REDUCING RISK OF LARGE SCALE SPACE SYSTEMS USING A MODULAR ARCHITECTURE

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Abstract

Future requirements may dictate the need for very large spacecraft architectures. At present, the only approach to placing large spacecraft into orbit is use of a heavy lift launch vehicle. But, given the new capabilities demonstrated by NASA's DART, and DARPA's Orbital Express, RASCAL, and FALCON, it is reasonable to envision an alternative means of placing large spacecraft into orbit, that being multiple responsive launches of discrete modules which are later assembled on orbit. An analysis was performed to compare the risks and benefits of single large spacecraft launch versus a multiple small module launch approach. The results of this probabilistic analysis show that fragmenting a system into modules can significantly reduce the deleterious cost and schedule impact incurred by possible failures. In short, a single launch of a monolithic spacecraft poses significant risk; should failure of a large spacecraft launch occur, the penalty is the significant sum total of both launch and spacecraft costs. By comparison, there remains some finite risk of failure for each launch of a smaller fragmented spacecraft module, but the impact of failure of a given launch is less severe. The analysis finds that the "assured" total life cycle cost for sum of all required modular launches can be nearly a factor of two less than the total "assured" life cycle costs for a single launch of a large spacecraft with the same capability. Here, "assured" is defined as when the cumulative probability of mission success is 99.9%. Additional benefits using the modular launch approach are realized because of production learning effects and the real value provided by the flexibility of a serviceable and scalable architecture.

Introduction

My ventures are not in one bottom trusted,
Nor to one place; nor is my whole estate
Upon the fortune of this present year;
Therefore, my merchandise makes me not sad
Shakespeare, The Merchant of Venice, Act I, Scene 1

Don't put all your eggs in one basket: this bit of advice is a golden rule of risk management. A more scholarly and succinct way of saying the same thing is to state, "diversify." Diversification is a fundamental precept in the arena of investment. In his seminal work, which was eventually awarded the Nobel Prize in Economics, Harry Markowitz provided the analytical framework which explains why and how a wise investor should choose an investment strategy based not solely on maximum return, but rather on a trade between efficient selection of the expected value of return and its variance (related to its volatility).[i] In Markowitz's analysis, it is shown that "efficient frontiers" exist which allow one to maintain desired levels of return but minimize risk by an appropriate diversification of investment in a multitude of equities.[ii]

Let us now turn to an analysis of how we, today, would invest in a large space system. Requirements for large transmission bandwidth, significant aperture sizes for sensing, and multiple mission capabilities may force spacecraft to very large sizes, possibly in excess of 10,000 kg. Such a system by convention would be (a) constructed monolithically and (b) launched on a heavy lift launch vehicle. Why do we do it this way? Well, there appears to be no other way. But, what if an alternate philosophical approach were taken? First suppose, instead of constructing a monolithic spacecraft, the system were broken up into

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distinct building blocks, i.e. modules. There are many advantages to this approach. Enhanced capability of on-orbit reconfiguration, upgrade, and replacement are among the benefits. In addition, it may be physically impossible to find a launch vehicle with the capacity to launch a large new space system, so there would be no other choice than to fragment the system and then later assemble the modules on-orbit. On-orbit assembly is a daunting and currently expensive task; our current experience exists only with manned assembly at International Space Station. Given our human spaceflight capability, such manned assembly can currently take place only in LEO – GEO type missions would require autonomous assembly capability. But new advanced technology demonstrations will begin to provide possible solutions to the challenging task of autonomous assembly of space structures. DARPA's Orbital Express and NASA's Demonstration for Autonomous Rendezvous Technology (DART) programs will demonstrate automated rendezvous, docking, and (in the case of Orbital Express) repair and upgrade of in-orbit spacecraft. Thus, we can assume that on-orbit rendezvous and assembly of modular systems are eventual possibilities. There probably will be some added cost due to complexity to the spacecraft, and it may also be more massive than the monolithic counterpart, but the flexibility provided by the system may provide significant value. In addition, some very modular systems could provide capabilities impossible with monolithic counterparts (e.g. very large sparse arrays).

Assuming now that modularization of a spacecraft is an eventual possibility, let us now turn to the second significant cost and risk component of the system, the launch vehicle. Even if we were to modularize a system, current economies of scale would dictate that we use the launcher with the greatest appropriate capacity. That is, one would most probably attempt to launch the greatest number of modules all at once. But, this paradigm could change. DARPA's Responsive Access Small Cargo Affordable Launch (RASCAL) and the DARPA/USAF Force Application and Launch from CONUS (FALCON) programs will develop and demonstrate space launch vehicles capable of rapidly and responsively placing small payloads into orbit at dramatically reduced costs. So, assume that it is just as economical to launch the modules of a large space system on small launch vehicles. In addition to the benefits of responsiveness, are there advantages to this approach? The answers to this question are the theme of this paper – and are very much related to a Markowitz-like approach to investment. By launching a large monolithic system on a heavy lift vehicle, one is putting all his eggs in one basket. After sweating a twenty to thirty minute ride to space, most times the investors in a large space system are very happy, and have maximized their return. But, the cost of variance is huge: one strike and you are out of hundreds of millions and possibly billions of dollars, as well as the immediate capability required for market advantage or national security. Compare this volatility to that encountered in a launch of just one small component of a space system: the probability of loss of this component will be similar to that of a large monolithic system, but the impact of this potential loss will be less severe. Of course, what is of interest is the volatility of the entire system, involving all required launches. Analysis is thereby required to compare the expected return (actually cost, with revenue held constant) and the variance of a space system with varying degrees of modularization.

The analysis which follows examines the hypothesis that risk – as measured by the standard deviation of lifecycle cost - can be reduced by a diversified strategy towards placing a large space system into operation. This diversification is accomplished by means of "fractionation" of a space system into modules and then launching those modules individually on smaller scale launch vehicles. Scaling inefficiencies due to modularization may occur and cost penalties associated with organic rendezvous and docking capability might exist. But, advantages brought about by production learning effects may exist. The impacts these factors have on the expected value of life cycle cost are examined in the course of this analysis.

Approach

The approach of this paper will be to model the costs of both large, monolithic spacecraft with some given capability and a large "fractionated" modular space system with identical capability. This analysis will concentrate on the non-recurring expense (NRE) of both types of approaches; operating costs (OC), will not be included as part of this analysis. It is typical for large space systems that OC are small as compared to NRE, hence it is assumed throughout this analysis that NRE for the space system (NRE_{system}) and Lifecycle Costs (LCC) are equivalent, i.e.,

$$NRE_{system} \approx LCC \quad \text{(Eq. 1)}$$

Once cost models for the monolithic and modular systems are determined, some assumption will be made to create a universal costing scheme, valid for either architecture.

Monolithic Spacecraft Cost

Assume a large monolithic spacecraft, with the characteristics shown in Table 1.

Table 1. Large Monolithic Spacecraft Characteristics

Monolithic Spacecraft
Mass (wet) = M
Capability=χ
Non-Recurring Expense=NRE_{mono}

χ represents the critical measurable system attribute, for instance total transponder bandwidth at some carrier frequency, or as another example, images per unit time at some given resolution. The NRE for the monolithic system, $NRE_{system,mono}$, is assumed to be a direct function of spacecraft costs, $C_{S/C,\ mono}$, and launch costs, $C_{launch,\ mono}$:

$$NRE_{system,mono} = N_{launches}\left(C_{S/C,mono} + C_{launch,mono}\right) \quad \text{(Eq. 2)}$$

Eq. 2 accounts for the chance that more than one launch will be required to achieve mission success (e.g. due to a launch failure), thus the total number of launches, $N_{launches}$, required for mission success appears. Ideally of course, $N_{launches}=1$.

