that it is the same in both tugs and self-assembled modules. The propellant requirements are calculated in another portion of the model. With these three inputs, the mass of each vehicle can be calculated. The tank mass m_{tank} depends on the amount of propellant required for the trip, 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.

TABLE 1: *Assembly Model Baseline Values and Ranges.*

Variable	Type	Baseline	Range	References
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	-	[23]
Module dry mass	Variable	15 mt	5 – 30 mt	-
Number of modules	Variable	5	1 – 15	-
Engine mass	Fixed	200 kg	-	[23]
Tug payload mass	Fixed	300 kg	-	[24,25]
Engine Isp	Fixed	310 s	-	[23]
Propellant Fraction f_{prp}	Fixed	0.12	-	[23,24,26]
Structures Fraction f_{str}	Fixed	0.15	-	[23,24,26]

For the space tug, the vehicle mass calculations are performed according to Eqs. 1.

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

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; it is assumed that the module mass already accounts for its structure. Likewise, the module's docking ports are already accounted for in the module mass.

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

With this framework, the space tug and self-propelled module can be modelled at a reasonable degree of accuracy. Note that the spacecraft 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, it is more expensive to outfit many small modules with their own propulsion systems.

2.3 Propellant Requirements Model

The model calculates propellant requirements by modelling the orbital manoeuvres required to perform rendezvous operations for all modules. Docking operations are not modelled (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 modelled; combined plane changes and altitude changes are not implemented. (These combined manoeuvres would affect most strategies equally, so they would not impact 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), and a Hohmann transfer from the parking orbit to the assembly orbit is then executed. The ΔV for these manoeuvres is calculated according to basic astrodynamics equations, and the propellant requirements are found from the rocket equation (see [23]). Because the tug pushes its own propellant as payload on some transfers, its propellant requirements are calculated iteratively (see [27] for further details).

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

2.4 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. This surrogate metric is here adapted to capture the comparison between the various strategies.

The comparison between the self- and tug-based 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, the overhead mass metric m_v is introduced. 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. 3 below.

Self: $m_v = n_{mod}(m_{str} + m_{tank} + m_p + m_{eng})$

Single Tug: $m_v = m_p + m_{tug}$

Multiple Tugs: $m_v = n_{tug}(m_{p,tug} + m_{tug})$ (3)

In-Space Refuelling: $m_v = n_{tanks}(m_{p,tank} + m_{tank}) + m_{tug} - m_{tank}$

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 modelled 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.

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

2.5 Baseline Parameters and 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.

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 (it has been shown that up to 27 modules may be required, and module masses may reach 100 mt [1]).

3. 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. Recall 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. First, the vehicle scenario parameters are varied, then the orbit design variables. Finally, sensitivity analysis is conducted to understand the impact of some of the assumed and baseline values.

3.1 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.

3.1.1 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).

In Fig. 4 (upper left), 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 slope that increases as the number of modules increases. The reason for this behaviour is that in this scenario, the tug is launched loaded with 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 (up to 6).

The multiple tugs and refueling strategies appear to have an 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 than all other strategies (except single tug at high numbers of modules). This is due to the requirement for a new tug spacecraft for every module transfer: tugs weigh more than the integrated propulsion system on self-assembled modules. Therefore, 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.

Note that the best option (least m_v) over all four graphs 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, 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 (because too many return transfers are required).

3.1.2 Module Mass

Results for variation of module mass from 5 to 30 mt show that the single tug case performs poorly as the module mass increases. Self-assembly and in-space refueling (when M/T is 1) show smaller increases in m_v as module mass increases. This makes sense because the engine mass is fixed and independent of module mass. Thus, as modules are increased in mass, the fixed engine mass is a smaller percentage of the total mass.

The results are plotted in combination with those for variation of the number of modules. Figure 5 shows the overhead mass as a function of both parameters (for M/T=1); the contour plot shows the minimum overhead mass possible at each point. 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 two or three modules. As the mass increases, in-space refueling becomes valuable at lower numbers of modules. The plot makes a very clear case for in-space refuelled space tugs as an assembly strategy.

