

# Exploring the F6 Fractionated Spacecraft Trade Space with GT-FAST

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Released in July 2007, the Broad Agency Announcement for DARPA’s System F6 outlined goals for flight demonstration of an architecture in which the functionality of a traditional monolithic satellite is fulfilled with a fractionated cluster of free-flying, wirelessly interconnected modules. Given the large number of possible architectural options, two challenges facing systems analysis of F6 are (1) the ability to enumerate the many potential candidate fractionated architectures and (2) the ability to analyze and quantify the cost and benefits of each architecture. This paper applies the recently developed Georgia Tech F6 Architecture Synthesis Tool (GT-FAST) to the exploration of the System F6 trade space. Combinatorial analysis of the architectural trade space is presented, providing a theoretical contribution applicable to future analyses and clearly showing the explosion of the size of the trade space as the number of fractionatable components increases. Several output metrics of interest are defined, and Pareto fronts are used to visualize the trade space. The first set of these Pareto fronts allows direct visualization of one output against another, and the second set presents cost plotted against a Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) score aggregating performance objectives. These techniques allow for the identification of a handful of Pareto-optimal designs from an original pool of over 3,000 potential designs. Conclusions are drawn on salient features of the resulting Pareto fronts, important competing objectives which have been captured, and the potential suitability of a particularly interesting design designated PF0248. A variety of potential avenues for future work are also identified.

## Nomenclature

$B_N$	= Bell number / size of SEA for $N$ components	$m$	= number of modules considered
$C_{add/replace}$	= average cost of adding or replacing component	$N$	= number of components considered
$C_{i,existing}$	= cost of adding component via an existing module	$n$	= number of components in cluster
$C_{i,separate}$	= cost of adding component via a dedicated module	$O_x$	= design objective number $x$
$D_N$	= size of SED for $N$ components	$S$	= Stirling number of the second kind
$F_N$	= size of Super-SEA for $N$ components		

## I. Introduction

RELEASED in July 2007, the Broad Agency Announcement for System F6<sup>1</sup> outlined the goal of the U.S. Defense Advanced Research Projects Agency (DARPA) for flight demonstration of an architecture in which the functionality of a traditional “monolithic” satellite is fulfilled with a “fractionated” cluster of free-flying, wirelessly interconnected modules. The potential benefits of the F6 approach include enhanced responsiveness in delivering initial capabilities to commercial or government customers, greater flexibility in responding to mid-life changes in requirements, and superior robustness against internal failure and external attack (i.e., enhanced survivability).

Two systems analysis challenges that are especially critical for the flexible and architecturally complex F6 concept are (1) the ability to thoroughly and systematically enumerate the many potential candidate fractionated architectures that exist and, more importantly, (2) the ability to assess and quantify the cost and benefits of each

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architecture, and in so doing rank the different proposed architectures according to the right metrics. System attributes such as flexibility and survivability, which are essential for systems operating in uncertain and rapidly changing environments, are not properly captured and valued in the traditional cost- or performance-centric mindsets of system design and acquisition; as a result, a value-centric approach accounting for these uncertainties is required to properly inform decisions regarding F6 architectures.

One element necessary in enabling such a probabilistic, value-centric analysis of F6 architectures is a systematic method for enumerating, sizing, and costing the many candidate architectures that are introduced by fractionating subsystems or resources. For example, in one previously published design for F6,<sup>2</sup> twelve instances of six distinct types of fractionatable components are distributed among seven free-flying modules. However, this distribution of components is just one of many possibilities. As will be shown in this paper, if only six components exist in the system and each can be independently placed in any of up to six modules, 203 distinct system configurations exist. If the number of components increases to twelve (akin to the design in Ref. 2), the number of possible configurations explodes to over 4.2 million. Furthermore, these numbers do not include the multitude of launch manifesting options.<sup>‡</sup> Clearly there is a need to be able to evaluate more than a handful of these alternative configurations in order to make an informed decision on the design of an F6 architecture.

### A. Overview of GT-FAST

As presented in Ref. 3, GT-FAST is a point design computer tool implemented in Microsoft Excel that is designed to help solve the systems analysis problem for fractionated spacecraft by allowing rapid, automated sizing and synthesis of candidate F6 architectures. The primary function of GT-FAST is to convert a user-defined configuration of fractionated components (i.e., a specification of which fractionatable components are assigned to which modules), launch manifest (i.e., which modules are carried on which launch vehicles), and several continuous variable inputs (e.g., orbit altitude, inclination, module design lifetime, payload mass, payload power, etc.) into a point design. Information output by GT-FAST for each point design is a mass, power, and cost budget for the cluster and for each module in the cluster. Also available for output are user-defined performance metrics.

Because GT-FAST is able to quickly and automatically size an F6 design based on a clear set of user inputs, the tool is well-suited for engineering trade studies. Thus, GT-FAST also has a built-in capability to run a series of input sets and track any number of user-defined metrics to allow for rapid trade analysis. These input sets are analogous to experiments that the designer might wish to run to characterize a design space and determine the optimum design, if such a design exists.<sup>§</sup> This trade study – or trade-space exploration – process is the subject of the present paper.

### B. Example Six-Component Fractionated Design

Figure 1 is an architectural depiction of an example six-component design named PF0248 that has been modeled using GT-FAST. This three-module cluster is assumed to operate in a 370 km, 28.5° inclination circular orbit and is designed for a two-year mission with two communications payloads. Design PF0248 is actually a Pareto-optimal F6 design that will appear later in this paper, but here we use it to illustrate several important conventions, typical inputs and outputs, and nomenclature.

First, it is important to define the terms component, module, cluster, and design, all of which will be used extensively in describing different parts of fractionated architectures. In this paper and other analyses, the basic unit of fractionation is called a fractionatable component, or a component for short. Depending on the resolution one desires in examining fractionated designs, these components can be subsystems (as in Ref. 5) or resources/payloads (as in Ref. 2). The analysis here uses the latter as definitions of components. Next, a compilation of components (and any required essential support subsystems, such as structure, thermal, and others) into a single free-flying vehicle is called a module. A compilation of modules into an independent on-orbit F6 system is called a cluster or architecture. Finally, a cluster with the specification of

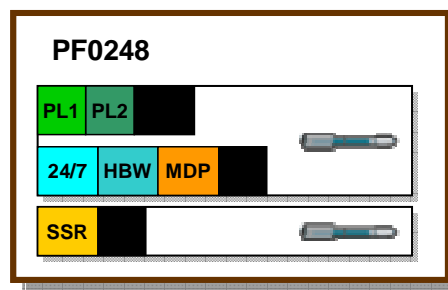


Figure 1. Architectural depiction of example design PF0248.

<sup>‡</sup> The nomenclature distinguishing components from modules, clusters, and designs is presented in Section I.B.

<sup>§</sup> If all inputs into GT-FAST were continuous variables, this process of running a variety of potential designs would be well-suited to a classical design-of-experiments approach<sup>4</sup>.

their launch manifest (e.g., on what vehicle each module was launched, acknowledging that multiple modules may launch on the same launch vehicle) is called a design. This nomenclature is illustrated graphically in Fig. 2.

The implementation of GT-FAST demonstrated in this analysis uses five different classes of fractionatable components, consistent with those of Ref. 2. An architecture contains one 24/7 communication unit, one high-bandwidth downlink, a solid-state recorder, a mission data processor, and up to two payloads. Icons used in this paper to represent these six individual fractionatable components are shown in Fig. 3. Payloads are specified by their mass, sunlight and eclipse power requirements, and pointing requirement. Unlike the Air Force Satellite Control Network (AFSCN) communications unit which every module is sized to include, a 24/7 communication unit provides near-continuous communications capability through a relay satellite such as the Tracking and Data Relay Satellites (TDRSs). High-bandwidth downlink units allow for high-volume downlinks that could not otherwise be provided with AFSCN or 24/7 links. A solid state recorder allows high-volume data storage, and a mission data processor is a resource allowing for onboard high-speed computing.

Thus, in the example design PF0248 shown in Fig. 1, there are three modules. The first holds both payloads. The second module holds the 24/7 communication unit, high bandwidth downlink unit, and mission data processor. The third module holds the solid state recorder. The black block on each module signifies that all modules also include all essential support subsystems, such as structure, thermal, power, and others. Fig. 1 also represents that Modules #1 and #2 are manifested to be flown on the same launch vehicle. Module #3 launches separately. Note that launch order is not represented by GT-FAST; that is, the representation in Fig. 1 does not preclude Module #3 from launching first or second.

Outputs for this design from GT-FAST include three tables with mass, power, and module-level cost budgets broken down by subsystem for each of the three modules in the design. For brevity, these tables are not shown here, but examples can be found in Ref. 3. For reference, the boosted masses of Modules 1, 2, and 3 are 201.9 kg, 138.6 kg, and 138.9 kg, respectively, and the total power requirements are 522.9 W, 503.5 W, and 425.5 W, respectively. Table 1 shows the estimated cost budget for the entire system, which includes costs estimated at the module level and cluster level.<sup>3</sup> Figure 4 graphically shows the cost breakdown of Table 1. As shown in Fig. 5, the launch vehicle selected for all three launches is the Pegasus XL at a cost of \$22 million (FY08).<sup>\*\*</sup> The Pegasus XL's 450 kg payload capacity to the desired orbit was sufficient for all launches, and \$22 million was the lowest launch cost in the database used for this launch vehicle selection (foreign and under-development vehicles were excluded).

**Fractionatable Component**  
"Component" for short



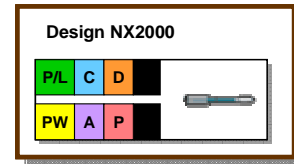
**Module**  
Independent, free-flying spacecraft



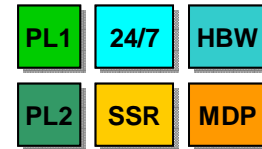
**Cluster/Architecture**  
Collection of modules on-orbit



**Design**  
Cluster manifested onto launch vehicles



**Figure 2. Nomenclature for F6 designs used in this paper.**



**Figure 3. Icons for fractionated components in this study.**

<sup>\*\*</sup> Note that GT-FAST does not require all launches to use the same launch vehicle; this coincidence is due to the particular payload requirements for this set of launches.

