Methodology for Evaluating Modular Assembly of Large Space Platforms

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Abstract. This paper presents a methodology for analytically comparing approaches to modular assembly of large space platforms. The methodology combines a physical model of the modules, a life-cycle cost model, and a risk model to capture influential trade-offs. The physical model includes alternative module design characteristics, assembly time scenarios, alternative work systems (human, robotic), and infrastructures. A life-cycle cost framework is defined to capture the benefits and costs of modular alternatives for single or multi-mission (programmatic) applications. A probabilistic risk model to address launch and assembly risks is employed to capture uncertainties in launch, as well as in the assembly approaches and their complexity (number of assembly steps, module connections). An illustration of the tradeoffs between these models for a single mission is described using a 448kW Solar Electric Transport Vehicle (SETV) supporting a human lunar mission. The illustration was limited to the launch and assembly phase from beginning of first element launch to completion of assembly. Results and observations are presented and discussed.

Keywords: Modular assembly, in-space construction, large structures.
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INTRODUCTION

The reduction of spacecraft development and mission costs has been a continuing objective of the National Aeronautics and Space Administration (NASA). Recent interest in modular systems as a design strategy for reducing mission and program costs has focused attention on approaches for evaluating and comparing alternative modular space system designs (Caffrey, et al., 2002). Historical space system designs have typically involved customization to requirements whereas modular system design implies some level of standardization via functional "modules." For example, power subsystems and propulsion subsystems that could be plugged together in order to "compose" a variety of systems that would meet a varied number of anticipated requirements.

The property of modularity may be attributable to a single mission (internal modularity) or a series of missions (external modularity). To the extent external modularity is maximized across a mission set, modules in the mission set become increasingly similar. Enforcing commonality across a mission set with varied requirements will tend to reduce the optimization of individual missions. As the missions become more similar in their requirements (e.g., communication satellites) the modularity benefits would be expected to increase.

The question of modularity raises the issue of determining when the benefits of a standardized modular design approach overtake a customized approach. A complicating feature of evaluating modular designs is the difficulty in accounting for the wide variety of affected design objectives. The advantages to affordability, servicing and maintenance, upgrades, reconfiguration, commonality, and reduction of verification and validation testing (the benefits), must be weighed against the costs of developing standardized modules and potentially sub-optimum performance. Modularity attributes are also influenced by the technologies used in the assembly components, the work agents that perform the assembly, and their supporting infrastructure. It is generally recognized in the electronics industry, automotive, and other product industries, that modular design decisions require a life-cycle approach (Kingston, 2003; Ishii, 1997). Recent methods aimed at space mission applications have used cost models (Weck et al., 2005; Enright, Jilla, and Miller, 1998) and geometric optimizations based on the physical properties (mass, volume) of candidate modules (Dorsey 2006, this volume).

Modularity may be defined as the property of a system or systems that allows pre-integrated and self-contained functionality. That is, the ability to combine multiple functions into pre-assembled, self-contained packages. Since the modules are by definition pre-assembled and self-contained packages, modular systems inherently lend themselves to possible in-orbit assembly. One of the major trade-offs for modular systems then becomes how much of the system to assemble on the ground versus in space. This paper will focus on trades dealing with various launch and assembly strategies for modular systems.

The methodology presented in this paper approaches the evaluation of modular designs as a decision problem over three dimensions: a physical model; a life-cycle model; and a risk model. The physical model captures the module characteristics in terms of their physical characteristics (mass, assembly time, number of launches, etc.). A life-cycle cost model approach is used to capture the economic benefits of modular systems, that typically occur during the operations phase and that must be compared to the investment costs of developing the module set. The risk model combines the uncertainties associated with alternative levels of modularity (probability of successful assembly of the completed system) and the impact on cost. Although not included here, a comprehensive model would quantify any decrease in performance due to modularity.

Generally, the advantages of modular systems become more apparent when the system(s) is(are) large enough to require multiple launches and at least some in-space construction. This paper focuses on evaluating modular designs of large space structures to illustrate the approach.

Defining measures of effectiveness for modular systems is fraught with a number of issues. Like cost or risk, modularity is affected by a range of design-related issues which, in turn influence a variety of system design attributes. For example, larger modules will lead to a lower assembly time, but smaller modules will lead to more flexibility in the launch strategy. Table 1 shows additional tradeoffs between modularity levels with respect to in-space assembly.