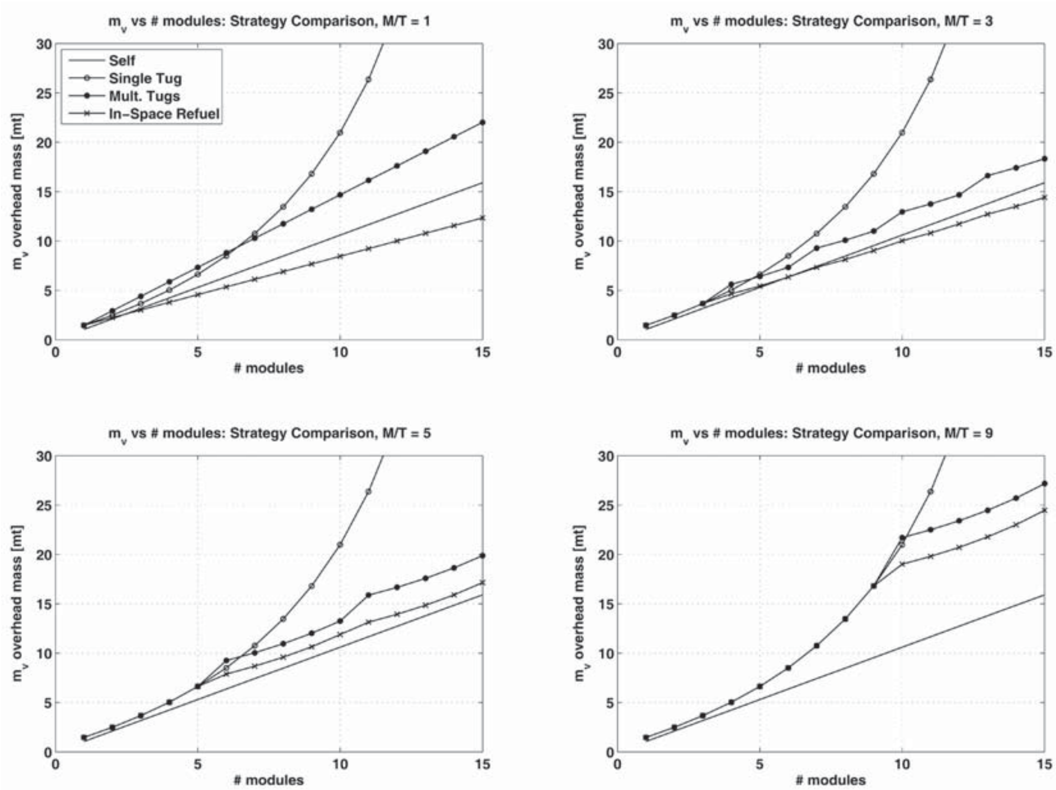


Fig. 4 Results showing the change in overhead mass as the number of modules is varied.

3.2 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 while the parking orbit is held fixed at its baseline value (185 km). The number of modules in Fig. 6a is fixed at 2, and in 6b at 5. In these plots, no inclination changes are required (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 Figs. 6a and 6b, it is clear that increasing the altitude of the assembly orbit increases the overhead mass for all strategies. The results differ based on the number of modules. In Fig. 6a, with a 2-module assembly task, the self-assembly strategy is consistently favoured, for all orbit altitudes. On the other hand, in Fig. 6b (5 modules), the self-assembly task performs worse than in-space refueling when M/T = 1. As found in the previous section, self-assembly has the advantage for small numbers of modules.