**Table 1. Overall PF0248 Cost Budget**

Cost Element	Cost (FY08\$M)
<b>Module-Level Costs</b>	
Module #1	55.9
Module #2	13.8
Module #3	13.4
Program Management	13.6
Software	38.7
Ground Segment Development	75.6
Operations	24.6
<i>Pre-Margin Subtotal</i>	<i>235.5</i>
Margin (25%)	58.9
<i>Post-Margin Subtotal</i>	<i>294.4</i>
Launch	44.0
<b>Total</b>	<b>338.4</b>

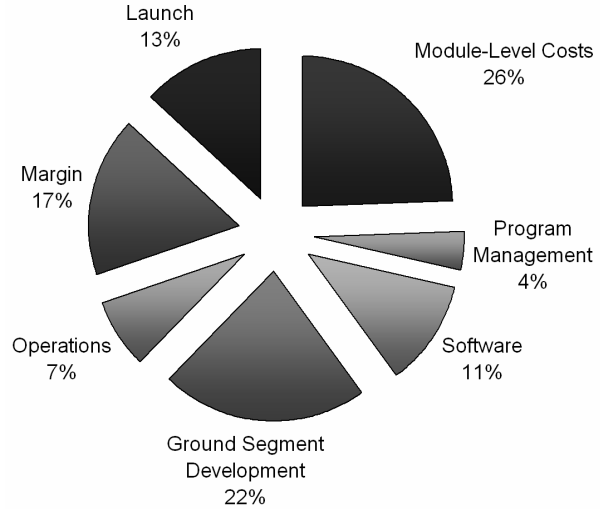


Figure 4. Breakdown of Costs from Table 1.

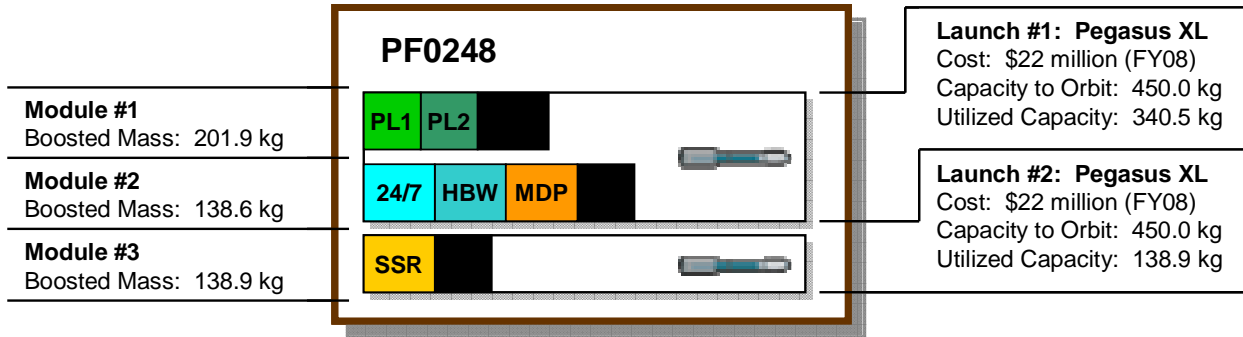


Figure 5. Launch Summary for Design PF0248.

## II. The Combinatorial Trade Space for Fractionated Spacecraft Designs

The focus of this paper is the application of GT-FAST, which has been briefly described above, to the exploration of the F6 fractionated spacecraft trade space. As such, it is necessary to define this trade space in terms of the variables or system characteristics that can be controlled by the designer. For the purposes of this study, the trade space consists of the discrete combinatorial options for the configuration of an F6 design. Continuous variables are set at their default values (i.e., all designs are set to a 370 km altitude, 28.5° inclination orbit, have a two-year design life, use a given set of payload mass and power assumptions, etc.). In this context, the PF0248 design described in Section I.B is just one of 3,190 designs considered in this trade study; the “PF” indicates that the cluster is partially fractionated (i.e., at least one module contains more than one fractionatable component) and the “0248” designation indicates that this design is the 248<sup>th</sup> design (out of 3,190) in the chosen enumeration scheme. The enumeration of these combinatorial options is covered in this section.

### A. Theoretical Development: Size of Trade Space with no Constraints

As mentioned in Section I.A, the principal discrete inputs into GT-FAST – and the combinatorial configuration options in this trade study – deal with specification of which fractionatable components are present in which modules and which modules are carried on which launch vehicles. First we illustrate this problem for a simple 3-

component architecture, and then we generalize this using the combinatorial definitions of Stirling and Bell numbers.

1. Example 3-Component Design Trade-Space

For this example problem, assume that the fractionatable components include exactly three distinct payloads (PL1, PL2, and PL3, using similar icons to Fig. 3).<sup>††</sup> In the case of a monolithic architecture, all of these payloads would be housed in the same module (i.e., a one-module architecture). In the case of a fully fractionated architecture, each payload would be housed on its own module. In the fully fractionated case, this equates to three modules (one for each fractionatable component). However, solutions also exist for two-module architectures. For example, PL1 and PL2 could be housed in the same module while PL3 could have its own dedicated module. There are three such two-module architectures. All five architectures are shown pictorially in Fig. 6, and this collection of all possible architectures will be referred to as the Suite of Enumerated Architectures (SEA) for the 3-component trade-space.

The SEA just defined accounts for all possible ways of placing components into modules. Another important consideration is how to place modules onto launch vehicles. Currently, GT-FAST considers launch vehicles independent of launch order; that is, from the perspective of manifesting, Launch Vehicle #1 (LV1) is indistinguishable from Launch Vehicle #2 (LV2). Thus, for each

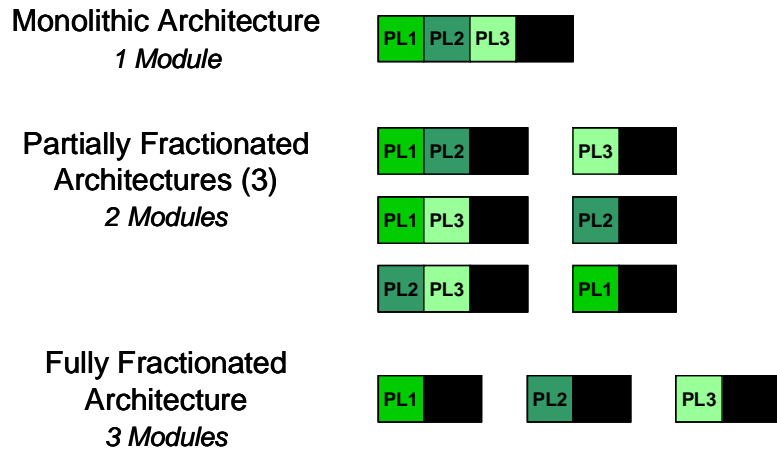


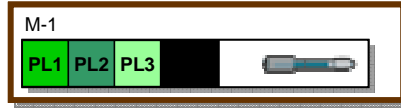
Figure 6. SEA for the 3-component case.

architecture in Fig. 6, several designs exist in terms of which modules are launched together or separately. For the one-module architecture (monolith), only one design exists since this one module must be launched on one launch vehicle. For each two-module architecture, there are two possible designs since the two modules can be launched together on a single vehicle or separately on two vehicles. For the three-module architecture, modules can be launched all together, all separately, or two can be launched together and one separately. For the three-component case considered in this example, this results in a total of 12 designs. All 12 designs are shown pictorially in Fig. 7, and this collection of all possible designs will be referred to as a Suite of Enumerated Designs (SED).

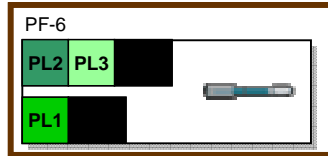
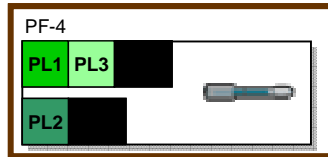
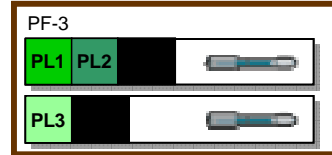
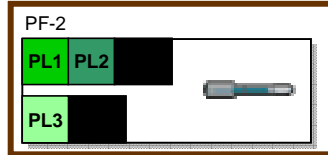
Finally, it must be recognized that the option to fractionate does not necessarily impose the decision to fractionate; the option can be exercised or not. That is, if one *can* fractionate a component, it does not necessarily mean that one *must* fractionate that component. Thus, if a 3-component case is considered, so must a 2-component case and 1-component case. This consideration introduces 12 additional designs, shown in Fig. 8. For example, a 2-component case can be defined for the sub-cases where the vehicle carries only PL1 and PL2, PL2 and PL3, or PL3 and PL1. For each of these 2-component sub-cases, a SEA and a SED can be defined using the logic from earlier; for a 2-component case, this simplifies into three designs, the first of which is a monolith, the second of which is two modules launched separately, and the third of which is two modules launched together on the same launch vehicle. The 1-component case consists of the simple scenarios where a payload is carried aboard a monolithic spacecraft. Thus, the 12 designs in Fig. 7 are added to the 12 designs in Fig. 8 to complete the collection of all designs that should be considered when deciding upon the configuration of a fractionated architecture which can accommodate up to three fractionatable components. This collection of designs is referred to in this paper as a Super-SEA.

<sup>††</sup> In DARPA terminology, this is an example of a distributed-payload monolith since no subsystems are fractionated.<sup>6</sup>

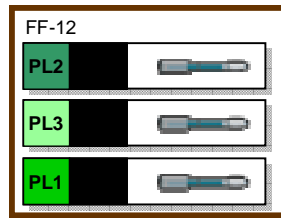
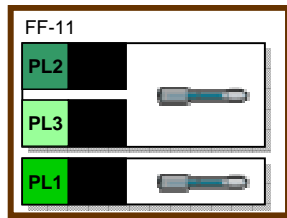
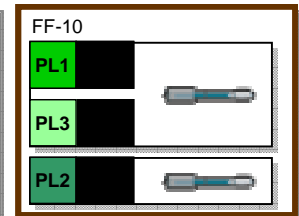
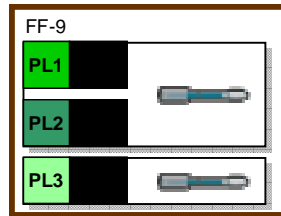
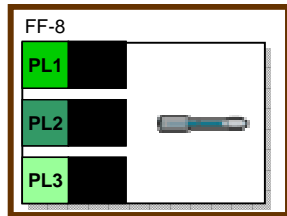
**Monolithic Designs**  
*1 Module*