TABLE 1. Modular In-Space Assembly Trade-Offs

Options	Advantages	Disadvantages
Large modules	Lower overhead per module Lower assembly time May be easier to service (not examined in this trade-study)	Lower flexibility in launch strategy Harder to replace or repair damaged modules (damaged during assembly or during operations)
Small modules	Higher flexibility in launch strategy Easier to replace or repair damaged modules (damaged during assembly or during operations)	Higher overhead per module Longer assembly time May be more difficult to service (not examined in this trade-study)
Large number of low capacity launches	Lower cost per launch Lower impact if lose a single launch	Higher probability of a launch failure Longer schedule since need time between launches More numerous payload integrations Potentially higher nominal cost
Small number of higher capacity launches	Lower probability of a launch failure Shorter schedule Potentially lower nominal cost	Higher cost per launch Higher impact if loose a single launch Fewer payload integrations
Autonomous assembly with robotic agents	Less hazard exposure (higher safety) Can work longer hours than human agents	Higher probability of failure that cannot be repaired Less able to respond to unanticipated events
Assembly requires human agents	Lower probability of failure that cannot be repaired Capability to respond to unanticipated events	More safety constraints Restrictions on hours worked Impacts on design
Near human access	Allows for repairs in event of anomalies	More safety precautions
No human access	Reduced safety constraints	No contingency for robot or assembly anomalies

PHYSICAL MODEL

Because each modular alternative has an associated set of requirements, modules, assembly sequence, assembly work-agent, and associated infrastructure, the following notation for a modular system is employed to formalize the definition of modular alternatives, *Ai*. Since each modular alternative to be evaluated is composed of a series of properties, the definition attempts to correlate these properties to the modular systems. Let:

$$A_i = \langle F_i, S_i, M_i, W_i, I_i \rangle, \tag{1}$$

where:

A_i = Modular alternative, i, designed to meet a set of functional requirements, F_i.

F_i = Functional requirements set (specifications on capabilities of modules and work-agents) for alternative i.

S_i = Set of assembly sequence tasks to assemble modules for alternative i.

M_i= Set of hardware modules to assemble alternative i. Each module object defines a set of physical parameters that map to work-agent assembly performance.

W_{ik} =Work-agent performance set that transforms assembly sequence tasks and module i physical parameters into assembly time estimates for work-agent, k, where k = (1) Extra-vehicular assembly by human, (2) Extra-vehicular robotic assembly, or (3) Autonomous deployment.

I_i = Support infrastructure for the assembly sequence that includes jigs, tools, and special fixtures for modules and work-agents to facilitate and enable the assembly process. The effect of different infrastructures is reflected in the performance times of the assembly sequence work-agents and overall costs of different alternatives, as well as the ability to repair, in some cases. The infrastructure is assumed fixed at the module level.

LIFE CYCLE COST MODEL

The definition of a modular alternative outlined above enables comparative estimates of assembly time and work-agent technology performance to be made. To evaluate the economic impact of modularity, a life-cycle cost approach was outlined to compare alternative modular cases. The differences in life-cycle costs and capital investments between modular system alternatives can be used to identify preferred systems. Note that the investment costs of modularity development specific to each case are included in the analysis. The effects of using human versus robotic work-agents can also be compared by adding the investment costs of human, robot, and infrastructure technology developments. The evaluation of alternative modularity options requires not only a variety of cost inputs, but a number of technical inputs to characterize the benefits associated with advanced technologies, alternative work systems, and special infrastructure needed to assemble the modular elements.

The calculation of net life-cycle cost savings for modular alternative, A_2, versus another less modular alternative, A_1, can be computed as the difference in life-cycle costs minus the capital investment cost of developing the modular technologies (where LCC(A_i) denotes the life cycle cost for modularity case A_i):

$$\begin{aligned} \text{Net Savings} &= \text{LCC}(A_1) - \text{LCC}(A_2) + \text{Capital-Investment Costs}(A_1) - \text{Capital-Investment Costs}(A_2) \\ &= (\text{Initial cost of } A_1 + \text{Operating cost of } A_1) - (\text{Initial cost of } A_2 + \text{Operating cost of } A_2) \\ &\quad + \{(\text{Modular development cost of } A_1 - \text{Modular development cost of } A_2) \\ &\quad + (\text{Work-agent development cost for } A_1 - \text{Work-agent development cost for } A_2) \\ &\quad + (\text{Infrastructure development cost for } A_1 - \text{Infrastructure development cost for } A_2)\} \end{aligned} \tag{2}$$

If the net savings is positive, then modularity alternative A_2 indicates a savings over A_1; if the difference is negative, then modularity alternative A_2 indicates a loss (increased cost) over A_1. For the sake of simplicity here, the following discussion assumes that the work-agent and infrastructure costs are common to both alternatives since the technologies are likely to be comparable for the time horizon of interest, therefore those costs cancel in Equation 1.

In a fully comprehensive model, estimates are needed for the operating costs incurred from the assembly, maintenance, and servicing tasks for each modularity case using assumed work-agents for assembly and their associated infrastructure. The difference in savings from Equation (1) of operating costs for both cases would be discounted over the time period from the first launch to the end of assembly, summed, and compared with the discounted investment cost of any modularity, work-agent, and infrastructure technology investments.