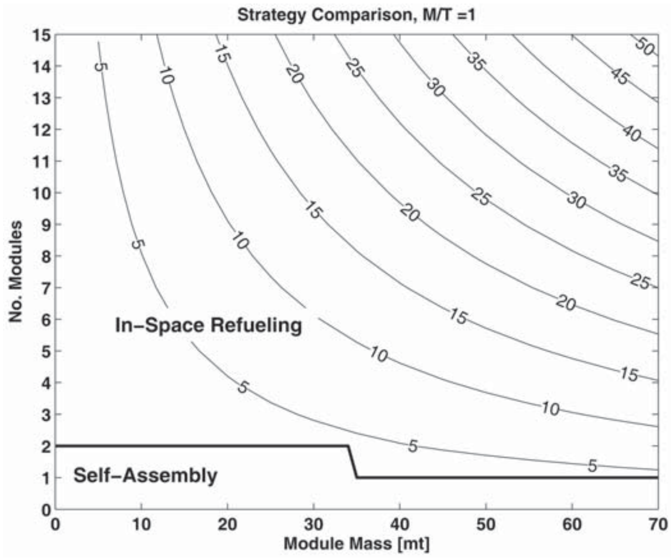


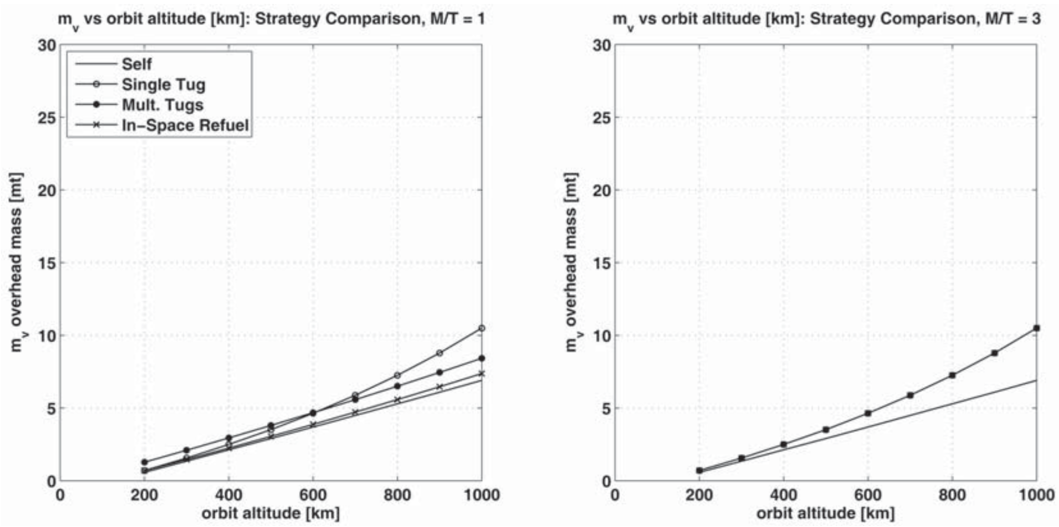
Fig. 5 Contours of minimum overhead mass as a function of module mass and number of modules.

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 a low overhead mass. At 400 km, the baseline assembly orbit, the strategy's overhead mass is significantly higher than most of the others, explaining why the single-tug case always appears poor in the rest of the study. Clearly, the single tug strategy is only competitive when the propellant requirements between parking and assembly orbits are small.

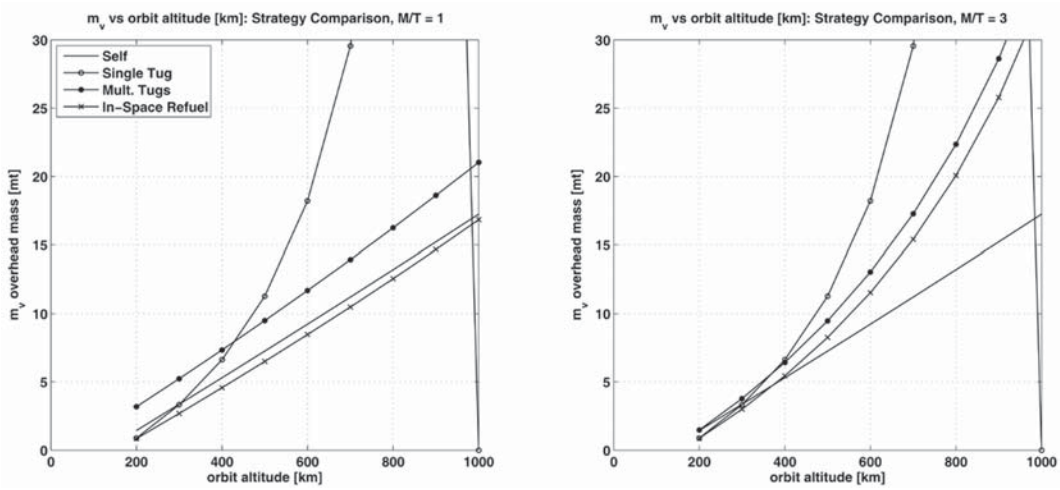
3.4 Sensitivity Analysis

It is important to understand the sensitivity of these results to changes in the assumptions. The most important assumptions are the fixed engine mass m_{eng}, the tug payload mass m_{pld}, the engine Isp, and the propellant and structures fractions f_{prp} and f_{str}. Each of these parameters is subjected to sensitivity analysis, in which each value is varied from the baseline, and the results are analysed to determine the direction and extent of the ensuing change in the results. The analysis shows very little sensitivity to the tug payload mass, the propellant fraction, and the structures fraction (see [27] for more details).