The two main components of NRE_{mono} can be determined as functions of spacecraft mass, M:

$$C_{S/C,mono} = MS_{cpm,mono} \quad \text{(Eq. 3)}$$

$$C_{launch,mono} = ML_{cpm,mono} \quad \text{(Eq. 4)}$$

Where $S_{cpm,mono}$ and $L_{cpm,mono}$ are the costs per unit mass of a large monolithic spacecraft and a heavy-lift launch of a monolithic spacecraft respectively. Note that a simplifying assumption is made here that $C_{launch,mono}$ is expressed as a function of spacecraft wet mass, whereas parametric cost analyses would most typically rely on spacecraft dry mass for cost estimation relationships. Combining Eq.'s 2-4 therefore,

$$NRE_{system,mono} = N_{launches}M\left(S_{cpm,mono} + L_{cpm,mono}\right) \quad \text{(Eq.5)}$$

Modular Spacecraft Costs

Now, consider a modular building block approach to orbiting a large spacecraft. The following assumptions apply to this modular approach:

1. The new modular spacecraft is broken into “m” modules, n_1, n_2, n_3, …. n_m. For purposes of further analysis, $N_{modules}$.= m.
2. Each module will be launched individually and then self assembled.
3. Although all modules do not necessarily share the same functionality or capability, each module is of equal mass, and equal cost.
4. Once all $N_{modules}$ are assembled the new spacecraft has the same on-orbit capability, χ, as the large monolithic spacecraft.

The modular spacecraft has the following general characteristics:

Table 2. Modular Spacecraft Characteristics

Modular Spacecraft
Total System Mass (wet) = M_m
Module Mass (wet) = $M_{modules}$
Capability= χ
Non-Recurring Investment=$NRE_{system,modular}$

Note that since M_m is simply the sum of the mass of all modules,

$$M_m = N_{modules} M_{modules} \quad \text{(Eq.6)}$$

The non-recurring cost of the modular system, $NRE_{system,modular}$, can be computed using Eq. 2 as an analogue, that is:

$$NRE_{system,modular} = N_{launches}\left(C_{S/C,modular} + C_{launch,modular}\right) \quad \text{(Eq. 7)}$$

$C_{S/C,modular}$ is the non-recurring cost of a given module and $C_{launch,modular}$ is the cost of launching an individual module. $N_{launches}$ are the total number of launches required so that $N_{modules}$ are orbited, docked, and achieve χ capability. Since it is assumed that one module is launched at a time, ideally $N_{launches}$= $N_{modules}$.

As with the relationships derived for the large monolithic spacecraft cost elements, the modular spacecraft cost elements of Eq. 7 can be determined as function of module mass, $M_{modules}$. That is,

$$C_{S/C,modular} = S_{cpm,modular} M_{modules} \quad \text{(Eq. 8)}$$

$$C_{launch,modular} = L_{cpm,modular} M_{modules} \quad \text{(Eq. 9)}$$

Where $S_{cpm,modular}$ and $L_{cpm,modular}$ are the costs per unit mass of a module and an individual module launch, respectively. Combing Eq. 6–8,

$$NRE_{system,modular} = N_{launches} M_{modules}\left(S_{cpm,modular} + L_{cpm,modular}\right) \quad \text{(Eq. 10)}$$

It can be assumed that the total mass of the modular system is simply equal to the mass of the capability equivalent monolithic spacecraft, with some mass efficiency factor for modularization applied. Specifically,

$$M_m = \alpha M \quad \text{(Eq. 11)}$$

Where α is the mass modularization factor, which represents the scaling inefficiencies (α >1) realized when a spacecraft is broken down in modular pieces. Note that it is plausible that α will be some direct function of $N_{modules}$, increasing monotonically as a system becomes more fragmented due to packaging issues. There may exist cases with α<1, with α being inversely proportional to $N_{modules}$: Free flying distributed modular antenna or optical elements can be used to create a very large array. In this case, the modules would make up array elements and are not connected by structure, which results in a very mass efficient design. Bekey has suggested that such a system could be orders of magnitude lighter than a more conventional space structure with the same capability (if such a conventional space structure could be built!)[iii]. It is understood of course that $\alpha=1$ when $N_{modules}=1$.

Combining Eq.'s 6 and 11 then,

$$M_{modules} = \frac{\alpha M}{N_{modules}} \quad \text{(Eq. 12)}$$

Inserting Eq. 11 into Eq. 9 therefore,

$$NRE_{system,modular} = N_{launches} \frac{\alpha M}{N_{modules}} \left(S_{cpm,modular} + L_{cpm,modular} \right)$$
(Eq. 13)

Eq. 5 and Eq. 13 provide an initial framework for comparison of system costs for large monolithic and fractionated spacecraft.

Comparing Monolithic and Modular Architecture Costs

Spacecraft Costs

Costs per spacecraft mass have been expressed for both a large unitary spacecraft and for fractionated modules, reflected respectively in the terms $S_{cpm,mono}$ and $S_{cpm,modular}$. It is now assumed that spacecraft costs for both large and small-scale spacecraft systems (assuming equivalent complexity) are about the same. The assumption is reasonable; for example, the reasonable costs of a large DOD spacecraft with a mass of 10,000 kg are about \$1B. Comparatively, a small DOD spacecraft with a mass of 100 kg and same technical complexity is about \$10M. In both cases, the cost per unit mass of either spacecraft is \$100,000/kg. It is appropriate therefore that costs, on a per mass basis, of a spacecraft module can be assumed to be equal to those of large spacecraft (i.e. $S_{cpm,mono} = S_{cpm,modular}$.), with two exceptions:

1. Production learning effects will act to reduce the costs of modules manufactured after the first production unit. In general, production learning is modeled by the following equations:

$$y = ax^b \quad \text{(Eq. 14)}$$

$$b = \frac{\ln(LF)}{\ln(2)} \quad \text{(Eq. 15)}$$

Here, in Eq. 14, "y" represents the price of the "x"th unit, where first unit costs are "a". "b" is the production learning function, and can be determined using Eq. 15, where "LF" is the learning factor. LF represents the percentage costs of a second unit relative to first unit costs. For example, an LF of 0.85 denotes that the second unit costs are 85% those of the first production unit. Using this approach, an average unit cost, ybar, given m units produced, can be computed with the aid of the following relation:

$$\bar{y} = \frac{\sum_{x=1}^{m} ax^b}{m} \quad \text{(Eq. 16)}$$

Realistically, production learning is present only when there is a large degree of similarity between consecutively produced units or lots. Arguably, with a modular system, there could be a baseline module bus for each module, with only the main "payload" of that module being distinct from any other.

2. There will be a requirement for each module to robotically rendezvous and dock with the host modular system being populated. This requirement will add additional non-recurring costs (here, docking operations are considered as part of NRE, not OC), whether the assembly is conducted inorganically or

organically (i.e., with or without a separate servicing agent).

Given the above logic, the cost per unit mass of fractionated modules can be assumed to be equal to those costs of a large spacecraft, adjusted for production learning effects and adding normalized docking costs:

$$S_{cpm,modular}(N_{modules}) = \beta(N_{modules})S_{cpm,mono} + \gamma S_{cpm,mono} \quad \text{(Eq. 17)}$$

where β represents an average production learning factor and γ is a docking system cost penalty metric. Eq. 17 notes that $S_{cpm,modular}$ is a function of the number of modules designed into the space system, $N_{modules}$. This dependence is created by β With the aid of Eq's 14-16, β is determined by the following expression:

$$\beta = \frac{\sum_{x=1}^{N_{modules}} S_{cpm,modular}^{first-unit}\left[Lot(x)\right]^{b}}{N_{modules} S_{cpm,modular}^{first-unit}} \quad \text{(Eq. 18)}$$

As shown in Eq. 18. β represents the average reduction in total cost of building $N_{modules.}$,and ($0<\beta\leq 1$) for $N_{modules} \geq 1$. This calculation of β is a function of the cost per unit mass of the first unit module, $S_{cpm,modular,\ first\ unit}$. It is assumed that production learning is encountered in successive lot builds, where Lot(x) represents the lot number build of the xth unit. Figure 1 displays the behavior of β for a lot size = 10, parametric with various standard learning factors.