In this paper, modularity comparisons for single missions are performed from first element launch through assembly-complete. The operational benefits are assumed to be similar if not identical (the same functional requirements apply). However, multi-mission programmatic evaluations would need to include the operations phase to account for the alternate costs and benefits of different modular architectures and the interactive benefits between missions (commonality, repairability, reconfigurability). Considerations of differences in development costs, as well as the effects of inflation, are left for a future paper.

LAUNCH AND ASSEMBLY RISK MODEL

For each modular alternative, the costs and assembly times from first launch through initial operations are required. Cost and time can be calculated as sums of the costs and times of the launches and assembly steps to assemble the system. Risk, as incorporated in this study, was simulated through probabilistic failure modeling of launch vehicles and assembly construction steps. The expected values and standard deviations of the assembly-phase costs and times are calculated to provide a measure of the launch and assembly uncertainties on cost and time.

The probability distributions of launch vehicle failure and assembly failure can be viewed as Bernoulli processes with the number of trials equal to the number of launches or assembly steps. However, the calculation of the distribution of actual expected costs and time is complicated by the need to take different actions in the event of a potential launch failure, assembly step failure, whether a repair can be performed, and the likelihood the repair is successful. If a launch failure occurs, that entire payload must be replaced; if an assembly failure occurs, only a single module need be replaced. If a repair can be attempted, additional launch may be averted. The decision variables for the approach described in this paper focused on the expected assembly cost incurred and the expected time required to go from first launch until the system would be operational (assembly-complete) .

A Monte Carlo simulation approach is proposed to model the probabilistic relationships underlying the expected time and costs of the launch and assembly process. The inputs required to simulate the assembly risks include: (1) definition of the launch vehicle manifests and corresponding launch vehicles as a function of each level of modularity; (2) the probabilities of launch failure for each launch vehicle examined (from historical data); and (3) specification of an assembly sequence, S_i, for each launch, including the probabilities of successfully completing each step. The simulation can then map the uncertainties in launch vehicles with the uncertainties in completing the entire assembly sequence and the actions if a failure occurs, into the estimates of the means and standard deviations of the expected cost and assembly-time. The three classes of failures contributing to the assembly risk were assembly step failures, failure of a module autonomous deployment sequence, or a launch failure. The added cost and time required for contingency launches and repairs can be added to the running estimates of cost and time as the simulation progresses. This provides total expected cost and time estimates for the launch and assembly phase of the mission.

The simulated expected values, E[--],were computed using:

$$E[Cost_{Launch\&Assembly}] = \sum_{i=1}^{N} Cost_i / N$$
$$E[Time_{Launch\&Assembly}] = \sum_{i=1}^{N} Time_i / N \qquad (3)$$

where:

$Cost_i$ = Cost of launch, assembly, human repair, and support costs incurred during Monte Carlo trial i.

$Time_i$ = Time required for launch, delays incurred due to failed launches and assembly problems, time for assembly, and time for replacement or repair (if available) during Monte Carlo trial i.

N = Number of Monte Carlo trials performed in the simulation.

For each modular design case, the cost and time required are calculated from technical design inputs (the physical model), cost inputs (the life-cycle cost model for launch, assembly, and replacement modules/launches), and estimates of the assembly-step and launch vehicle failure rates. It was necessary to capture the costs of all launches including scheduled (baseline) launches plus any additional launches required due to launch or assembly failures. The expected cost of assembly (in space), $E[Cost_{Launch\&Assembly}]$, was derived from these launch costs, the assembly time and number of steps required and the cost of any repairs that required human intervention. The expected time for assembly (in space), $E[Time_{Launch\&Assembly}]$, was derived from the time required for all baseline launches, the time required for assembly, the additional time required to prepare after a failed launch or assembly step, and the time required for any replacement or repairs.

MODULAR SPACE TRANSPORT CASE STUDY

A candidate 448kW solar electric transport vehicle (SETV) for the transport of logistics supplies from low Earth orbit to lunar orbit and return was selected to illustrate the methodology and is described elsewhere in this volume in detail (Wingo, this volume). The vehicle uses solar electric propulsion with electric power provided by solar arrays feeding a series of xenon thruster propulsion units. The design consists of a center keel beam with side truss supports that carry the solar arrays and propulsion units.

The smallest SETV unit or module consists of the appropriate combination of truss beam, solar array package, and primary propulsion units (PPU) to make a 28kW module. Various levels of integration on the ground into larger modules can then be considered. For the concept analyzed in this study two levels of modularity and four assembly scenarios were considered [HIGH or LOW integration on the ground/LOW or HIGH assembly required on orbit]:

A1. HIGH/LOW-2LAUNCH: Two fully deployable 224kW modules transported with 2 launch vehicles. Modules are launched and released from the launch vehicle as separate units. Both modules have stability and control capability and use automated deployments to reach full size. Modules autonomously rendezvous and berth together. Assembly failures must be replaced with new modules launched separately. No capability for repairs by human or robot during assembly. This option required a total of two Delta IVH launches.