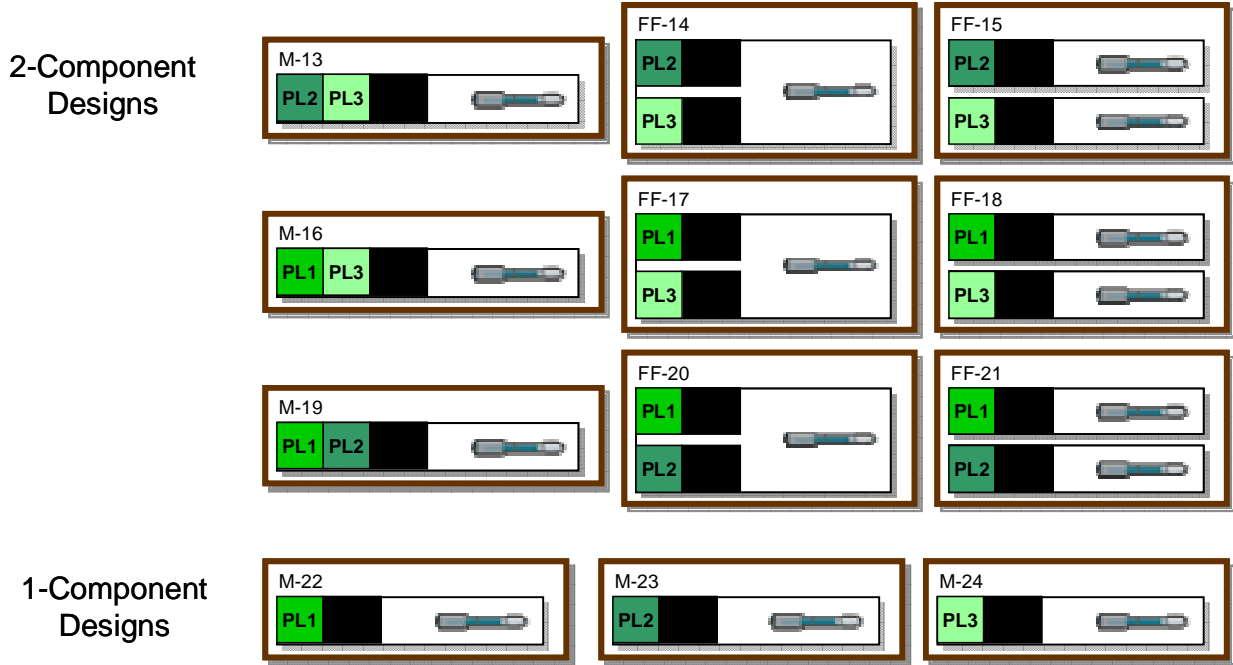
**Partially Fractionated Designs**  
*2 Modules*



**Fully Fractionated Designs**  
*3 Modules*



**Figure 7. SED for the 3-component case.**



**Figure 8. Additional designs that must be added to the 3-component SED to create a 3-component Super-SEA.**

## 2. Generalized $N$ -Component Design Trade Space

Thus far we have shown that, even in the relatively simple case where only 3 fractionatable components are considered, 24 designs exist which should be considered by the system designer or decision-maker. Now we generalize this combinatorial problem to one consisting of  $N$  fractionatable components.

As in the example problem, first we define the size of a SEA for an  $N$ -component case. Recalling that the size of the SEA is defined by the number of ways that exist to place  $N$  distinguishable fractionatable components into any of one to  $N$  modules, it can be seen that this is actually the sum of Stirling numbers of the second kind.<sup>7</sup> From the study of combinatorics, a Stirling number of the second kind, denoted as  $S(n,m)$ , physically describes the number of ways that exist of placing  $n$  distinct objects into  $m$  numbered but otherwise identical containers with no container left empty. Mathematically,  $S(n,m)$  is defined by Eq. (1) below:

$$S(n,m) = \frac{1}{m!} \cdot \sum_{k=0}^m (-1)^k \cdot {}_m C_{m-k} \cdot (m-k)^n \quad (1)$$

Thus, in the 3-component example from earlier, we have 3 distinct objects (components) distributed into one, two, and three containers (modules), and the size of the SEA is  $S(3,1) + S(3,2) + S(3,3) = 1 + 3 + 1 = 5$ . A summation of this type has been defined in mathematics as a Bell number. Formally, a Bell number, and consequently the size of a SEA, is defined by Eq. (2). A table of these values is given by the second column of Table 2.

$$\text{Size of SEA} = B_N = \sum_{k=1}^N S(N,k) \quad (2)$$

Next, we concern ourselves with defining a SED, recalling that a SED is the number of ways that exist to place  $N$  distinguishable fractionatable components into any of one to  $N$  modules, and those modules into launch vehicles. The first step in this development is to recognize that the number of ways to distribute  $K$  distinguishable modules into any of one to  $K$  launch vehicles (considered indistinguishable, since launch order is not considered) is actually a

Bell number itself (by the same logic from above that distributing distinguishable components among indistinguishable modules is described by a Bell number). Thus, for each architectural possibility in a SEA (there were 5 in the demonstration case), there are  $B_K$  ways to distribute that architecture onto launch vehicles, where  $K$  is the number of modules in the architecture. Mathematically, we define the size of a SED consisting of  $N$  fractionatable components by the symbol  $D_N$  in Eq. (3). A table of values for  $D_N$  is given by the third column of Table 2. For the demonstration case,  $D_N = 12$ .

$$\text{Size of SED} = D_N = \sum_{k=1}^N S(N, k) \cdot B_k \quad (3)$$

Finally, what remains is to define the size of a Super-SEA, or the total number of designs a decision-maker should consider in his trade-space given that not all components that *can* be fractionated *must* be fractionated. As described earlier, assuming that all components have the option of being non-fractionated<sup>‡‡</sup>, the Super-SEA considers the possibilities of including  $N$  components,  $N-1$  components,  $N-2$  components, etc., until the case where only one component is included. Initially, one might consider this to be simply the sum of  $D_N$  from  $N=1$  to  $N$ . However, this does not account for the fact that, for example, there are multiple ways of choosing which components are included in the  $(N-1)$ -component SED (i.e., when defining the  $(N-1)$ -component SED, which component should be left out?). The number of ways of choosing  $X$  components for each new number of components is described mathematically by  ${}_N C_X$ . In the example case, there were  ${}_3 C_2 = 3$  ways of creating a 2-module SED. Thus, the total number of designs that a decision-maker should consider (the Super-SEA), denoted by  $F_N$ , is defined by Eq. (4). A table of values for  $F_N$  is given by the fourth column of Table 2. For the demonstration case,  $F_N = 24$ .

$$\text{Size of Super - SEA} = F_N = \sum_{j=1}^N (D_j) \cdot ({}_N C_{N-j}) \quad (4)$$

**Table 2. Sizes of SEA, SED, and Super-SEA as a function of number of fractionatable components ( $N$ ).**

$N$	Size of SEA ( $B_N$ )	Size of SED ( $D_N$ )	Size of Super-SEA ( $F_N$ )
1	1	1	1
2	2	3	5
3	5	12	24
4	15	60	130
5	52	358	813
6	203	2,471	5,810
7	877	19,302	46,707
8	4,140	167,894	416,510
9	21,147	1,606,137	4,073,412
10	115,975	16,733,779	43,289,930
11	678,570	188,378,402	496,188,630
12	4,213,597	2,276,423,485	6,095,737,867

<sup>‡‡</sup> For payloads, this implies that some payloads can be left out, if trade studies warrant it. For subsystem components (e.g., communication equipment, data storage and processing equipment), non-fractionation implies that these components can either be omitted or automatically included within the generic mass and power budgets of the sizing and synthesis tool; in the latter case, clearly the location of the component (i.e., on which spacecraft it is housed) is no longer in the trade space. In practice, the designer may not wish to allow some components to be non-fractionated, in which case, the Super-SEA must be modified (and the trade-space will become smaller).



Table 2 summarizes the sizes of the SEA, SED, and Super-SEA for values of  $N$  up to 12. Recall that the SEA deals only with the number of possible clusters/architectures, the SED includes consideration of all launch options, and the Super-SEA addresses the fact that not all components that *can* be fractionated *must* be fractionated. The Super-SEA is of most relevance to the study in this paper, and the major observation one can take away from Table 2 is that the size of the Super-SEA increases dramatically with  $N$ . If  $N$  is doubled from 6 (as in this study) to 12, the number of designs that must be considered increases from 5,810 to 6,095,737,867 – a factor of over one million! The sheer size of the trade space for practical values of  $N$  – as well as the rapidity with which it expands as  $N$  increases – illustrates the need for a systematic method for enumerating and evaluating F6 designs.

## B. Accounting for Constraints

According to Table 2, the Super-SEA for a 6-component design is  $F_6 = 5,810$ . However, earlier it was mentioned that the PF0248 example design is one of 3,190 designs considered in this trade study. This apparent discrepancy (between 5,810 and 3,190 possible designs) is the result of the exclusion of cases in the trade space due to practical application-specific constraints.

In the case of the components considered in the present analysis, it was assumed that every cluster must include a 24/7 communication unit, high bandwidth downlink unit, solid state recorder, mission data processor, and at least one payload. As a result of this constraint, the smallest architecture allowed to be considered is a 5-component design in which one of the payloads is omitted. Which payload to omit is of course an option, and so the number of cases considered is almost perfectly described by  $D_6 + D_5 + D_5 = 3,187$  (see Table 2). The final three cases examined in the set of 3,190 designs are monolithic (single-module) spacecraft that contain intra-cluster wireless units and are thus F6-enabled<sup>§§</sup>; one of these cases contains PL1, another contains PL2, and the third contains both PL1 and PL2.

## C. Enumerating Designs

While the discussion thus far has been concerned with counting the number of possible designs, the task still exists to enumerate, or list, each design so that it can be input and analyzed using GT-FAST. Covered in this section is an overview of how a SEA is enumerated, followed by a discussion of how this is extended to a SED and translated into inputs for GT-FAST.

### 1. Enumerating a SEA

To illustrate this process, Fig. 9 graphically shows how a 3-component SEA is generated; the same logic applies to the larger-dimensional 6-component designs considered for the trade studies in this paper. This logic is based on the idea of dividing strings of component orderings using indistinguishable partitions.

As illustrated in Fig. 9, the enumeration process starts with the definition of both component permutations and partition schemes. The component permutations simply show all possible ways of ordering the  $N$  components (where each component is given a number from 1 to  $N$ ). For an  $N$ -component design, there will be  $N!$  such orderings. The partition schemes are more involved and are generated from a full factorial design with  $N-1$  factors (since at maximum there can be  $N-1$  partitions in an  $N$ -component string), each of which has  $N$  levels. The resulting list is filtered such that all remaining schemes are sequential; for example, since each number in the partition string represents the location of an indistinguishable partition, there is no difference between the schemes [1 2] and [2 1], both of which indicate that partitions are to be placed after the first and second components in the component permutation string.

Next, each partition scheme is applied to each component permutation; i.e., partitions as defined by each partition scheme are placed within each of the component permutations. In the case of the 3-component design, this results in a list of 36 clusters. However, many of these clusters are duplicates; for example, the 3--21 cluster is the same as the 3--12 cluster (where the dashes indicate partitions). Once duplicates are eliminated, the enumeration of a SEA has been completed.