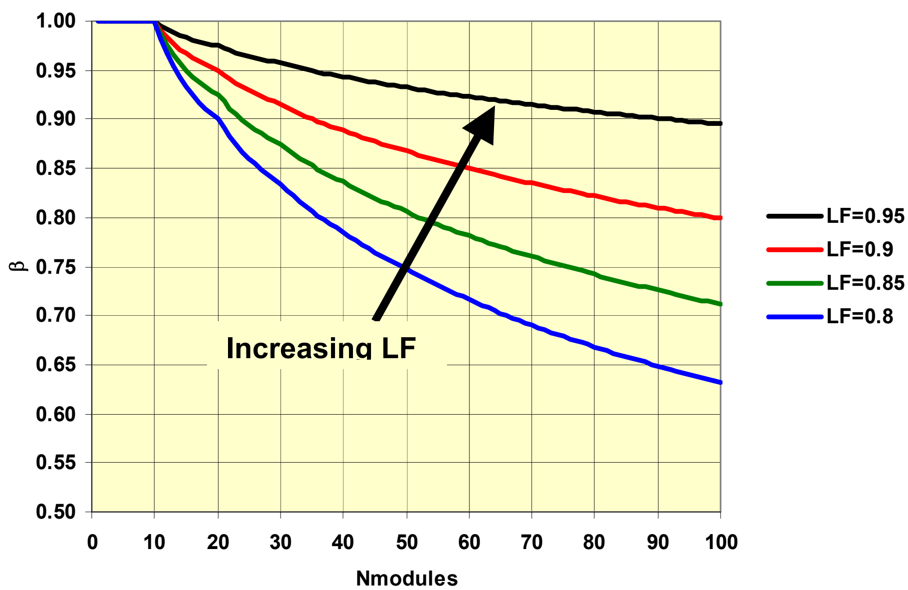

Figure 1. Behavior of Average Production Learning Factor, β, as Function of Number of Modules to be Built. Lot size = 10.

The second component of Eq. 17, γ, the docking system cost penalty, represents the percentage increase in spacecraft costs per unit mass to be added to nominal costs because a robotic docking and assembly requirement has been added to the space system, which is the case when $N_{modules} > 1$. The value of γ will be influenced by the degree of complexity and precision required in the autonomous docking process. There may exist a requirement for a mother spacecraft to accomplish the modular construction process; it can be assumed that γ would capture the additional cost of building and operating this mother spacecraft. It is understood that $\gamma=0$ when $N_{modules}=1$. Unlike α, γ is most probably a weak function of $N_{modules}$.

Note that given previous assumptions and Eq. 18 , for $N_{modules}=1$, $\gamma=0$ and $\beta=1$. Thus, from Eq. 17, $S_{cpm,modular} = S_{cpm,mono}$. In this case, Eq.'s 5 and 13 are equivalent. Therefore, this analytical framework allows a monolithic spacecraft to be modeled as one module, i.e., $N_{modules}=1$. It will be useful now to refer to spacecraft costs per unit mass in general terms, given as the term S_{cpm}, where

$$S_{cpm} = S_{cpm,mono} \quad \text{(Eq. 19)}$$

Therefore, combining terms and rewriting Eq. 17,

$$S_{cpm,modular} = S_{cpm}(\beta+\gamma) \quad \text{(Eq. 20)}$$

Launch Costs

At present, small-scale launch systems cost at least four times more on a per mass basis than large scale launch systems. For instance, an EELV launch vehicle, capable of orbiting about 5,000 - 10,000 kg of payload, costs about \$10,000/kg.[iv] A Pegasus launch vehicle, on the other hand, can orbit about 500 kg of payload with a cost of about \$40,000 kg, or a factor of four greater than the large launch system.[v] DARPA's FALCON Program SLV R&D effort has an objective of launching 100-1000 kg for no more than \$16,500/kg. RASCAL has a goal of less than \$10,000/kg for a 75 kg (LEO) payload. Assuming SLV and/or RASCAL lead to a small-scale launch system(s) with costs approximately equal to larger scale systems, the following approximation can be made:

$$L_{cpm,modular} = L_{cpm,mono} = L_{cpm} \quad \text{(Eq. 21)}$$

This is a significant assumption in this analysis, which will ultimately help to lead to an interesting result.

Generalized Cost Analysis for Large Systems

Given Eq's 13, 20, and 21, the NRE cost relation for either large monolithic systems, or large modular systems can be generalized by the relation:

$$NRE_{system} = \frac{N_{launches}}{N_{modules}} \alpha M \left(S_{cpm}(\beta+\gamma) + L_{cpm}\right) \quad \text{(Eq. 22)}$$

This relationship provides the analytical basis to compare the non-recurring systems expense, NRE_{system}, of spacecraft systems decomposed into any number of modules, $N_{modules}$, including the case of a "module" size of one.

Note the first term that appears in Eq. 22., $N_{launches}/N_{modules}$, referred to hereafter as the "module assurance factor", or N*. The module assurance factor represents the fractional number of launches beyond the nominal minimum required to place a large monolithic space system into operation. Replacing $N_{launches}/N_{modules}$ with N* then,

$$NRE_{system} = N^{*} \alpha M \left(S_{cpm}(\beta+\gamma) + L_{cpm}\right) \quad \text{(Eq. 23)}$$

N* will be shown to be a random variable which depends on $N_{modules}$ and the probability of success of each individual module.

The minimum number of launches for a given architecture is of course $N_{modules}$; and in this case, N*=1. This special case can be referred to as the ideal case, in which $N^{*}=N^{*}_{ideal}$. It is useful as well to refer to an ideal NRE_{system} metric. The reference ideal cost is assumed to be for the case of the monolithic system, in which $N^{*}=\alpha=\beta=1$ and $\gamma=0$. Therefore,

$$NRE_{system,ideal} = M\left(S_{cpm} + L_{cpm}\right) \quad \text{(Eq. 24).}$$

As stated, N* is a random variable. To further explore the behavior of N*, use of binomial probability theory is required.

Negative Binomial Probability Distribution

When considering the attempt to place a given module into operation and then have that module operate for some pre-determined lifetime, there can be assumed to be a probability of success, p_S, where

$$p_s = p_L p_O p_D \text{ (Eq. 25)}$$

where p_L is the probability of success in launch, p_D is the probability of success in docking p_O is the probability of successful module operation for an assumed system lifetime. It is assumed that p_L, p_O, and p_D are independent of all prior and future events and are constant, hence, p_S for all modules is the same. This is somewhat of a simplification. First, some systemic reliability or quality problem could cause any of number of successive probabilities to be inter-related. Second, some failure modes of a module or a docking operation could result in partial or complete failure of the system of previously assembled modules. Finally, $p_D = 1$ for the first module (for all values of $N_{modules}$) since no docking is required.

Given p_S for each module, the question then is what is the probability of total mission success ($N_{modules}$ inserted and docked), p_m, given some number of launches for some (constant) number of modules designed into the system. Note that "mission success" is defined here to be achieved when χ capability is initially provided.

The launch, docking, and lifelong operation of a module can be modeled as a simple Bernoulli trial, with the outcome being either a success, or a failure. Of pertinence in modeling the behavior of $N_{launches}$ then is the negative binomial distribution; the negative binomial distribution is the probability distribution of the number of trials needed to get a fixed (i.e., non-random) number of successes in a Bernoulli process. This distribution is given by the following:

$$p_r(x) = \binom{x-1}{r-1} p^r (1-p)^{x-r} \text{ (Eq. 26)}$$

where

$$\binom{x-1}{r-1} = \frac{(x-1)!}{(x-1)!(x-r-2)!} \text{ (Eq. 27)}$$

In Eq. 26, $p_r(x)$ is the discrete probability that the r^{th} success occurs in x trials, where each trial has an independent probability of success of p. The mean, μ (also referred to as the expected value), and standard deviation, σ, of this probability function are given as follows:

$$\mu = \frac{r}{p} \text{ (Eq. 28)}$$

$$\sigma = \frac{\sqrt{r(1-p_s)}}{p} \text{ (Eq. 29)}$$

The Probability Distribution of N*

In the above description, the number of successful trials required, r, is equal to the number of modules in the system, $N_{modules.}$ The random variable x is simply the number of launches required to succeed, which is $N_{launches}$. The probability of success for each trial, as given before, is p_s. Therefore, substituting terms into Eq. 26,

$$p_m(N_{launches}) = \binom{N_{launches}-1}{N_{modules}-1} p_s^{N\,modules} (1-p_s)^{Nlaunches-N\,modules}$$

(Eq. 30)

To reiterate, this equation provides us the following information: suppose you design a space system fragmented into $N_{modules.}$, with each module having a probability of success from the moment of launch until the end of its lifetime of p_s. Pick a given number of launches $N_{launches}$,(equal to or greater than $N_{modules}$,of course). By plugging all three of these variables into Eq. 30, the probability of mission success for the entire system (i.e. all $N_{modules}$ successfully launched, docked, and operated for mission lifetime) can be determined.