A2. LOW/HIGH-2LAUNCH: Sixteen deployable 28kW modules, combined with robot assembly and divided between two launch vehicles. This option differs from A1 in that the large 224kW modules have been subdivided into eight smaller modules that must be separately grappled and positioned on the main keel by a robot work system. Each set of eight modules is launched in a container which has basic stability and control capability. No capability for repair by humans. This option requires a total of two Delta IVH launches.

A3. LOW/HIGH-2LAUNCH-Repairable: Identical to A2 except the option to repair by human EVA is available (i.e. assembly is performed in the vicinity of the ISS), with a given probability of successful repair. If a repair is unsuccessful, another module is launched with its associated costs. This option also required a total of 2 Delta IVH launches.

A4. LOW/HIGH-8LAUNCH: Sixteen deployable modules combined with robot assembly and divided between eight launch vehicles. This option is similar to A2 except the modules have been distributed across eight Delta II-7925H launches to examine the effects of lower individual launch cost on modular assembly costs.

The modular analysis methodology was applied to each of the four options to illustrate the approach, with the life-cycle time period constrained to the assembly phase to capture differences due to module size, assembly times, and launch vehicles.

The inputs for the physical model were the masses of each module, the number of modules required, and the capability (payload mass) of the launch vehicles. The masses determined the launch vehicle packaging and manifest for each launch. Also input were the assembly sequences, including type and number of assembly steps of each type.

The life-cycle inputs included the cost and time estimates for assembling each case. The assembly steps were broadly grouped into five activities: detachment of items from the payload shroud for assembly; attachment of items to their target location (keel beam); autonomous deployment; verification of successful attachment and deployment; and berthing of modules. Activity time estimates were based on the sizes and masses of the modules. Launch vehicle costs focused on two vehicle types with the largest payload mass capacities in their class, the Delta IV-H and the Delta II-7925H. Because the performance requirements for each of the four systems were the same, the initial development cost was assumed to be the same for all cases and were not included in the analysis. The costs for launch vehicles, assembly, and replacements, if necessary were the primary cost inputs.

TABLE 2. Summary of Modularity Cases.

Module Option	**Assembly Features**	**Module Configuration**	**Module Mass,kg**	**Launch Vehicle**	**Launch Number**	**Launch Cost $M/launch**
HIGH/LOW-2LAUNCH	Deployment, autonomous rendezvous and berthing	2x200kW	19,387 x 2	Delta IV-H	2	204
LOW/HIGH-2LAUNCH	Deployment, robotic crane for 16 module emplacements on keel beam prior to deployments	1x50kW + 6x25kW +8x25kW	2,423 x 16	Delta IV-H	2	204
LOW/HIGH-2LAUNCH-Repair	Deployment, robotic crane for 16 module emplacements on keel beam prior to deployments; potential for correction of assembly failures by human EVA	8x25kW + 8x25kW	2423 x 16	Delta IV-H	2	204
LOW/HIGH-8LAUNCH	Deployment, robotic crane for 16 module emplacements on keel beam prior to deployments; additional launch integrations.	(2x25kW) x 8	2423 x 16	Delta II-7925H	8	89

The risk model required inputs of failure probabilities for the launch vehicles and for each of the types of assembly steps. Since the focus of this example was on the effects of assembly and launch risk, mission risk, development cost risk, and technical risks were not addressed for the purposes of this illustration. The tradeoffs are limited to those between the module size (mass), assembly time, assembly risks, number of launch vehicles, and their cost to transport the system to orbit. Tables 2 and 3 summarize the inputs used in this analysis. Probability of launch vehicle failure for the Delta II-7925H was set at 0.02 per launch, based on historical data, and the same value was used for the Delta IVH. The values for assembly were derived by analogy to other in-space tasks by grouping assembly primitives into five large categories: detach, attach, deploy, verify, and berth. These frequencies of each category were estimated for each module design option and the probabilities of step failures were estimated based on comparisons to construction of the International Space Station.

The physical model, life-cycle model, and risk model were embedded within a Monte Carlo simulation using a commercial mathematics software package. The simulation tracked any assembly or launch failures from trial to trial while accounting for additional costs and times. For Case A3 with repair capability, a probability of repair was included to address situations where assembly failures could be resolved by human-performed repairs. The simulation maintained running means and standard deviations of the total assembly costs and assembly times reported below as the primary measures for comparing the alternative cases.

RESULTS

The numerical results are presented in Table 4 revealing that the costs and assembly times for case A4 were significantly larger than for the other cases. This was primarily due to the much higher cost/lb of payload for the smaller launch vehicles compared to the larger ones. Even though the Delta II-7925H launches made more efficient use of their payload capabilities (100% vs 67% for the Delta IV-H), the effective cost/lb was still a factor of 1.8 x that for the Delta IV-H. The expected assembly times almost tripled because the required time to execute all the launches was longer. Therefore, only in the unlikely situation where the failure probabilities for the Delta IV-H and/or the assembly/deployment steps are much higher than considered here, would case A4 be cost effective.