The analysis of the engine mass m_{eng} shows little sensitivity to decreasing engine mass; however, the results are somewhat sensitive to increases in engine mass. In-space refueling remains the dominant strategy in all cases, but gains an even



(a)



(b)

Figs. 6a & 6b (a) Results for varying assembly orbit altitude, *with 2 modules*. (b) Results for varying assembly orbit altitude, *with 5 modules*.

greater advantage over the other three strategies. In addition, the multiple tugs strategy (for M/T=3) is an improvement over self-assembly for most assembly tasks. Therefore, it can be concluded that the results are indeed sensitive to *increases* in the engine mass: including this larger fixed mass on each module makes self-assembly less attractive and tug-based strategies more advantageous.

It is expected that the choice of propellant type, or Isp, for the engine will have a similarly significant effect on the results. The baseline value was 310 s, chosen to match standard bi-propellant propulsion systems. Minor changes in Isp (within the range of chemical propulsion systems) do not significantly affect the results; however, giving the Isp a large boost to 1500 s does indeed change the results significantly. While the in-space refueling case remains dominant, the single tug strategy performs extremely well, and thus is very sensitive to increases in Isp. Therefore, while the results are insensitive to small changes in Isp, the use of electrical propulsion could change the study results significantly, making the use of space tugs more attractive.

For a more detailed discussion of this sensitivity analysis, see [27].

4. CONCLUSIONS

The results of this tradespace exploration clearly indicate that in-space refueling of tugs, as modelled 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, 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. Table 2 provides a concise summary of these results, showing the improvement in overhead mass over self-assembly for various assembly tasks (relative to the baseline case provided in Table 1).

4.1 Assembly Strategy Comparison

It is somewhat surprising that both of the non-refuelled tug-based strategies performed so poorly in this study. On closer examination, however, this result can be explained. The single tug strategy 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 very expensive for large numbers of modules. Single non-refuelable tugs for on-

TABLE 2: *Summary of Results.*

Assembly Task	Best Strategy	% Improvement in m_v Over Self-Assembly	Improvement in m_v Over Self-Assembly [kg]
Low Number of Modules (1-2)	Self-Assembly	-	-
Med-High Number of Modules (3-15)	In-Space Refuelled Tugs (M/T=1)	5-22%	100-3600 kg
Low Assembly Orbit (200 km)	In-Space Refuelled Tugs Or Single-Tug (M/T=1)	41%	600 kg
Med-High Assembly Orbit (400-900 km)	In-Space Refuelled Tugs (M/T=1)	4-14%	550-700 kg

orbit assembly 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, the same problems are encountered as in the self-assembly case: heavy propulsion, docking, and other hardware must be launched 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-refuelled tugs for assembly does not make sense. However, if the propulsion hardware is heavy, non-refuelled tugs could potentially be useful.

On the other hand, *refuelled* 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 refuelled 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, only the required propellant and tank are launched. The only caveat here is that this study does not account for additional propellant required to retrieve each newly launched tank (just as it does not account for propellant for rendezvous with modules, and any excess hardware that may be required to provide attitude control for the tanks). Adding 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 (i.e. traditional Earth orbit rendezvous) 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, self-assembly performs less well than refuelled tugs.

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. 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, it can be concluded 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.

4.2 Future Work

This study could be expanded to model more detailed assembly scenarios. By modelling relevant orbital perturbations such as drag and solar pressure, an optimal assembly orbit could be found (low assembly orbits would incur drag losses, while high assembly orbits require more propellant). The incorporation of non-uniform module masses would allow for the modelling of more realistic assembly tasks, such as lunar or Mars missions.

Additionally, future work could build upon the results of this study's sensitivity analysis for the Isp parameter, which 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). A more extensive investigation of the potential of electric tugs as assemblers, incorporating the capabilities for modelling spiral trajectories and comparing results in terms of time (since electric tugs are generally slow) would be enlightening. For chemically refuelled tugs, future work should focus on the design of an on-orbit refueling system. In addition, quantifying mission complexity and operations cost could affect the boundary between self-assembly and the refuelled tug strategy (see Fig. 5).

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