The mean and standard deviation of the number of launches required for success can be determined by substitution of variables into Eq.'s 28 and 29:

$$\mu_{Nlaunches} = \frac{N_{modules}}{p_s} \quad \text{(Eq. 31)}$$

$$\sigma_{Nlaunches} = \frac{\sqrt{N_{modules}(1-p_s)}}{p_s} \quad \text{(Eq. 32)}$$

Using Eq. 30, the probability distributions – more appropriately referred to as the Probability Mass Functions (PMF's) of $N_{launches}$ required to achieve total mission success, given a system size of $N_{modules.}$, can be determined. Assuming for instance a p_s of 0.92, the curves in Figure 2 are generated.

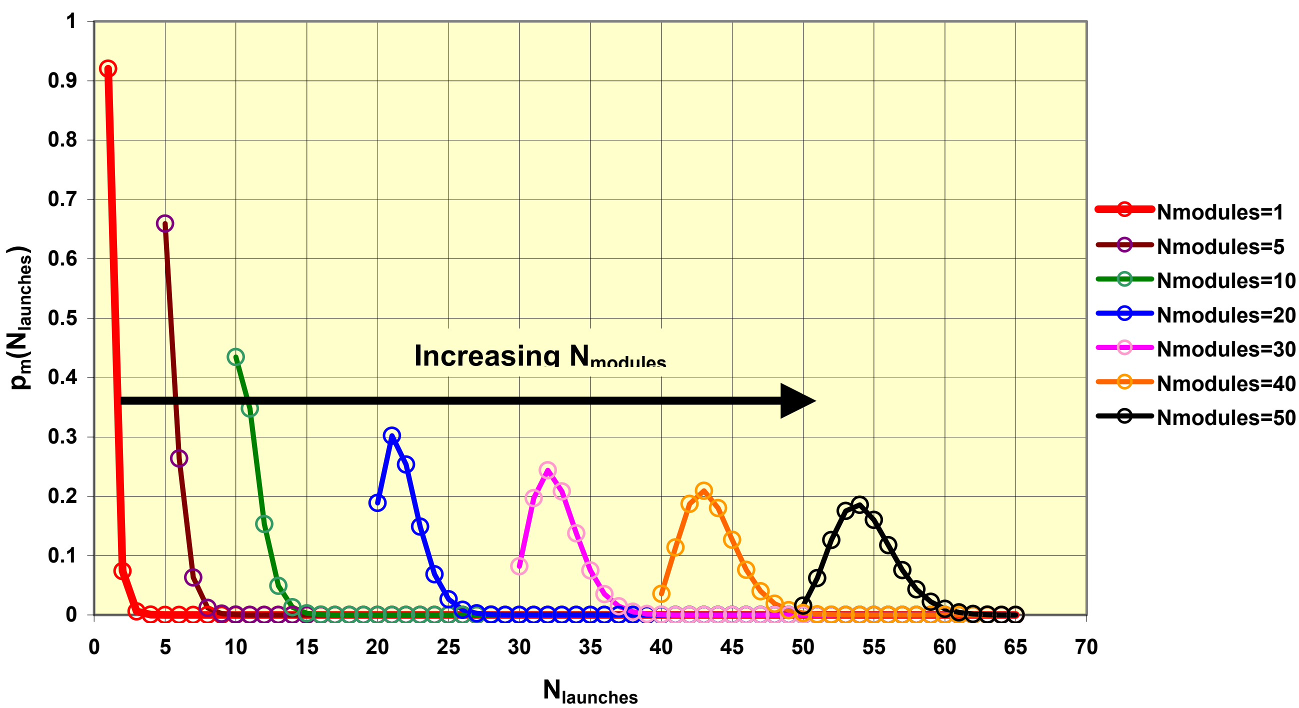

Figure 2. PMF's for $N_{launches}$, Given Required Successes is $N_{modules}$. Assumed p_s=0.92.

For example, it shows that for a module size of 40, there is a probability of approximately 0.2 that exactly 43 launches (in this case, the mode, or most frequent value, of the distribution) will succeed in lifelong mission success of the space system There likewise exists a cumulative probability of placing 40 modules into operation with no more than 43 launches, i.e. $p_m(N_{launches} \leq 43 \mid N_{modules}=40)$. This is equivalent to the sum of the individual mission success probabilities of $N_{launches}$ =40, 41, 42, and 43. In this case, $p_m(N_{launches} \leq 43 \mid N_{modules}=40) = 0.54$.

Also note that from Eq. 31, the expected number of launches required to place 40 modules into orbit successfully is 43.5 (close to the mode, which is as to be expected, since the distribution is mound-like).

It can be interpreted from the figure that there is a decreasing probability that $N^* = N^*_{ideal}$ as $N_{modules}$ increases. For example, for $N_{modules} = 1$, $p_m(N_{launches} = N_{modules}) = 0.92$, whereas for $N_{modules} = 20$, $p_m(N_{launches} = N_{modules}) = 0.19$.

The above results are interesting, but not conclusive. Recall from Eq. 23 that it is the launch assurance factor, N*, that ultimately dictates the behavior of NRE_{system}. Thus, it is the probability distribution of N*, not $N_{launches}$, that is of ultimate concern. A simple step is involved here. Since for a given system the term $N_{modules}$ is some constant (say "n"), the probability of achieving the required number of successes for the term N* is the same as for $N_{launches}$ alone, that is

$$p_m\left(N_{launches} \mid N_{modules} = n\right) = p_m\left(N^* \mid N_{modules} = n\right)$$

(Eq. 33).

The bottom line is that the PMF's of the function N* can be determined using Eq. 30 for a given $N_{modules}$, based on the appropriate value of $N_{launches}$. For example, for $N_{modules}$=40, it was shown that p_m=0.2 when $N_{launches}$=43, that is, $p_m(N_{launches}=43 \mid N_{modules}=40)=0.2$. For this specific case, N*=43/40=1.08. Therefore, using the identity given in Eq. 33, $p_m(N^* 1.08 \mid N_{modules}=40)=0.2$. Using this logic, the PMF's of N* for various $N_{modules}$ can be determined. Selected results are shown in Figure 3.

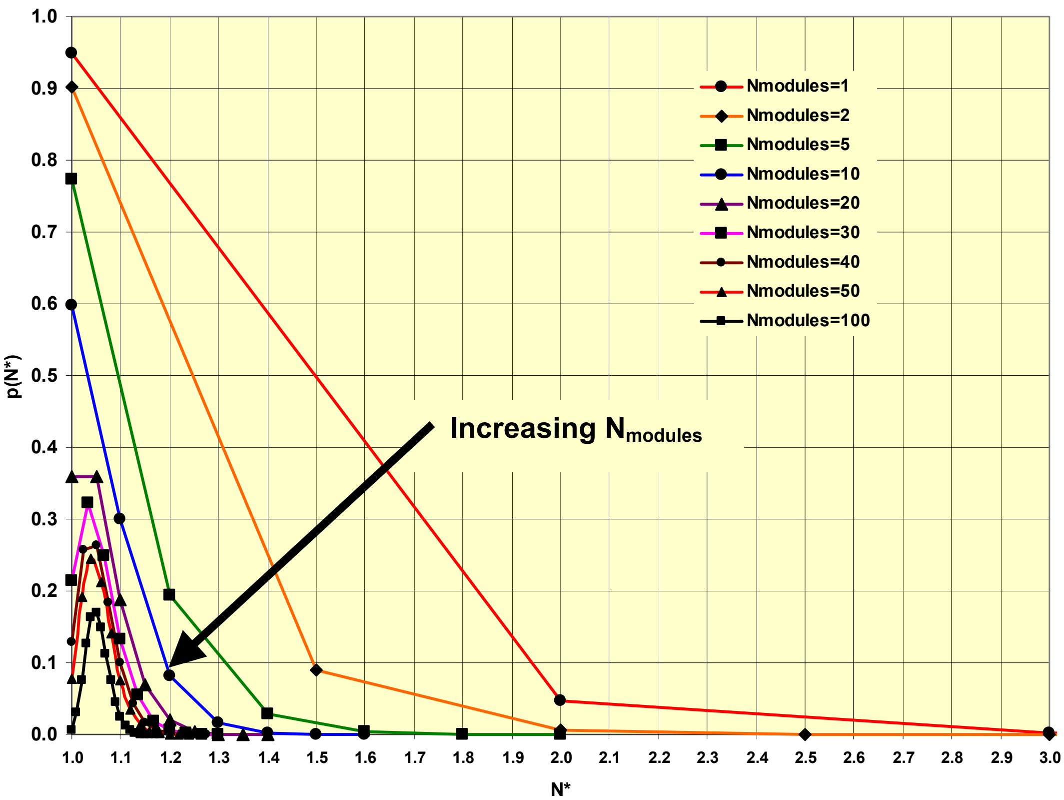

Figure 3. PMF's of N* to Achieve $N_{modules}$ Successes, p_s=0.92.