TABLE 3. Input Parameters for Modularity Analysis Model.

Input parameter	A1	A2	A3	A4				
Rebuild cost/module	\$184M	\$23M	\$23M	\$23M				
Rebuild time/module (months)	24	3	3	3				
Assembly step parameters								
Type of step	**Number of steps of each type**				**Hrs/step (robot)**	**Failure prob/step (robot)**	**Hrs/step (human repair)**	**Success prob/step (human)**
- Detach	2	16	16	16	1.2	0.0001	3	0.89996
- Attach	1	16	16	16	8	0.002	3	0.89910
- Deploy	88	80	80	80	0.25	0.0002	1	0.99980
- Verify	90	97	97	97	0.25	0.0002	0.5	0.99990
- Berth	1	1	1	7	6	0.001	3	0.99900
Cost/hr for assembly (robotic)	\$67K	\$67K	\$67K	\$67K				
Cost/hr for repair (human)	\$254K	\$254K	\$254K	\$254K				

Also shown in Table 4 are the nominal values for assembly cost and time. The nominal values are idealized estimates assuming no failures in assembly steps or launches. For A1, A2, and A3, the expected costs are close to the nominal costs. This is because the nominal failure probabilities assumed here are quite small. Furthermore, the nominal costs are dominated by the launch vehicle costs, the small differences between A1, A2, and A3 being due to differences in the numbers of assembly steps per case. The expected costs in the each case are, of course larger than the nominal costs, due to the potential for failures in launch and/or assembly. In all three cases, a failure of either or both of the two (nominal) Delta IV-H launches would require equally costly replacement launches. An assembly failure in case A1 would require a replacement launch and payload equal to the original one. However, in cases A2 and A3, an assembly failure would only require a Delta II-7925Hreplacement launch, with a single 28kW unit. Therefore, the increase in the expected cost over the nominal cost for case A1 should be larger than in cases A2 and A3, and this is seen in the figures and tables. In case A3, an astronaut repair can avoid a replacement launch; therefore, the effective probability of an assembly failure is reduced by a factor equal to the fraction of failures that can be repaired. So the expected costs for A3 should be less than for A2, and, again, the numerical results are consistent with this logic. Note that no additional costs associated with having astronauts available for repair have been considered in this study.

On further examination of options A1, A2, and A3 in Table 4, it is apparent that any observations about assembly costs must be informed by consideration of the standard deviations. The expected costs indicate small differences between A1, A2, and A3, however, even the smallest coefficient of variation (Case A3) is almost 20% of the expected cost (82/437 x 100% = 19%) indicating high levels of uncertainty effects from assembly and launch on cost. The case with the highest variability (26%) is A1 because both launch failures and assembly failures require an entire 224kW module replacement and a Delta IVH to launch it. Cases A2 and A3 each have a lower variability compared to A1, reflecting the lower cost impact of an assembly failure (one 28kW replacement unit launched by a

Delta II-7925H). The variability for Case A3 is slightly less than that for A2 because human repair of an assembly failure is significantly less expensive than a replacement launch. The assembly cost variability is lowest for option A4 because both assembly and launch failures can be mitigated by one or two 28kW replacement units launched by a Delta II-7925H.

The impacts of uncertainty are even more dramatic for expected assembly time. The increased uncertainty from the time delay impacts of assembly and launch failures yields standard deviations that exceed the mean (i.e., more than 100%). This result is due to the dominance of the launch schedule over the assembly times and the assumed very large impacts on the launch schedule if a failure were to occur. In any of the cases in which two Delta IVH launches are used (A1, A2, and A3), the assumed nominal launch schedule requires 3 months between launches. If a failure occurs requiring a new launch however, half of the entire payload needs to be completely rebuilt. This is assumed to take 24 months. Therefore, if no failures occur, the required time for launching the system is 3 months. If a failure occurs, this time jumps all the way to 27 months, causing an extremely large variation and standard deviation. This can be compared to the A4 case, in which eight Delta II-7925H launches are required. In this case the assumed nominal launch schedule requires 1.5 months between launches, leading to a nominal required time of 10.5 months for all 8 flights if no failures occur. If a launch failure occurs, 2--28kW modules are required to be rebuilt, leading to a additional 6 months of required time. Therefore, for case A4 the nominal launch schedule requires 10.5 months and the launch schedule with a failure requires only 16.5 months, leading to a much lower variation and standard deviation, as shown in Table 4. Clearly, different assumptions about times to rebuild or different strategies (e.g. developing spares prior to first launch) would lead to different values for the standard deviations.