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<sup>§§</sup> As described in Ref. 3, if only a single module exists in a cluster, GT-FAST excludes the intra-cluster wireless unit from mass, power, and cost budget estimation.

## Partition Schemes

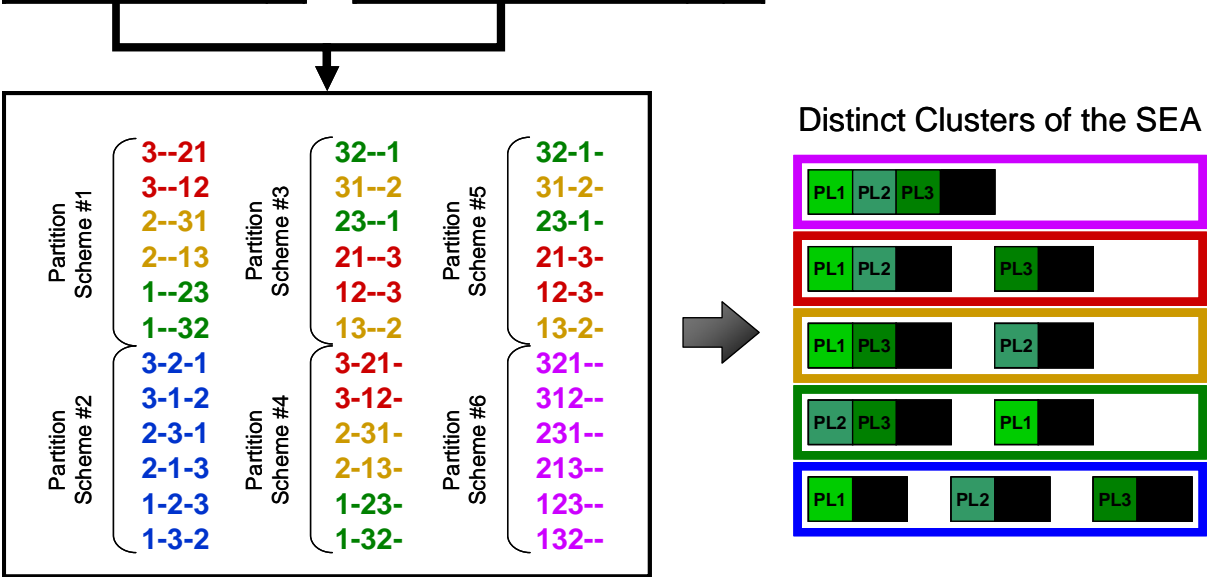
Filtered and Modified Full Factorial Design of  $N$  Levels and  $N-1$  Factors

Partition Scheme #1	1	1
Partition Scheme #2	1	2
Partition Scheme #3	2	2
Partition Scheme #4	1	3
Partition Scheme #5	2	3
Partition Scheme #6	3	3

## Component Permutations

All possible orderings of  $N$  components taken  $N$  at a time

Component Permutation #1	3	2	1
Component Permutation #2	3	1	2
Component Permutation #3	2	3	1
Component Permutation #4	2	1	3
Component Permutation #5	1	2	3
Component Permutation #6	1	3	2



**Figure 9. Example Enumeration Process for a 3-Component SEA.**

Note that the red, yellow, green, blue, and magenta colors in the 36 partition/permutation combinations indicate to which of the final six clusters in the SEA each combination corresponds.

## 2. Enumerating a SED and Defining the GT-FAST Input

As defined in Sec. II.A.2, a SEA is the set of architectures available when placing  $N$  distinguishable components in up to  $N$  indistinguishable modules. In comparison, a SED accounts for the placement of  $K$  distinguishable modules of a particular cluster into up to  $K$  indistinguishable launch vehicles. Thus, the process for enumerating the SEA can be reapplied for enumeration of the SED. Once SEDs are defined, they can be appended to each other to define all cases to examine; for example, recall that the 6-component design evaluated here consists essentially of one  $D_6$  and two  $D_5$  SEDs ( $D_6 + D_5 + D_5 = 3,187$ ). Thus, the full evaluation here involves evaluation of each SED.

The input into GT-FAST for SED evaluations is thus a list of strings describing each design to be evaluated. This format involves a string of numbers and commas. The first nine numbers are associated with the available fractionatable components and vary from 1 to 9 for each of the nine components available for modeling in GT-FAST. The first nine commas indicate divisions between modules; two sequential commas with no numbers between them indicate an empty (nonexistent) module. Similarly, the second nine numbers in the string represent modules as they are to be placed in launch vehicle, and the second nine commas indicate divisions between launch vehicles. GT-FAST then translates this string into the input matrices described by Ref. 3; the resulting matrices for PF0248 are shown in Figs. 10 and 11. Once the string has been read into GT-FAST, the sizing routines execute as described by Ref. 3. For the trade study discussed next, this process is repeated in an automated fashion for each string in the list of SEDs to be evaluated.

ARCHITECTURAL									
Number of Modules	3			Consistency Check					
	Payload 1	Payload 2	Payload 3	24/7 Comm 1	24/7 Comm 2	High BW 1	High BW 2	SSR	MDP
Module 1	P	P	N	F	N	F	N	F	F
Module 2	F	F	N	P	N	P	N	F	P
Module 3	F	F	N	F	N	F	N	P	F
Module 4	F	F	N	F	N	F	N	F	F
Module 5	F	F	N	F	N	F	N	F	F
Module 6	F	F	N	F	N	F	N	F	F
Module 7	F	F	N	F	N	F	N	F	F
Module 8	F	F	N	F	N	F	N	F	F
Module 9	F	F	N	F	N	F	N	F	F

Create this Architecture!

Figure 10. Input Matrix Mapping of Components to Modules for PF0248.

LAUNCH									
Number of Launches	2								
	LV 1	LV 2	LV 3	LV 4	LV 5	LV 6	LV 7	LV 8	LV 9
Module 1	O	N	N	N	N	N	N	N	N
Module 2	O	N	N	N	N	N	N	N	N
Module 3	N	O	N	N	N	N	N	N	N
Module 4	N	N	N	N	N	N	N	N	N
Module 5	N	N	N	N	N	N	N	N	N
Module 6	N	N	N	N	N	N	N	N	N
Module 7	N	N	N	N	N	N	N	N	N
Module 8	N	N	N	N	N	N	N	N	N
Module 9	N	N	N	N	N	N	N	N	N
Tot. Launch Mass (kg)	340.49	138.92	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Launch Cost (\$FY08M)	22.00	22.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Figure 11. Input Launch Manifest Matrix for PF0248.

### III. Defining Output Metrics

As mentioned earlier, key information output by GT-FAST for each point design is a mass, power, and cost budget for the cluster and for each module in the cluster. In addition, crucial to the evaluation and selection of potential F6 designs is the output of user-defined metrics that characterize performance attributes. In the present trade study, sixteen objectives are used in the assessment of potential designs, only one of which is a standard GT-FAST cost, mass, or power output. Five of these objectives are described in depth here.

#### A. Ability to Achieve Incremental, Independent-Order Launches

One objective of the F6 fractionated spacecraft system considered here is demonstration of the ability of the design to accommodate incremental buildup in capability and independence of launch order.<sup>1</sup> This objective, named  $O_6$ , is directed toward allowing System F6 to demonstrate attributes of flexibility and responsiveness that may be of interest to future customers of fractionation.

To capture the performance of a particular design with respect to this objective, quantified is the number of unique orders in which a given design can be launched with the restriction that the launch order must not launch a payload before an SSR, MDP, and high-bandwidth downlink unit are already on-orbit (or contained in the same launch as the payload). This restriction is here termed the “functional payload rule” and results in a launch order not being counted unless payloads can be operational once they reach orbit. The more usable launch orders that exist for a design, the greater its score is according to this objective.

To illustrate more clearly how this objective is computed, Fig. 12 shows the two possible launch orders for the PF0248 example design. In this case, the launch order on the left is not counted toward the  $O_6$  score since both payloads are launched before an SSR is available on-orbit. However, in the launch order on the right, the payloads can begin operations soon after launch since the SSR has been pre-launched. Thus, the score for PF0248 in this category is  $O_6 = 1$ . This value is actually the median score for all 3,190 designs in the trade study; the mean is  $O_6 = 1.54$ , the minimum is  $O_6 = 0$ , and the maximum is  $O_6 = 72$  (for the fully fractionated design).

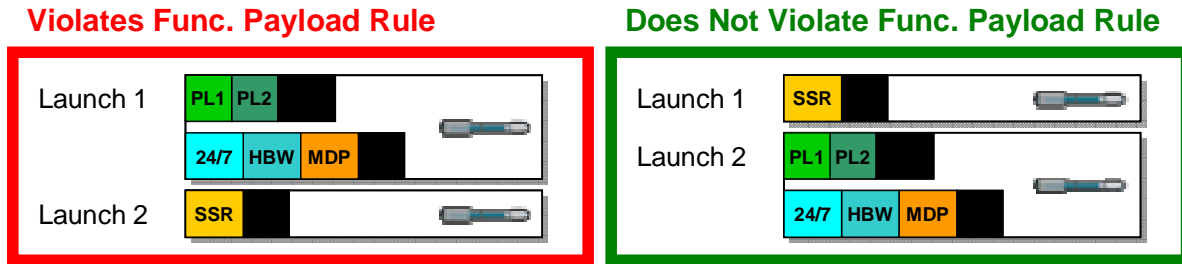


Figure 12. Application of the  $O_6$  objective on PF0248.

### B. Short Time to Operational Capability

Another objective of interest, named  $O_7$ , is minimization of the time required to reach operational capability for the F6 system, constrained by the requirement that the first launch be within four years of program start<sup>1</sup>. This objective is quantified by counting the minimum number of launches required for a given design to reach an initial operational capability with one or more payloads without violating the functional payload rule mentioned in Sec. III.A. A low score for  $O_7$  is desirable, and this imposes an inherent penalty on highly fractionated designs. For example, in a fully fractionated design where each module is launched separately, the minimum number of launches is four. The score for PF0248 is  $O_7 = 2$  (both launches must take place for operational capability to be reached). The median score for all 3,190 designs is  $O_7 = 2$ , the mean is  $O_7 = 1.84$ , the minimum is  $O_7 = 1$  (for example, a monolith), and the maximum is  $O_7 = 4$  (e.g., for fully fractionated designs).