The curves in Figure 3 are created by simple transformation of those equivalent curves provided in Figure 2: For points on each curve of Figure 2, the appropriate x value of N* is substituted for the value of $N_{launches}$, while ordinate values remain the same. These curves represent PMF's for N* parametric in $N_{modules}$. Each PMF indeed contains all possible outcomes, i.e. the cumulative probability represented by each PMF goes to 1.0. This is not intuitive since each curve does not contain equal areas. But, remember that these curves represent discrete, not continuous, functions. For instance, the $N_{modules}$=1 curve contains 3 possible values (1,2,3) for $1.0 \leq N^* \leq 3.0$, whereas the $N_{modules}$ =100 curve contains 16 possible values (1.00, 1.01, 1.02…1.15) from $1.0 \leq N^* \leq 1.15$.

The intriguing behavior of this distribution is the significant reduction in variability of N* with increasing $N_{modules}$., as shown by the narrowing of each PMF curve for increasing numbers of modules designed into a hypothetical system. For a module size of 1, note that there is a high probability – 0.92 in fact - that only one launch will be required for mission success. But – there is small, but non-trivial probability of about 0.075 that two launches (and hence two monolithic spacecraft) will be required to achieve mission success. In this case, the result would be a doubling of required NRE_{system}. Even worse – there is an obvious finite chance that N* is three! On the other hand, for a large module size of 50, for example, it can be seen that to cover most possibilities, a maximum number of launches 1.2 times the number of modules (that is, 60) will be required (note the correspondence with Figure 2). To be specific, $p_m(N^* \leq 1.2| N_{modules}=50) = 0.993$. Note that for the monolithic system, $p_m(N^* \leq 2.0| N_{modules}=1) = 0.994$. The implications (ignoring contributing effects of α,β, and γ) here are that there exists a maximum likely variation – i.e. risk – of a 20% increase in NRE for system composed of 50 modules, compared to a maximum likely variation of a 100% increase in NRE for a monolithic system given a p_s for each module of 0.92.. These results are somewhat trivial really – gut instinct tells us not to "put all eggs in one basket". Figure 3 is nothing more than a simple illustration of the value of reducing potential losses by something similar to diversifying investment. In this case, by increasing the degree of modularization in a large space system and by launching all modules separately, the impact of failure is diminished, and therefore risk is reduced.

As an aside, a p_s of 0.92 has and will be used in many examples because it is believed to be a good predictive estimate of large launch vehicle reliability (and the same figure is maintained for small launch vehicle reliability for comparative purposes). Descriptive statistical data show that the realized success rate for the heavy lift vehicles falls between 0.70 (Ariane 5) and 0.91 (Titan 4). EELV's have thus far shown a perfect success rate, but it is less conservative to use such descriptive data for predictive purposes of risk analysis. Guikema and Paté-Cornell have recently shown using Bayesian analysis that posterior estimates of mean future frequencies of success are relatively low for launchers with a limited history.[vi] For example, a launch vehicle that has a mission success rate of 100% in two launch attempts still only has a mean future predictive success rate of about 0.85.

Since the term $N_{modules}$ is a constant for each case considered, the expected value and standard deviation of N* can be found by dividing Eq's 28. and 29 by $N_{modules}$:

$$\mu_{N^*} = \frac{1}{p_s} \quad \text{(Eq. 34)}$$

$$\sigma_{N^*} = \frac{1}{p_s}\sqrt{\frac{(1-p_s)}{N_{modules}}} \quad \text{(Eq. 35)}$$

Note that from Eq. 34, the expected value of N* is constant for all values of $N_{modules}$, depending only on independent probability of successful module operation, p_s. Given p_s = 0.92,

μ_{N^*}=1.09, which corresponds to the observed behavior in Figure 3. From Eq. 35, the standard deviation of N* is inversely proportional to the square root of $N_{modules}$, which again corresponds to the behavior of the curves shown in Figure 3. Note that these results provide more insight into the impact of modularization on reduced variability of relative number of required launches. In the most recent example, the expected valued of N* is 1.09 for both $N_{modules}$ =1 and $N_{modules}$ =100. For the Nmodules=1 case, N* will take on discrete values of 1+n, where n is an integer, ($0 \le n \le \infty$). That is, N* will most likely be 1, but sometimes 2, and possibly 3. On the other hand, for $N_{modules}$ =100, N* can take on discrete values of 1 + 0.01n. Therefore, in this case, an N* of the mean 1.09 can actually occur (when $N_{launches}$=109). Thus, it can be seen that there is a quantization effect that results in less absolute variation of N* as $N_{modules}$ increases.

It is convenient to encapsulate the important elements of the preceding observations in an overarching framework. It will be useful to determine the "assured" value of N* - referred to as $N^*_{assured}$ - as a function of both $N_{modules}$ and p_s. $N^*_{assured}$ is chosen to be the expected value of the mission assurance function plus 3 standard deviations, i.e. 3-sigma. For mound-like distributions, the 3-sigma confidence limit encases 99.9% of all possible outcomes. PMF's distributions shown for N* are skewed and do not become mound-like until approximately $N_{modules}$ >30. In any case, the approximation is made that $N^*_{assured}$ represents the 99.9% cumulative probability, or assurance, of all N* possibilities, regardless of the magnitude of $N_{modules}$. Subsequent results show that this is a good and proper approximation.

From Eq.'s 34 and 35,

$$N^*_{assured} = \frac{1}{p_s}\left[1+3\sqrt{\frac{(1-p_s)}{N_{modules}}}\right] \quad \text{(Eq. 36)}$$

Values of $N^*_{assured}$ as function of $N_{modules}$ and p_s are plotted in Figure 4 below.

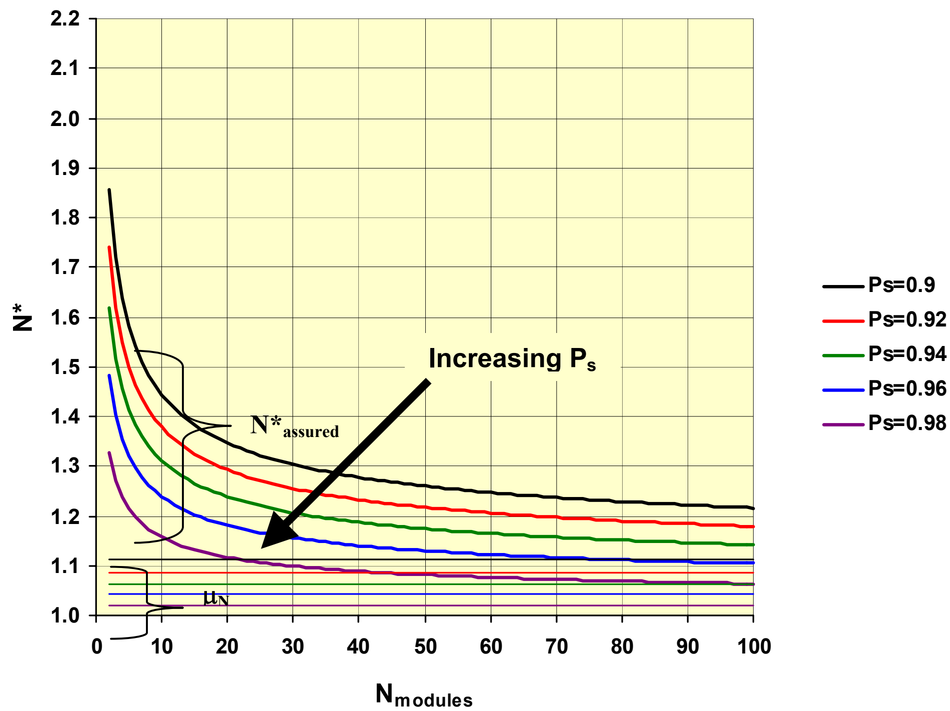

Figure 4. Behavior of Launch Assurance Factor as a Function of Number of Modules in System and Independent Probability of Successful Module Insertion.