Figure 1 displays the results by plotting each of the four cases as rectangles with dimensions equal to plus or minus one standard deviation from the mean for assembly cost and time. The larger the area of a rectangle the larger is the degree of uncertainty represented by the standard deviation. The expected values in each case are plotted as small cubes in the center of the rectangles. The graph shows the similarity of cases A1, A2, and A3 due to their shared two-launch feature. Case A4, the eight-launch case has such a high nominal (i.e. no failure) cost, that A4 is significantly separated from the other cases in the diagram.

TABLE 4. Results of Modular Analysis Showing Expected Assembly Cost and Time Values with Standard Deviations and Coefficients of Variation.

		Assembly Cost (Millions of 2005 dollars)			**Coeff. Of Variation**	**Assembly Time (Months)**			**Coeff. Of Variation**
Case	*Modular Option*	*Nominal Cost*	*Expected Cost*	*Std Dev'n*	$\frac{\sigma}{\mu}x100\%$	*Nom'l Time*	*Expected Time*	*Std Dev'n*	$\frac{\sigma}{\mu}x100\%$
A1	HIGH/LOW-2LAUNCH	$412 M	$443 M	±$113 M	26%	3.1 mos	5.0 mos	±7.1 mos	142%
A2	LOW/HIGH-2LAUNCH	421	446	±90	20%	3.3	4.5	±5.3	118%
A3	LOW/HIGH-2LAUNCH-Repairable	421	437	±82	19%	3.3	4.2	±5.2	124%
A4	LOW/HIGH-8LAUNCH	728	761	±68	9%	10.8	12.1	±2.8	23%

To examine the sensitivity of the results to the input parameters, a number of input values were modified by simultaneously increasing/decreasing their nominal values by 25%. The result was a best case/worst case range for expected cost and assembly time. The parameters varied included: the probabilities of a launch vehicle failure, an assembly step failure, successful repair of an assembly step failure (Case A3), as well as cost of the launch vehicle, hourly cost of the assembly time, and the times for assembly and repair (Case A3).

The numerical results are shown in Figure 2 and in Tables 5 and 6 for assembly cost and time, respectively. The cost results (Table 5) indicate that changes in results are approximately linear with changes in inputs—a 25% change in the inputs yields a 26-27% change in the outputs. The assembly time results in Table 6 appear to be more robust in their resistance to the effects of changes to the inputs—a 25% change in parameters only yields at most, a 12% change in the resulting expected assembly time and in most cases, less than a 10% change effect.

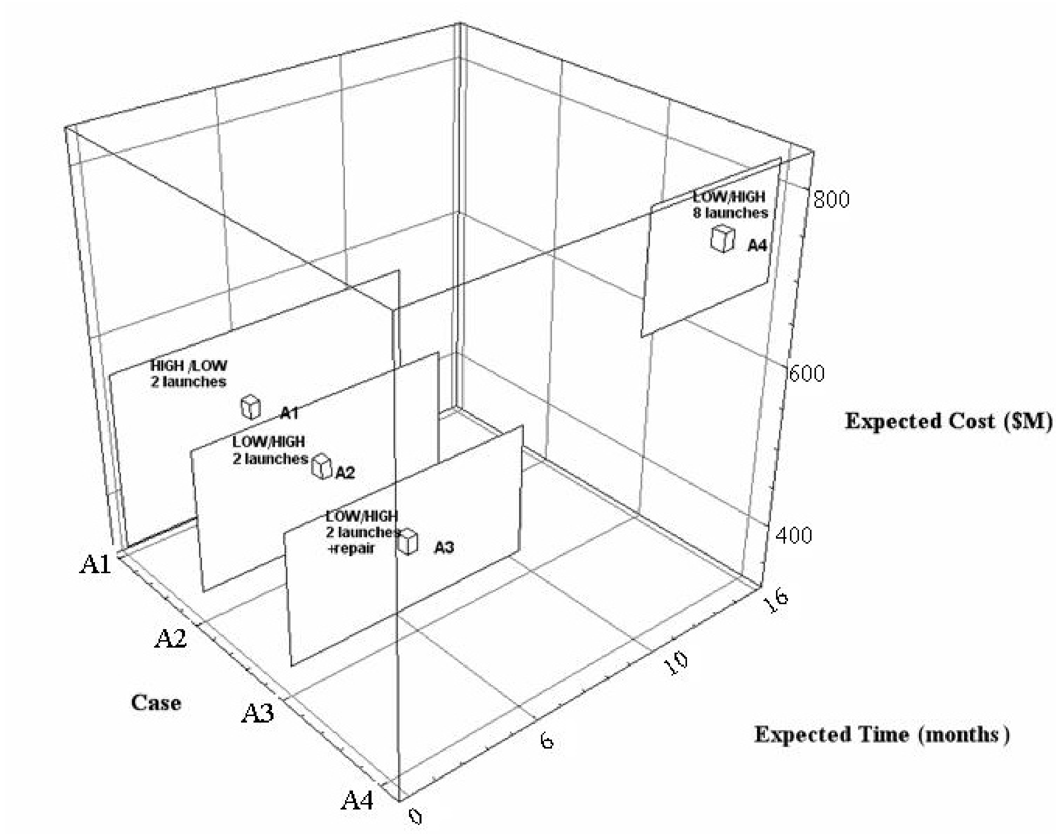

FIGURE 1. Expected Cost and Assembly Time for the Four Cases. Expected Costs and Times are Shown as the Small Rectangles in the Middle of the Ranges, Which are Cost and Time +/- 1 Standard Deviation.