### C. Relevance to Prospective Fractionation Customer

A third objective of the F6 demonstration program is to demonstrate the relevance of the fractionated spacecraft approach for future users. Since these future users will essentially be providing payloads, it is reasonable to believe that the most relevant design to them would be one with a dedicated payload module (in other words, a design in which the payload is alone in its own module, with the other supporting components in one or more separate modules). This notion gives rise to a third objective, quantified through objective  $O_{13}$ , which is the minimum number of non-payload components accompanying a payload for a given design. This effectively captures the degree of payload isolation, and  $O_{13}$  varies from  $O_{13} = 0$  (for designs incorporating a dedicated payload module, such as PF0248) to  $O_{13} = 4$  (for example, for monoliths), where low values are preferable. The median value of  $O_{13}$  for all 3,190 designs is  $O_{13} = 0$ , and the mean is  $O_{13} = 0.36$ .\*\*\*

### D. Ease of Accepting New Components

A key flexibility-related metric is the ease with which new components can be added to the cluster. The desire to launch a new component may stem, for example, from increases in market and capability demand or availability of technology upgrades and enhanced capabilities; a desirable characteristic is for the cost of adding these components to be low.

The metric chosen here to represent the ease with which a design accepts new components is the average cost of adding or replacing a component of the cluster. This metric, named  $O_{10}$  or  $C_{add/replace}$  as defined in Eq. (5), considers the fact that a given single component  $i$  can be added to the cluster in one of two practical ways. First, the user could choose to launch the needed component as part of a module that is a duplicate of one that is already on-orbit. This strategy takes advantage of the fact that no research, development, test, and evaluation (RDT&E) costs are incurred since the module has already been manufactured before. The cost to implement this option is reflected as  $C_{i,existing}$  in Eq. (5). The second option for the user is to simply launch a module with the single component  $i$  that is needed (for an example of a single-component module, see Module #3 in Fig. 5). This strategy takes advantage of the low cost associated with a small, single-component module but has the disadvantage that, unless this module had been developed for the original cluster, RDT&E costs are incurred. The cost of this option is  $C_{i,separate}$  in Eq. (5).

\*\*\* This is an interesting result, since it highlights the fact that over 50% (actually, 71%) of the 3,190 possible designs have the characteristic of payload isolation (i.e., a dedicated payload module).

The  $C_{add/replace}$  metric is based on the idea that a user would prefer the lowest-cost option when it comes to adding or replacing a single component. However, since it is not obvious which components will require addition or replacement in the future, the average is taken over all the  $n$  possible components of the lowest-cost addition/replacement options. This is reflected in Eq. (5), and this metric is evaluated in GT-FAST for each of the 3,190 designs considered. These can be formed into a histogram, shown in Fig. 13. In this particular problem, the minimum  $C_{add/replace}$  is \$42.5 million and the maximum is \$83.5 million, with a median of \$52.2 million. If only this objective were considered, a fully-fractionated design (consisting only of single-component modules) would be optimal since each single-component module is pre-developed.

$$\bar{C}_{add/replace} = \frac{1}{n} \sum_{i=1}^n \min(C_{i,separate}, C_{i,existing}) \quad (5)$$

### E. Robustness to Threats

An important advantage to a fractionated spacecraft is its inherent robustness to external threats. To generate a measure of this objective, named  $O_{15}$ , a score is formulated which reflects the expected degree of functionality for the cluster after it is subject to failure of an entire module (which could be caused, for example, by orbital debris strikes or anti-satellite missile attacks). For example, if both payloads are lost when a module fails, then it is assumed that functionality is effectively zero. If only subsystem components are lost (for example, the solid state recorder, the high-bandwidth downlink unit, etc.), then a lesser degradation is imposed. When this metric is computed, the loss of each module is considered to be equally probable and is equally weighted in determining the expected functionality score after a module failure; the value of the  $O_{15}$  functionality score is always between zero and unity.

The  $O_{15} = 0$  value occurs for monolithic spacecraft where the loss of a module is also the loss of the cluster. In this study, a design with  $O_{15} = 1$  is of course never found; the maximum performance value for this objective is  $O_{15} = 0.54$  for fully fractionated designs with two payloads. This result itself is quite interesting in that it implies that a fully fractionated spacecraft on average might be expected to retain over half its functionality if a module is lost at random, which is quite a benefit over a monolithic spacecraft. For this metric, the median and mean were quite close at 0.42 and 0.41, respectively. For reference, the PF0248 design scores rather low in this category, with  $O_{15} = 0.23$ ; this is largely due to the placement of both payloads in the same module, since the cluster will have virtually no functionality if one of the three modules is lost.

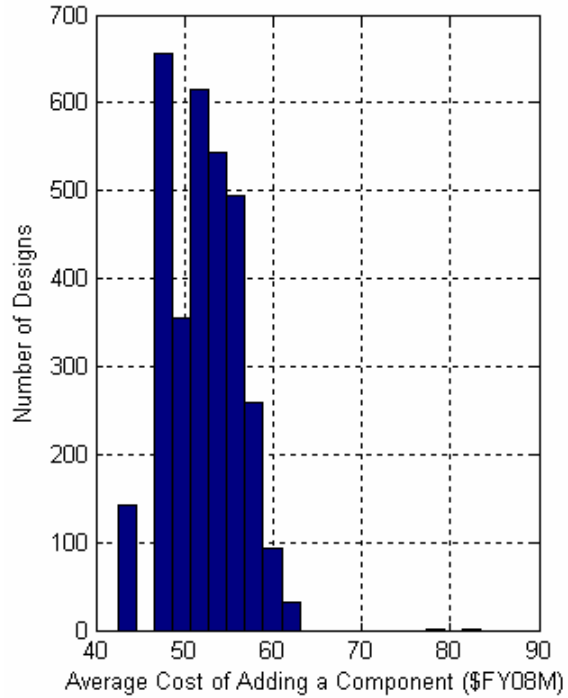


Figure 13. Histogram of  $C_{add/replace}$  metric.

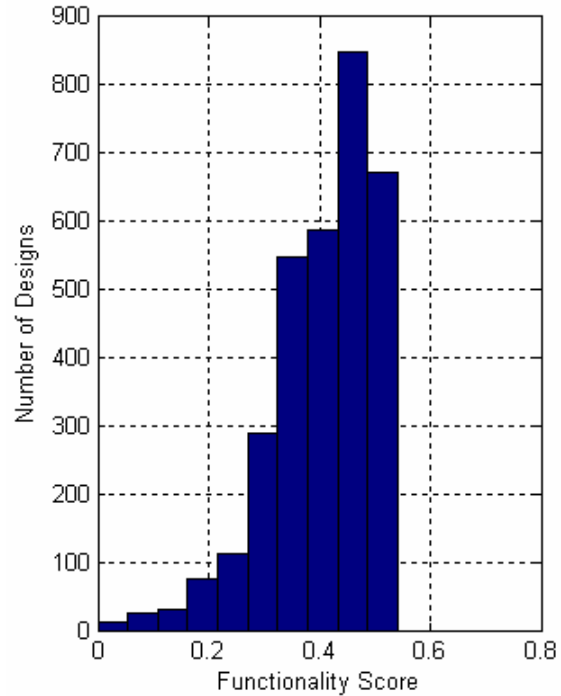


Figure 14. Histogram of  $O_{15}$  robustness to threats functionality score metric.

## F. Other Objectives

The five quantified objectives above are only examples of the total 16 objectives used in the following trade space exploration. One of the most obvious objectives not discussed was total program cost, a histogram of which is shown in Fig. 15. Total program cost is a core output of GT-FAST and did not need to be programmed as a user-specific output. Details on the cost estimation assumptions and procedures can be found in Ref. 3.

Table 3 summarizes the 16 objectives considered. These objectives were the result of an extensive brainstorming session, and although each is defined well in a conceptual and qualitative sense, not all can be resolved quantitatively to a level of fine detail with the sizing information available from GT-FAST. In the case of eight objectives, fine resolution is available similar to the five described earlier. In the case of four objectives, coarse resolution is given based on qualitative considerations (for example, programmatic risk is likely correlated with complexity in terms of the average size of modules and the number of modules that must be developed, but the exact correlation is unclear at this stage and is divided only into categories of low, medium, and high risk). Insufficient information existed for the evaluation of the final four objectives, and these were not analyzed.

The rightmost column of Table 3 provides the relative weighting assigned to each objective based on an interview session using an analytic hierarchy process (AHP) prioritization matrix. For example, this column shows that relevance to potential fractionation customers is the highest-priority objective. Note that a weighting is not given to total program cost because this objective will be displayed separately on the second axis of a Pareto front plot in the trade space exploration; the weightings shown here will only be used to aggregate all non-cost objectives into a single “performance” or “effectiveness” score. Also note that the fact that four objectives are unresolvable at this stage is accounted for by giving identical scores to every design in those categories (i.e., not by assigning a weight of zero).

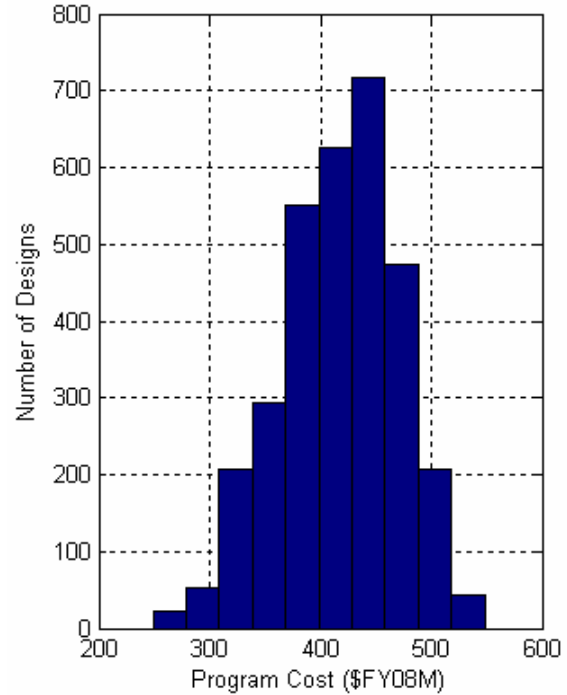


Figure 15. Histogram of F6 Program Cost.

Table 3. Summary of the 16 objectives considered for this trade space exploration.

No.	Objective Name	Resolution	Weighting ( $\times 100$ )
1	Availability	Not Available	1.4
2	Ground Signature Minimization	Coarse	3.5
3	Payload/Mission Performance	Coarse	4.3
4	Low Total Program Cost	Fine	N/A
5	Low/Diversified Programmatic Risk	Coarse	5.1
6	Ability to Achieve Incremental, Independent-Order Launches	Fine	1.9
7	Short Time to Operational Capability	Fine	1.5
8	System Longevity	Not Available	4.5
9	Manufacturability & Testability	Fine	4.7
10	Ease of Accepting New Components	Fine	7.5
11	Ease of Changing Cluster Configuration	Not Available	8.4
12	Reprogrammability & Functional Reconfiguration	Not Available	11.1
13	Relevance to Potential Fractionation Customer	Fine	13.2
14	Robustness to Failure	Coarse	12.7
15	Robustness to Threats	Fine	6.0
16	Extensive Technology Demonstration	Fine	10.3

## IV. Visualizing the Trade Space

Having computed the sixteen metrics shown in Table 3 for each of the 3,190 designs in the defined trade space, the problem exists of how to filter and plot this data in a way conducive to selecting desirable designs and observing trends. A multitude of techniques exist, and by no means are the methods presented here the only ones possible. However, we have found these to be intuitive and helpful to the exploration of the F6 trade space.