The following behavior is observed from Figure 4:

1. As $N_{modules}$ increases, the worst case N*, described by the function $N^*_{assured}$, decreases notably. For example, for a p_s=0.92, $N^*_{assured}$ is approximately 2 for a monolithic system, whereas for a system composed of 100 modules, $N^*_{assured}$ is approximately 1.18.
2. As described by Eq. 23, μ_{N^*} does not change with $N_{modules}$ for a given p_s.
3. As p_s increases, the difference in $N^*_{assured}$ between monolithic and highly modular systems decreases.
4. As p_s increases to what would be considered exemplary levels of 0.98, $N^*_{assured}$ for a monolithic system is still 45% above N^*_{ideal}.
5. As p_s increases, highly modular systems have an $N^*_{assured}$ which approaches both μ_{N^*} and N^*_{ideal}. For example, for p_s=0.98, N*=1.06.
6. $N^*_{assured}$ for highly modular systems with a relatively low reliability (e.g. p_s =0.90) is still lower that for monolithic systems with a relatively high reliability (e.g. p_s =0.98). This behavior has larger implications; Turner and Wertz have surmised that launch vehicles designed for a lower reliability will have much lower costs relative to other launchers with similar capability[vii].

Probability Distribution of NRE_{system}

The observed characteristics of N* have profound implications, since space system cost and uncertainty are directly proportional to this figure as described in Eq. 23. N* has been shown to be a discrete random variable, therefore NRE_{system} is a discrete random variable as well. The PMF's of NRE_{system} can be found by simply cross referencing each probability value of N* used in the calculation of NRE_{system} for a given $N_{modules}$. Mathematically,

$$p_m\left(NRE_{system} \mid N^*(N_{modules}=c)\right)=p_m\left(N^*(N_{modules}=c)\right)$$
(Eq. 37)

The expected value and standard deviation of each probability distribution of NRE_{system} can be found using Eq. 23:

$$\mu_{NREsystem}=\mu_{N^*}\alpha M\left(S_{cpm}(\beta+\gamma)+L_{cpm}\right) \text{(Eq. 38)}$$

$$\sigma_{NREsystem}=\sigma_{N^*}\alpha M\left(S_{cpm}(\beta+\gamma)+L_{cpm}\right) \text{(Eq. 39)}$$

where these expressions show the mean and standard deviation of NRE_{system}, respectively. Extending the concept of assured mission risk, substitution of $N^*_{assured}$ into Eq. 23. will provide the value of assured NRE for the space system, represented by the term $NRE_{system,assured}$:

$$NRE_{system,assured}=N^*_{assured}\ \alpha M\left(S_{cpm}(\beta+\gamma)+L_{cpm}\right)$$
(Eq. 40)

The above analysis can be used to describe possible outcomes for space system NRE – and, from Eq. 1, approximate LCC – depending on various features of the system design architecture and production approaches. These equations allow LCC to be modeled with improved determinism as compared to more conventional approaches. Modularization has a significant impact on the expected and worst case values of LCC. Specifically,

1. Fragmenting the system into more modules has the effect of reducing the variability of the ratio of actual number of launches to the minimum and ideal number of launches, as shown by the

behavior of N*, which is directly proportional to NRE_{system}. The degree of variation for N* between monolithic and a given modular system is reduced as the probability of module mission success (p_s) is increased.

2. Modularization may create scaling inefficiencies that result in total system mass for a modular system to be greater than that for a monolithic system. This penalty has been represented by α; both $\mu_{NREsytem}$ and $\sigma_{NREsytem}$ increase in direct proportion to α, thereby offsetting gains in (1) previously. Possible scaling efficiencies for large aperture systems, previously discussed, should not be ignored.
3. Production learning effects, represented by β, could have the impact of reducing costs of modules after successful builds. The effect on NRE_{system} will depend first upon the degree of similarity between modules in the system, which will determine if and how much learning effect can be applied in the production process. Once β is determined; the relation in magnitude between S_{cpm} and L_{cpm} will then determine the effect of β on NRE_{system}. For $S_{cpm} >> L_{cpm}$, $\mu_{NREsytem}$ and $\sigma_{NREsytem}$ increase in direct proportion to β. On the other hand, if $S_{cpm} << L_{cpm}$, the effect of production learning on NRE from spacecraft modules is nil.
4. Additional costs will be incurred by forcing the fragmented components to have an autonomous and precise rendezvous and docking capability. Here, this penalty has been represented by the term γ. $\mu_{NREsytem}$ and $\sigma_{NREsytem}$ will increase in direct proportion to γ, which itself represents the percentage change in S_{cpm} above a monolithic system that has no docking capability.

From the above quantitative conclusions, it can be seen that the net effect on the expected value of LCC of a modularized spacecraft system will vary depending on the gains provided by production learning versus the losses realized by scaling and complexity costs. Nonetheless, the impact of N* on NRE_{system} is significant; potential variability in space system cost is reduced as the degree of fragmentation is increased.

A hypothetical case will help to illustrate the above observations.

Example Comparison of LCC for a Monolithic and Modular System

Assume that a large new space system has the characteristics given in Table 3.

Table 3. Hypothetical Assumed Large Space System Characteristics.

Characteristic	Assumed Value
M	10,000 kg
S_{cpm}	\$100,000/kg
L_{cpm}	\$10,000/kg
α	1.2
γ	0.1
LF*	85%
Lot Size	10
p_s	0.92

***Assumes extra modules produced as replacements due to failure do not count toward overall production total.**

Given the assumptions above, the following selected characteristics of two different system designs are derived from various equations provided previously:

Table 4. Hypothetical Derived Monolithic and ModularLarge Space System Characteristics.

	Characteristic	Derived Value	Reference Equation(s)
	$C_{S/C,mono}$	$1.0B	3
	$C_{launch,mono}$	$100.0M	4
$N_{modules}$=10	M_{module}	1200 kg	12
	$C_{S/C,modular}^{Lot\#1}$	$132.0M	8,17,18
	$C_{launch,modular}$	$12.0M	9,21
$N_{modules}$ =100	M_{module}	120 kg	12
	$C_{S/C,modular}^{Lot\#1}$	$13.20M	8,17,18
	$C_{S/C,modular}^{Lot\#10}$	$9.74M	8,17,18
	$C_{launch,modular}$	$1.2M	9,21
	NRE_{ideal}	$1.1B	24

Given the values of Table 3 and using Eqs. 23 and 37, PMF's can be created which show the probability distribution of NRE_{system} for various architectures. Assuming a p_s of 0.92, selected PMF's are shown in Figure 5. Likewise, curves of $\mu_{NREsystem}$, $\sigma_{NREsystm}$, and $NRE_{system,assured}$ can be created using Eq.'s 38-40. These curves are provided in Figure 6.

The following observations are made for Figures 5 and 6:

1. The behavior of the PMF distribution of NRE_{system} shown in Figure 5, where increasing the number of modules leads to a reduction in variation, is very similar to that previously shown for N* in Figure 3. This is of course due to the direct relationship between the two variables.
2. It is apparent from Figure 5, as compared to Figure 3, that the curve for $N_{modules}$=2 is biased noticeably to the right. As $N_{modules}$ increase, curves shift back to the left. In other words, the mean of curves for $N_{modules}$>1 jumps up and then gradually decreases. Details of this behavior are more apparent from Figure 6. The cause of this phenomenon is twofold. First, α and γ cause module inefficiencies which result in, for example, two modules with the same capability as a monolithic spacecraft to be more massive, complex, and therefore more costly than the monolithic system. Second, as the degree of fragmentation increases, production learning effects begin to drive down the costs of modules, thereby offsetting other cost penalties. Note that the expected value of NRE_{system} for monolithic and highly modular ($N_{modules}$ =100) systems in this example are nearly equivalent.