This robustness is due in large part to fixed assumptions about the length of time required between launches and after a launch failure. The effects of changing low probabilities of failure by 25% are likely diluted by the small numbers (e.g., increasing a launch failure probability from 2% by 25% yields a value of 2.5%).

TABLE 5. Sensitivity Analysis of Cost Results to +/- 25% Variation of Inputs.

		Assembly Cost (Millions of 2005 dollars) Baseline Results		**Assembly Cost (Millions of 2005 dollars) Sensitivity Results**		
Case Identifier	**Modular Option**	**Expected Cost**	**Standard Deviation**	**–25% Change**	**+25% Change**	**Effect (change)**
A1	HIGH/LOW-2LAUNCH	$443 M	±$113M	$330 M ±$87	$561 M ±$145	–26% to +27% change
A2	LOW/HIGH-2	446	±90	329 ±65	568 ±116	*–26% to +27%*
A3	LOW/HIGH-2 Repairable	437	±82	324 ±62	553 ±103	*–26% to +27%*
A4	LOW/HIGH-8	761	±68	563 ±48	964 ±$116	*–26% to +27%*

TABLE 6. Sensitivity Analysis of Assembly Time Results to +/- 25% Variation of Inputs.

		Assembly Time (Months) Baseline Results		Assembly Time (Months) Sensitivity Results		
Case Identifier	**Modular Option**	**Expected Time**	**Standard Deviation**	**–25% Change**	**+25% Change**	**Effect (change)**
A1	HIGH/LOW-2LAUNCH	5.0 months	±7.1 months	4.6 months ±6.3	5.6 months ±8.0	–8% to +12%
A2	LOW/HIGH-2	4.5	±5.3	4.1 ±4.5	5.0 ±6.0	–9% to +11%
A3	LOW/HIGH-2 Repairable	4.2	±5.2	3.9 ±4.4	4.5 ±5.7	–7% to +7%
A4	LOW/HIGH-8	12.1	±2.8	11.7 ±2.4	12.6 ±3.1	–3% to +4%

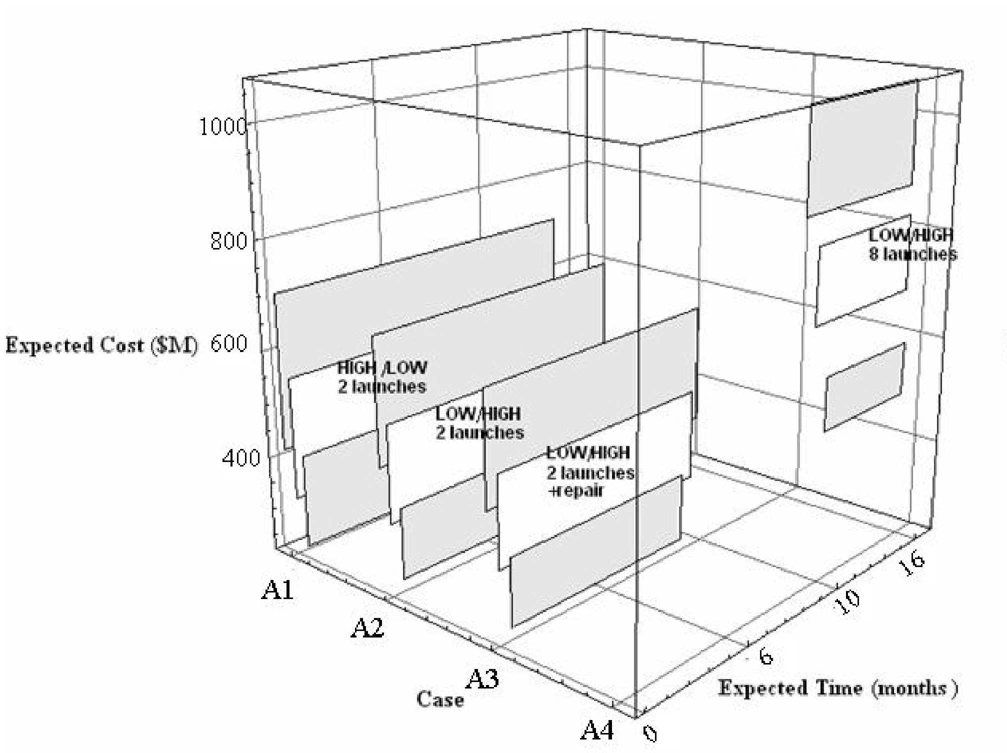

FIGURE 2: Expected Values and Standard Deviations for Cost and Time with ± 25% Increase/Decrease in the Input Parameters as Specified in the Text. Light Areas are Baseline Regions; Dark Areas are Sensitivity Regions.