The approach of this analysis makes extensive use of Pareto frontiers (or fronts), which allow for identification of non-dominated solutions in an objective space. In the representations that will be shown, each design will be represented by a point whose coordinates are the values of two objectives associated with the design. The Pareto front is the set of points which are non-dominated in the objective space (i.e., at a non-dominated point, it is impossible to find another design that improves all objectives simultaneously). This approach has the advantage that it helps narrow the trade space significantly and avoids the naming of a single optimum solution, which by definition does not exist for a multiobjective problem. It also provides helpful visualizations which allow identification of the “knees” of Pareto fronts, if they exist.

One disadvantage of Pareto fronts is that they quickly become unwieldy and difficult to visualize as the number of objectives being tracked increases past two. To overcome this limitation, the second part of this analysis uses the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to aggregate all non-cost objectives into a single “performance” or “effectiveness” metric (analogous to the effectiveness parameter in the technology frontier approach of Ref. 8). Although there are always limitations whenever multiple objectives are combined into a single metric, we find this useful in identifying several highly desirable designs. It is worth noting that nowhere in this analysis do we identify a definitive optimum design due to the multiobjective nature of the problem; we limit our discussion to noting several promising designs and, importantly, the relevant characteristics common to them.

### A. Basic Two-Objective Pareto Fronts

#### 1. Minimum Launches to Operational Capability vs. Feasible Launch Combinations

Figure 16 shows an interesting Pareto frontier in the  $O_7$  vs.  $O_6$  objective space. Recall that  $O_6$  represents the number of feasible launch combinations (i.e., those that do not violate the functional payload rule) and  $O_7$  represents the minimum number of launches required for an initial operational capability. The user would prefer to maximize  $O_6$  and minimize  $O_7$ , all other things being equal, so the ideal solution would be in the bottom right corner of Fig. 16 and the Pareto front (the red line) has a positive slope. In part, what this Pareto front indicates is the inherent design trade between maximizing the number of possible launch orders and minimizing launches to initial operational capability. If the designer wishes to have operational capability after one launch, it is impossible to achieve more than three feasible launch orders. If the designer wishes to be able to choose from 72 possible launch orders, then the minimum launches to initial capability cannot be less than four.

Recall also that each blue “x” in Fig. 16 represents a design.<sup>†††</sup> Thus, this allows for the identification of designs on the Pareto front (also called Pareto-optimal solutions). At the location marked as A in Fig. 16, 30 designs exist which have three feasible launch combinations and a single launch for initial operational capability. One of these designs is PF0031, shown in Fig. 16. This design groups all essential components into a single module launched on a dedicated launch vehicle (allowing for the single-launch initial capability) and the remaining two components on their own dedicated modules, each of which having their own dedicated launch vehicle (allowing for multiple feasible launch combinations). At the other extreme, at the location marked as D in Fig. 16 sits the fully-fractionated design with six dedicated launches (the maximum possible), allowing for the maximum possible feasible launch orders but simultaneously requiring at least four launches for an initial operational capability. The progression from A to D can be seen in example designs at locations B and C as shown in Fig. 16. Here, the usefulness of the Pareto front approach should be clear in that it identifies the set of best designs a designer could choose; if a designer were only interested in the  $O_6$  and  $O_7$  objectives, he should choose one of the designs (as indicated by Fig. 16) at the A, B, C, or D locations.

#### 2. Ease of Accepting New Components vs. Total Program Cost

Figure 17 shows a particularly interesting Pareto frontier in the  $O_{10}$  vs.  $O_4$  objective space. Recall that  $O_4$  is the total program cost and  $O_{10}$  is the average cost of adding or replacing a component of the cluster. The user would prefer to minimize both  $O_4$  and  $O_{10}$ , all other things being equal, so the ideal solution would be in the bottom left

<sup>†††</sup> For the discrete outputs of Fig. 16, many different designs might have the same combination of  $O_6$  and  $O_7$ , so the “x” marks overlap and 3,190 distinct marks are not visible.

corner of Fig. 17 and the Pareto front (the red line) has a negative slope. In part, what this Pareto front indicates is the inherent design trade between minimizing the total program cost and minimizing the average cost of replacement; that is, an additional investment must be made up-front in the form of total program cost if the user wishes to reduce the cost of replacement.

Recall also that each blue “x” in Fig. 17 represents a design, again allowing for the identification of Pareto-optimal designs. At the location marked as A lies a monolithic spacecraft design that excludes PL1 (the more massive and more costly payload).<sup>†††</sup> Design A has a very low total program cost but also has the highest average cost of adding a component since the addition of a component requires the launch of a new monolithic spacecraft. For the small added cost of an intra-cluster wireless unit (i.e., the creation of a “fractionatable” monolith), Design B has a \$20 million reduction in the average cost of adding a component since the option exists to send small single-component modules instead of a new monolithic spacecraft. Design C is interesting because it lies at a very distinct “knee” on the Pareto front and has both a low program cost and low average component replacement cost. This design fractionates the payload and solid state recorder each into single-component modules but permits the 24/7 communication unit, high bandwidth downlink unit, and mission data processor to remain in the same module; this particular compromise between the economies of scale of the traditional monolith and flexibility of the fully fractionated spacecraft presents an appealing design from the perspective of objectives  $O_4$  and  $O_{10}$ . Designs D and E, each of which is fractionated among more modules than Design C, have slightly lower costs of adding components but are significantly more expensive to develop and field.

## B. Pareto Fronts involving TOPSIS Scores

In contrast to Figs. 16 and 17, which considered only two objectives at a time, Figs. 18 and 19 aggregate all non-cost objectives into a single score and plot this score against total program cost for each of the 3,190 designs. To create this score, the TOPSIS multi-attribute decision-making technique is used, and objective weightings are taken from Table 3. As a result, the designs that will be identified on the Pareto fronts in Figs. 18 and 19 are predominantly “compromise” solutions that perform well in many categories but perhaps are not the best in any single category.

The Pareto front in Fig. 18 exhibits several interesting characteristics. The lowest-cost design, the monolithic spacecraft carrying only PL2 as a payload, anchors the Pareto front in the bottom left. The design with the highest TOPSIS score, the fully fractionated design with dedicated launches and both payloads, anchors the Pareto front in the top right. Interestingly, the TOPSIS score increases dramatically at a program cost about \$10 million above the anchoring monolithic spacecraft; the design at the knee of this segment of the Pareto front is PL2-PF2874, a three-module design in which all three modules launch on the same vehicle. To the right of PL2-PF2874 are six designs that offer incremental improvements in TOPSIS score for significant increases in program cost. These designs can be grouped into two families of designs, as outlined by red and blue boxes in Fig. 18. Each family has a common module configuration and has variations only in the number of launch vehicles. The final two Pareto-optimal designs are fully fractionated designs which offer significant TOPSIS score increases (and value to the customer) but at significant costs. One remark to make at this point is that Fig. 18 has effectively narrowed the trade space of 3,190 designs to just eleven designs (a reduction by a factor of 290).

One limitation of the Pareto-optimal designs identified in Fig. 18 is that many of them (particularly the lower-cost options) are single-launch solutions, which probably do not meet the expectations of DARPA for the F6 program. Another limitation is that most of these Pareto-optimal designs include only a single payload, another attribute that probably does not meet DARPA’s expectations. Figure 19 shows the results of filtering out these undesirable cases, i.e., cases with only one launch or only one payload. The resulting Pareto front is shifted somewhat to the lower right compared to the first front, and a major difference is that the lowest-cost option is now above \$300 million, whereas it was about \$250 million in Fig. 18. This lowest-cost option is PF0730, a two-module, two-launch design, and the highest-TOPSIS-score design remains as the fully-fractionated design with dedicated launches. An interesting knee in this curve occurs at a cost of \$340 million: The PF0248 design, the example design carried through examples earlier in this paper, is a two-launch solution with the significant advantage of a module dedicated only to carrying payloads, meaning PF0248 performs well in the heavily-weighted category of relevance to potential fractionation customers. PF0248 also has average performance in several other categories and, along with a low cost, makes an appealing option. Significantly, PF0248 is identical to the PL2-PF2874 design at the knee of the curve in Fig. 18 except that (1) PF0248 includes both PL1 and PL2 and (2) PF0248

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<sup>†††</sup> In fact, the three designs that can be seen with a replacement cost above \$75 million are the three monoliths (one with PL1 only, another with PL2 only, and the third with both PL1 and PL2).



launches on two launch vehicles instead of one. These differences are identical to the constraints imposed on Fig. 18 to result in Fig. 19, and so it is interesting that the design at the knee of the Fig. 18 Pareto front is nearly the same as the design at the knee of the Fig. 19 Pareto front. Again, however, it is not claimed that PF0248 is the “best” design since Fig. 19 shows that higher TOPSIS scores are possible with the expenditure of additional funds on the total program cost; the designs that achieve these higher scores gradually consist of earlier more modules and more launches, eventually leading to the highest-scoring fully fractionated design mentioned earlier.