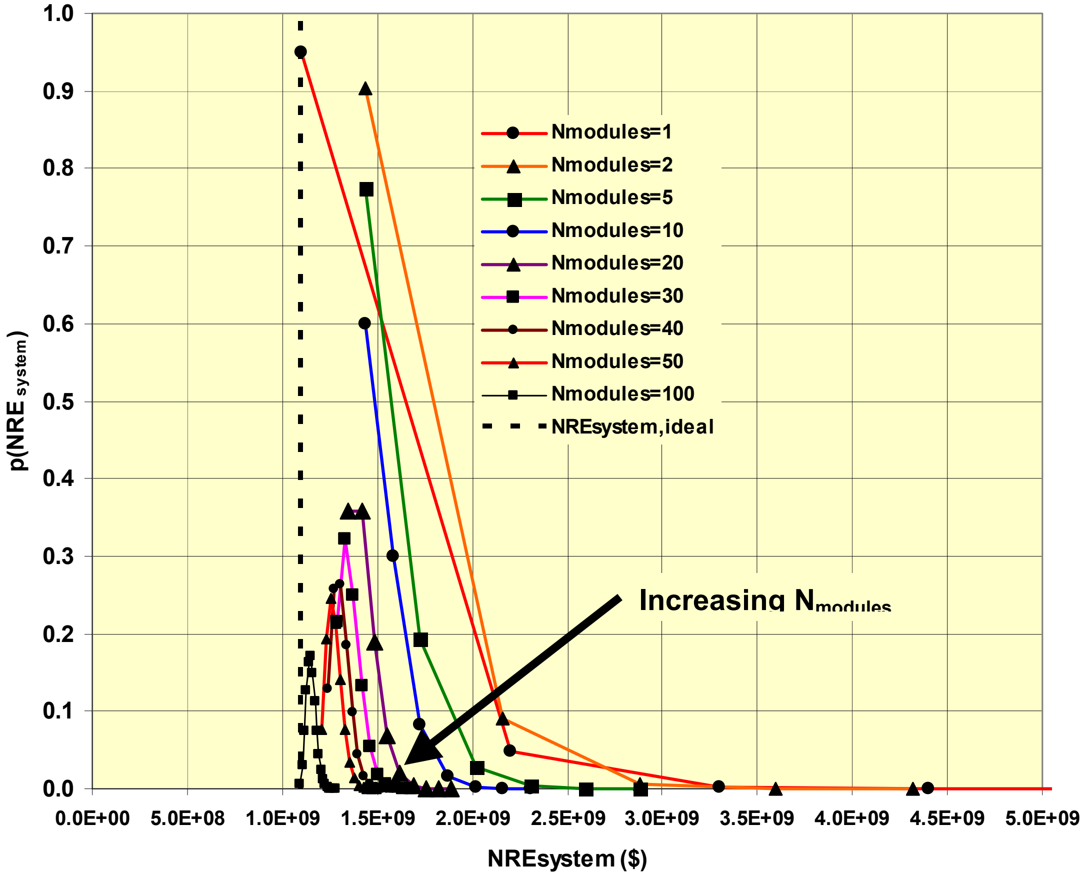

Figure 5. Probability Distribution of NRE to Achieve NRE_{system}, p_s=0.92.

3. In general, as shown in Figure 6, $NRE_{system,assured}$ decreases monotonically as $N_{modules}$ increases. There is one particular case where this is not true. For $N_{modules}$=2 and p_s=0.92, $NRE_{system,assured}$ increases above that for $N_{modules}$ =1. This behavior is once again caused by the increase in system cost due to α and γ effects. Since the lot size in this example is 10, production learning effects are not captured for this module size (nor for $N_{modules}$=2). Although there is N* advantage, the increased module cost results in an overall higher cost risk for the entire system. It was noted earlier in that α may in fact increase with increasing $N_{modules}$. This type of behavior could result in a "bathtub" type of curve for both $NRE_{system,assured}$ and $\mu_{NREsystem}$. In this case, some optimal and intermediate value or range of values of $N_{modules}$ would exist.

This straw man example is a good illustration of the competing effects in cost and risk when considering modular systems.

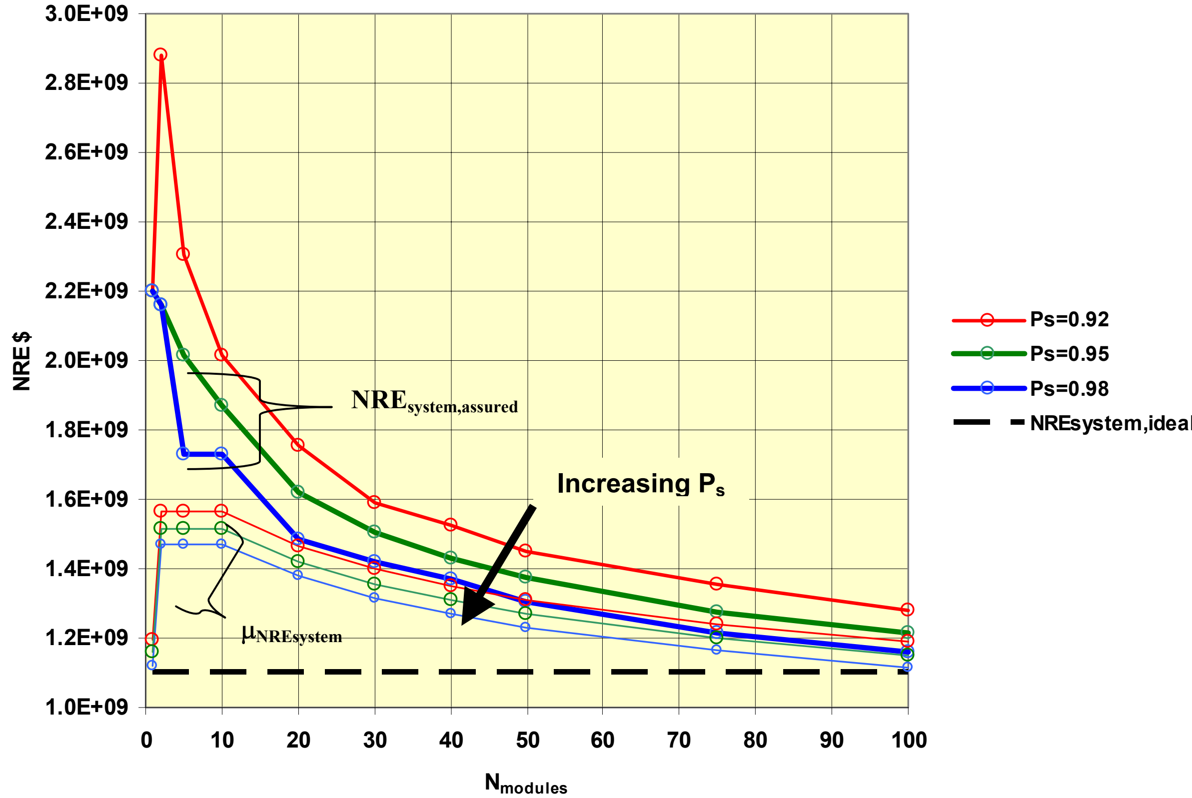

Figure 6. Behavior of Mean and Assured Values of NRE_{system} as a Function of Number of Modules in System.

Added Benefits of Modularization

Thus far, it has been shown that the value in a modular space system approach is related to the reduction of cost risk. There are other added benefits of modularization tied directly to the flexibility it provides both designer and operator. deWeck et al. of MIT recently studied the value of stage deployed and orbital reconfiguration of a LEO personal communication (Iridium) constellation.[viii] In this study, some initial operational capability for the system was provided to meet current demand by a small higher orbit constellation. As demand grew, more spacecraft were launched, and a new constellation was created by lowering the orbit of previously inserted spacecraft to that of the newly inserted spacecraft. The outcome of this approach to development of a space system is that "Real Options" are provided to the designer. These Real Options have a measurable dollar value; value increases as uncertainty of the set of future requirements goes up. A large modular space system could similarly be developed in an incremental fashion. Some initial capability could be provided after launch and insertion of core modules (of course, for some missions, the idea of incremental capability may be dubious). This initial capability could be provided at some time well before that possible for an equivalent monolithic system. This initial capability would allow an evolutionary acquisition strategy, or in essence, a spiral development approach towards building a large space system. As shown in deWeck's study, the impact of evolutionary development is reduced risk and reduced life cycle cost.

The modular system will inherently offer additional flexibility after initial operational capability (IOC). Repair and upgrade of failed or technologically outdated subsystems will be easier with a system designed with a building block approach. Saleh et al. have demonstrated that the flexibility offered from an on-orbit servicing architecture has real value.[ix] Applying Real Options theory, the value of a serviceable architecture was shown not to be a function of cost, but rather intrinsically linked to future volatility and the revenue associated with the product of the spacecraft.

In the analysis shown here, it was assumed that production learning effects could be applied to spacecraft systems, but not launch vehicles. Arguably, there will be learning effects with successive launch vehicle builds and/or operations (when considering reusable systems): such effects will act to drive down costs of launch. So, for example, Eq. 23 would include a second β-like term applied to L_{cpm}.