DISCUSSION AND CONCLUSIONS

The methodology described in this paper was developed to compare alternative modular designs. Recognizing that modularity is composed of multiple competing objectives required the development of a multi-dimensional methodology. The resulting approach contained a three-fold set of sub-models to capture the major features of modular systems and their tradeoffs. The first sub-model represented the physical attributes of a modular system in terms of its requirements, mass, volume, assembly sequence, assembly times, work-agents for assembly, and infrastructure to support the assembly process. The second sub-model represented the life-cycle characteristics of the assembly process through estimation of costs and time estimates for launch, assembly, replacements, and eventual operations. The third sub-model was intended to capture the risks and uncertainties pertinent to the launch and assembly phase in order to determine total expected launch and assembly costs and times.

The approach was limited in a number of ways. The first limitation was the scope of the physical model. The use of launch mass and assembly times to represent the primary physical attributes were useful as a first approximation, but there may be other constraints such as launch volume or power requirements that could impact the expected costs and assembly times. Future model development to expand the modeling of physical properties of modular systems is recommended.

Another limitation of the approach is the need for techniques to capture some of the more elusive benefits of modularity, such as reconfigurability, commonality, and reliability. A need for comparing different technological approaches to assembly was also identified. Examples include the analysis and comparison of modular alternatives using deployable, erectable, and inflatable structures. More work is needed to expand the modeling of uncertainties for the physical attributes of the alternatives. For example, the masses and assembly-step times used for the modules were uncertain quantities. The costs used for the life-cycle model were also highly uncertain and could be modeled with probability distributions over their ranges.

While the SETV case study was intended as an illustration of the methodology, it suffered from a number of shortcomings. The SETV was a singular mission—no attempt was made to identify potential benefits of reconfigured mission applications that would allow comparison of modular systems with and without capabilities for reconfiguration. In addition, because the SETV was a single mission, no comparisons could be made of the programmatic benefits potentially available in a multi-mission environment where a variety of standardized sub-modules (power subsystems, propulsion subsystems, etc.) could have cross-cutting benefits across a number of missions. Another shortcoming of the case study was the restriction of the lifetime selected for the life-cycle sub-model to the assembly phase through assembly-complete. No benefits of modular design were accounted for in the operations phase of the mission which may have altered some of the results.

Other metrics can be added to or substituted for those used in the SETV case study. It is straightforward to investigate the sensitivity of the chosen metrics to any or all of the parameters which characterize the problem of interest. As in any analysis of this type, the validity of the results is determined by the quality of the input data, though general conclusions can often be drawn even in cases where the inputs are simply ‘educated guesses’.

During the course of this study a number of observations and conclusions were drawn.

The Methodology:

- The methodology presented here was useful for understanding the interactions and tradeoffs between the physical, life-cycle, and risky elements of modular design for a single mission.

- Because modularity is a complex of multiple and competing elements (reconfigurability, affordability, reliability), the methodology was based on the physical characteristics of module designs, the life-cycle costs of the designs, and the inherent uncertainties in the assembly processes and launch vehicles. This three-fold approach provides a triangulation on the nature of alternative modular designs with the aim of finding minimum cost and risk solutions.

- Without loss of generality, the approach should be readily extensible to the analysis of programs with multiple missions. The method is not specific to the application considered here (i.e. to the SETV) and could easily be adapted to a wide range of different missions.

The SETV Case Study:

The SETV case study clearly illustrated critical determinants of modular design for large space structures. These included: the expected costs and assembly times for building a modular system, the transportation (launch) costs of subdividing modules for the purpose of determining tradeoff between large modules and small number of launches versus small modules and larger number of launches, the uncertainties associated with assembling the modules (assembly step failure probabilities), and the uncertainties associated with transportation systems (launch failure probabilities).

A sensitivity analysis of the results revealed that the launch costs and launch interval times were the major influential factors in the analysis. It was found to be cost effective to use as large a launch vehicle as practical—in this case, launching on two Delta IV-H's was substantially less expensive than on eight Delta II-7925H's, given the failure probability for the two vehicles was comparable. Given the choice of a large launch vehicle, it is somewhat more cost and time effective to divide a systems into smaller modules because the consequences of an assembly failure on orbit are less severe. In addition, the ability to mitigate or repair assembly failures (including autonomous deployments) provided an advantage as long as the infrastructure costs were not charged entirely to the mission.

This work has outlined an approach for comparing complex modular design options toward the development of large in-space structures. A top level comparison of several different SETV approaches was used to illustrate the approach and open a window on the complexities of this relatively unexplored area of space systems design research.

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