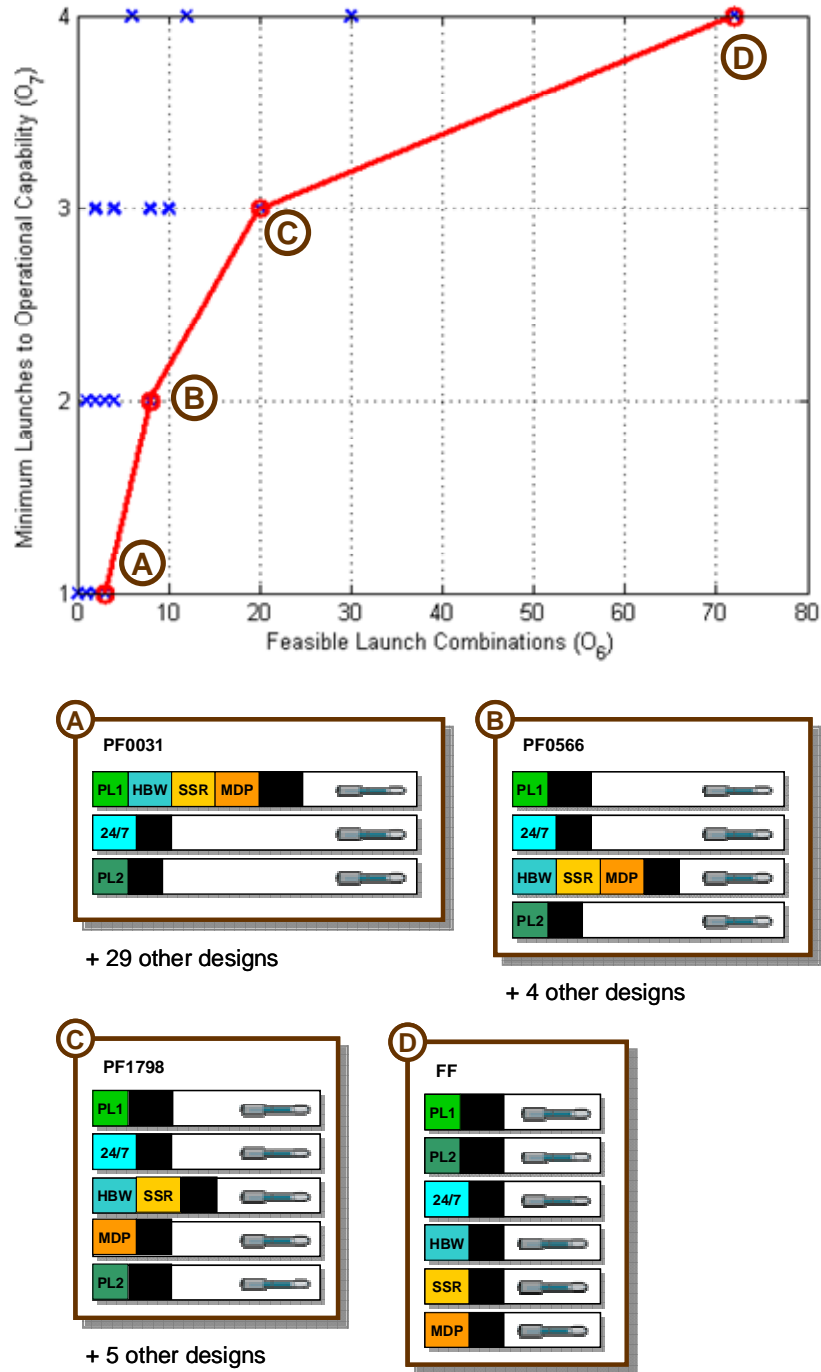


Figure 16. Pareto front between objectives  $O_6$  and  $O_7$ .

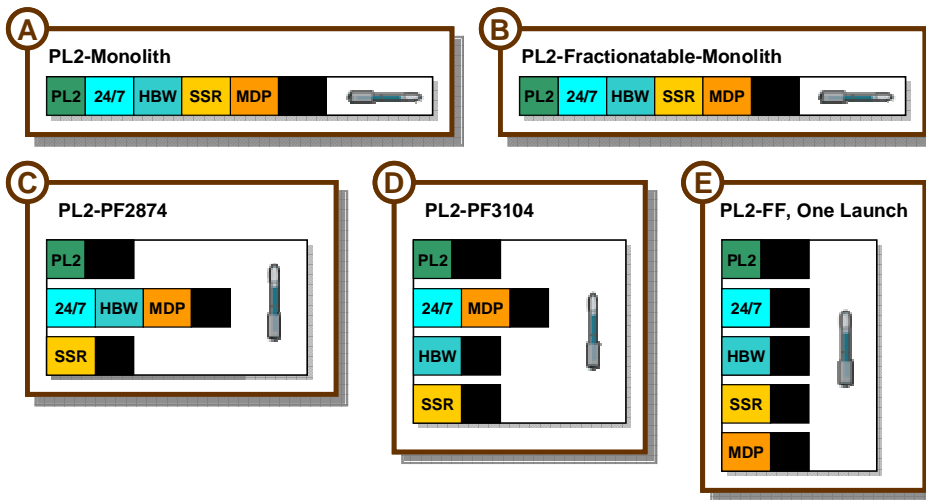
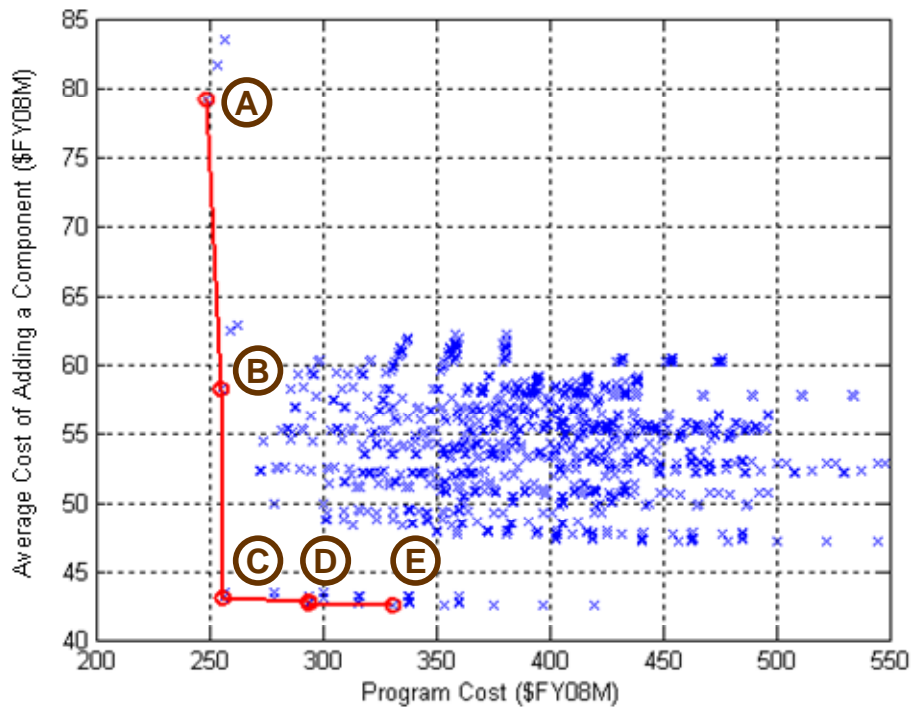
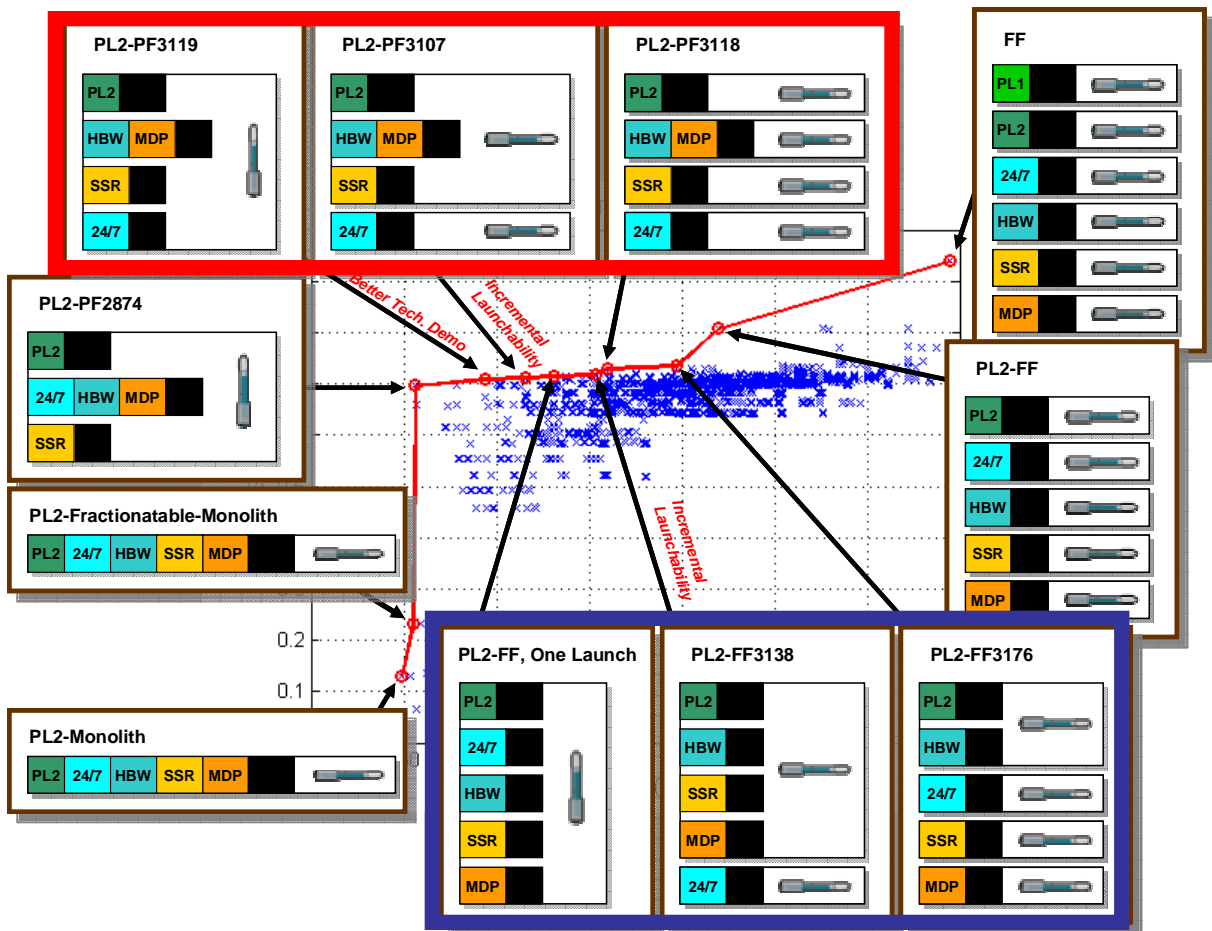
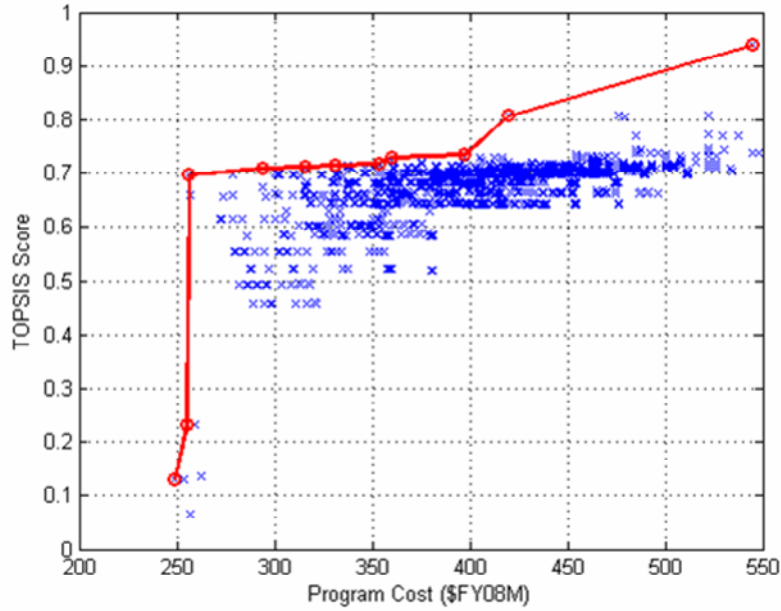


Figure 17. Pareto front between objectives  $O_4$  and  $O_{10}$ .