Another assumption applied in this analysis was that all module insertion attempts were mutually exclusive of all others, so p_s remained unchanged. In 1964, Duane of GE Company presented data to the IEEE showing that a "reliability learning curve" could be developed from empirical data for complex electromechanical systems, such as "complex aircraft accessories…[that]…follow a relatively simple and predictable pattern and are approximately inversely proportional to the square root of cumulative operating time."[x] Satellite launch operations are so infrequent and each launch event so short that the effect of reliability learning is lost literally through generations of engineers. Lessons learned are institutionalized. Some lessons are remembered, others forgotten. Recent experience shows that typical new launch systems suffer through an early campaign plagued by poor mission success performance, only to enjoy a success rate closer to that predicted by hard-core reliability analysis. Using Duane's approach, one could model launch vehicle reliability as a function of the number of previous launches. In this case, p_s would increase with $N_{launches}$. An "average" p_s could be computed based on $N_{modules}$ and used to determine values of $NRE_{system,assured}$ and $p_m(N_{launches})$ Otherwise, a Monte-Carlo approach would be required, since the binomial probability functions used assume a constant p_s. Regardless, the net effect would be to make even more attractive modularization of space systems, as p_L, p_O, and p_D would all show improvement with increasing $N_{modules}$.

Making Modularization More Attractive

A key explicit assumption in this analysis has been that costs per unit mass for a small module launch were approximately the same as that for a very large space system. An implicit, but equally important assumption, in this analysis is that the launch vehicle system, especially for a very modular system, is capable of high-flight rate. Such high-flight rates would be required to enable timely insertion of the fragmented system. Regardless, both assumptions require that Operationally Responsive Spacelift becomes a reality. One point that must be emphasized: at present we cram as much onto one launch vehicle as possible to enjoy maximum rate of return. So, why not just put a large number of modules onto a large, "economical" launch vehicle? The problem with this approach is that the significant reduction in cost risk is lost: once again, all eggs, or at least a large number of them, are placed into one basket.

The other major challenge assumed solved in this analysis is the demanding task of robotically building a space system on-orbit. Using a conventional approach, "connecting" modules together on-orbit requires not only a mechanical interface and connection, but interface and connection of electrical and data systems as well. There are several implications for the presence of such interfaces, all of which drive up cost and cost risk: p_D decreases, α and γ both will increase because of electrical and data interface requirements. An interesting approach to help alleviate this issue would be the use of a wireless data and/or power architecture. With such a system, there would potentially be no need for electrical and data interfaces – the passage of all such information would be performed optically or by means of RF. There would be other implications as well, including "virtual systems tests" of flying modules with those still in the production facility and the enhanced capability for organic rendezvous and docking processes. In fact, mechanical connections could possibly be virtual as well, utilizing electromechanical force fields or specially applied orbits to maintain proper relative module position. With such approaches, fragmented and loosely coupled space systems- connected only by information - are conceivable.

Throughout this analysis, it has been assumed that each space system has been fragmented into modules of equal size. For a given mission objective, it may prove in fact that the optimum architecture is one in which certain subsystems are built monolithically and others very modularly. For example, it may prove that a law of comparative advantage exists whereby more capability, flexibility, reliability, etc. is provided by building a stand-alone power subsystem that is used by the entire space system. It is cases like this that would still drive the need for launch vehicles with heavy lift capacity.

Conclusions

> "1. *Cost has replaced mission success as the primary driver in managing space development programs*, from initial formulation through execution. Space is unforgiving; thousands of good decisions can be undone by a single engineering flaw or workmanship error, and these flaws and errors can result in catastrophe….
>
> "2. *Unrealistic estimates lead to unrealistic budgets and unexecutable programs*. The space acquisition system is strongly biased to produce unrealistically low cost estimates throughout the process….."

Report to the Defense Science Board/Air Force Science Advisory Board Joint Task Force on Acquisition of National Security Space Programs, May 2003

Space is indeed an unforgiving place. Architects and users of space systems know that the relentless environment of "Space" really begins the second a launch vehicle leaves the pad. Through the past half-century, the harsh reality of "one-strike and you're out" has set back many programs vital to both national security and stakeholders of commercial corporations. For instance, past shareholders of Globalstar will probably well remember the day a Zenit launch vehicle, purchased because of its economy of significant capacity, crashed into the hinterlands of Kazakhstan carrying 12 Globalstar spacecraft. The time lost getting the system into initial operation did not help a program challenged by competing markets. Of particular concern to national decision makers and taxpayers, is the significant risk posed by the problem of placing a very large space system into orbital operation. Mission success must be the primary goal; cost should be minimized, yet cost must be held subservient to mission success. A second issue with cost is determinism; as the Defense Science Board has pointed out recently, space system costing is too inaccurate; such inaccuracies put the success of the mission in peril, even well before hardware arrives at the launch base. Couple this cost estimation issue with that of mission risk: should a mission fail, cost estimates are most probably off by a factor of 100%, since all eggs have been placed in one basket.

There may exist a way out of this conundrum. New technologies and new systems may enable and enhance the capability to build large scale space systems using a fragmentized, modular approach. This analysis has considered the impact on cost and risk such an approach would have. It was found in the course of this analysis that the most dramatic impact of large space system fragmentation is that the impact of single failures – be they with a launch vehicle or spacecraft – are less severe as the degree of fragmentation is increased. The net effect is that the variability of total lifecycle costs is reduced for the space system. Applying reasonable assumptions, it was shown by example that a highly modular system has an "assured" life cycle cost nearly half that of a monolithic large spacecraft. There are issues to be dealt with, primarily relating to scaling inefficiencies of modules and the adding cost of docking capability. But, assume that such inefficiencies and added costs are known. Using a cost and risk modeling approach like that offered here, decision makers can trade expected cost for reduced cost risk. Modularization also provides on-orbit flexibility for repair, replacement, and upgrade. Stage deployed options are also possible. Such flexibility results in Real Options for the user: these options have real value (not cost!) measurable in dollars.

Just as Markowitz suggested there is no optimal solution for a portfolio, there is no optimal solution to the degree of modularization. What is important is that decision makers have information that allows them to trade cost, risk, and value. The analysis here provides a glimpse of a possible approach towards solving this problem.

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[i] Markowitz, Harry, "Portfolio Selection," *Journal of Finance,* 7 (March 1952): 77-91.

[ii] The key to reduced volatility is to select those equities which have a minimum sum of covariances – that is, dependencies – on each other. Such a grouping of equities is referred to more properly as a portfolio. Portfolios now have a following in government circles, where for example a technology manager's "portfolio" is made up of a diversified selection of development projects. The program manager hopes to maximize return on investment, while minimizing his risk by offsetting risky, but possibly groundbreaking technologies with more progressive, but less disruptive programs.

[iii] Bekey, Ivan, ""Advanced Space Systems and Technologies, 2010-2030+"

[iv] http://www.astronautix.com (based on price and payload capacity figures).

[v] http://www.astronautix.com (based on price and payload capacity figures).

[vi] Guikema, Seth and M. Elisabeth Paté-Cornell, "Bayesian Analysis of Launch Vehicle Reliability," presented at 41st Aerospace Sciences Meeting, January 6-9, Reno, Nevada.

[vii] Turner, Andrew and James R. Wertz, "Launch Cost as a Function of Vehicle Reliability", presented at National Space Society's 20th Annual International Space Development Conference, January 2001.They have suggested using such vehicles where "failure is an option" for delivery of commodities (e.g. propellant) to orbit. Using this mindset, it is conceivable that highly modular systems could trade launch vehicle reliability for the expected value of N*, the value of L_{cpm}, and $N^*_{assured}$ to reach a desired balance of risk and cost. (Note that this is not an argument for relaxed engineering discipline or relaxed quality assurance in space system design and manufacturing!)

[viii] de Weck, Olivier L.,Richard de Neufville, and Mathieu Chaize, "Enhancing the Economics of Communications Satellites via Orbital Reconfigurations and Staged Deployment," presented at AIAA Space 2003 Conference and Exposition.

[ix] Saleh, Joseph H., et al., "Flexibility and the Value of On-Orbit Servicing: New Customer-Centric Perspective", Journal of Spacecraft and Rockets, 40:2 (March-April 2003): 279-291.

[x] Duane, J.T., "Learning Curve approach to Reliability Monitoring," *IEEE Transactions on Aerospace*, 2:2 (April 1964): 563-566.