**Figure 18.** Pareto front between TOPSIS Score and Program Cost ( $O_4$ ). Blue marks denote individual designs, the red line indicates the Pareto front, and red text indicates reasons for increases in the TOPSIS score for particular designs as one moves to higher program costs.

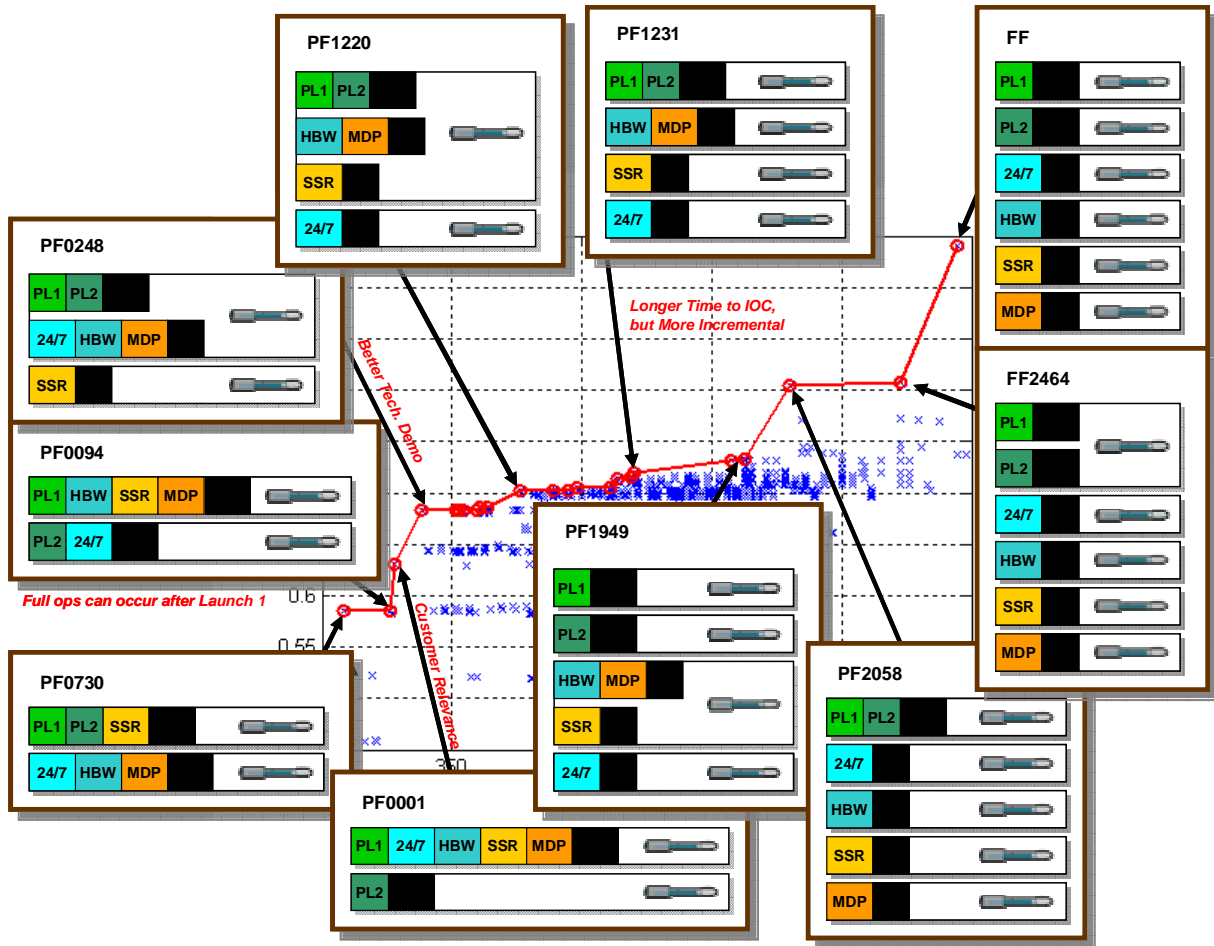
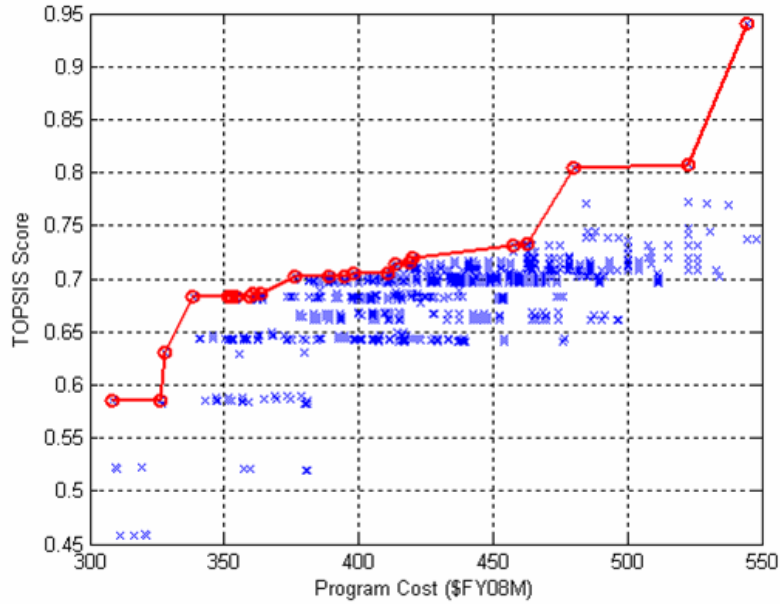


Figure 19. Pareto front between TOPSIS Score and Program Cost ( $O_4$ ), excluding single-payload and single-launch cases. Blue marks denote individual designs, the red line indicates the Pareto front, and red text indicates reasons for increases in the TOPSIS score for particular designs as one moves to higher program costs.

## V. Conclusions

This paper has presented the application of the Georgia Tech F6 Architecture Synthesis Tool (GT-FAST) to the exploration of the System F6 trade space. Combinatorial analysis of the architectural trade space itself was presented, providing a theoretical contribution applicable to future analyses and clearly showing the explosion of the size of the trade space as the number of fractionatable components increases. Several output metrics of interest to this study were defined, and next Pareto fronts were used to visualize the trade space. The first set of these Pareto fronts allowed direct visualization of one output against another, and the second set presented cost on the horizontal axis and on the vertical axis a TOPSIS score aggregating the performance characteristics of 15 of the 16 objectives. These techniques allowed for the identification of a handful of Pareto-optimal designs from an original pool of 3,190 designs.

### A. Selecting a Design

Some of the most interesting and practical conclusions are derived from the Pareto fronts in Figs. 18 and 19. In both of these figures, there are large gains in TOPSIS score (which can be considered a performance or effectiveness metric) associated with small increase in program cost above the minimum-cost design. This is especially evident in Fig. 18. Following this initially steep rise is a shallow-slope region extending for \$100-150 million before the Pareto front slope becomes steeper again as the complex and costly fully fractionated designs are approached. In this shallow-slope region, complex interactions exist among the various low-priority objectives to make some designs marginally more preferable than others; in this region, many designs have similar overall performance characteristics and designs are thus more difficult to distinguish on this basis, particularly considering that the objective weightings (see Table 3) are likely to be at least moderately dependent on the customer.

Perhaps one of the more appealing designs is PF0248 at a knee of the Pareto front in Fig. 19 (a design which is also related to the PL2-PF2874 design at the knee in Fig. 18). PF0248, also the example design carried through this paper, is a two-launch design with the significant advantage of a module dedicated only to carrying payloads, meaning it performs well in the heavily-weighted category of relevance to potential fractionation customers. PF0248 also has average performance in several other categories and, importantly, has one of the lowest program costs.

Additionally, regardless of decision-maker preferences for any particular design, this analysis has captured the competing effects associated with increasing the number of launches for a particular architecture. While the additional launches are desirable in order to demonstrate the ability to field the architecture incrementally and on launches that are order-independent, they also increase the time it takes to finish fielding the system as well as increase cost. This analysis has also captured the potential advantage to dedicating one or more launches to modules containing components nonessential to initial operational capability, such as a second payload or 24/7 communications unit. A strategy such as this allows initial operational capability to be reached in a single launch (for example, if all essential components are on the first launch) while also providing other launches as opportunities to demonstrate the ability to add infrastructure components or payloads. However, this analysis has also revealed that decisions such as this must be traded against potential cost and flexibility implications; in the case of PF0248, had the 24/7 communication unit been placed in a dedicated module instead of the SSR, the total program cost would have been \$50 million higher and the average cost of adding a component would have been \$7 million higher.

### B. Potential Future Work

A number of avenues for future follow-on work exist. First, the combinatorial analysis presented here is not easily applicable to scenarios with complex constraints (the  $D_6 + D_5 + D_5$  scenario here was relatively simple), and it also overcounts the number of possible designs if two components are not distinct (e.g., if there were to be two indistinguishable SSRs in a cluster). Second, regardless of whether a combinatorial theory is available to count the number of possible designs, the task still exists of how to efficiently enumerate them; the algorithm illustrated by Fig. 9 works quickly for relatively small values of  $N$  but quickly becomes time-consuming as  $N$  increases.

In terms of the trade space exploration process, a helpful next step would be the analysis of a constrained Super-SEA with  $N > 6$  (perhaps at about  $N = 9$ ) to allow consideration of redundant components. Along with this should come refinement of the objective weightings and an assessment of the sensitivity of the TOPSIS-based Pareto fronts to these weightings (the pure two-objective Pareto fronts in Figs. 16 and 17 are of course unaffected). Another area of future work is the refinement of the objective metrics themselves and increased resolution on the objectives listed with “Coarse” or “Not Available” resolution in Table 3.

Overall, this paper has contributed theoretical and practical processes and results toward the systematization of future decision processes for fractionated architectures. All of the processes and theoretical developments here are

applicable to future fractionated architecture analyses and decision processes, and the data generated here presents some relevant and interesting conclusions for the particular case of the System F6 demonstrator spacecraft. It is hoped that the ideas presented here find use with engineers and decision-makers considering fractionated systems in the future.

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