

A BOTTOM-UP MODELING APPROACH FOR THE PROFIT ANALYSIS OF CELLULARIZED
SPACECRAFT ARCHITECTURES

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This paper proposes a bottom-up modeling approach applied to changing satellite morphology on the Phoenix project. Phoenix's main operational goal is to cooperatively harvest and re-use valuable components from retired, nonworking satellites in geostationary Earth orbit, thereby creating new space systems at greatly reduced cost. The envisioned Phoenix spacecraft architecture is cellularized, i.e., multiple satlets are used together in an aggregate system to achieve required mission functionality. In this paper, an initial model is presented which calculates the detailed satlet and aggregate system architecture costs. The Phoenix mission costs and profits are then compared, which assists in finding optimal architectures for given missions and assumptions. This model includes the computation of aggregate system performance and cost. A novel approach was required because of the fractionated architecture and the novelty of the concept. A profit analysis, which allows for the exploration of the profitability of different architectures across varying market scenarios, was performed. These important metrics will be used in a related tradespace exploration (conducted by NASA's Jet Propulsion Laboratory and Aurora Flight Sciences) based on input assumptions. The analysis conducted by the MIT team determined that a certain level of heterogeneity is optimal, and also that the most robust satlet architecture can only be determined through extensive market analysis. The results of our analysis are subject to specific assumptions and shall not be taken as the only possible instantiation of a satlet architecture. **The views expressed are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.**

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I. INTRODUCTION

The Phoenix project was conceived “to develop and demonstrate technologies to cooperatively harvest and re-use valuable components from retired, non-operating satellites in [graveyard] geostationary Earth orbit and demonstrate the ability to create new space systems at greatly reduced cost.”ⁱⁱ The hypothesis behind the project is that a new type of satellite morphology referred to as “satlets” can be used in conjunction with a “servicer/tender” craft to reclaim valuable assets from non-functioning satellites. Since the 1960s, approximately 1000 satellites have been sent to geostationary earth orbit (GEO), representing over \$300B of value retained in orbit.ⁱ Due to the nature of satellites, some subsystems and components expire before others. Those salvageable subsystems and components are the motivation behind the Phoenix program.ⁱ

Satletsⁱⁱ are a new concept of small modular objects that do not individually have the full functionality of a traditional satellite. Multiple cellularized satlets are used together in an aggregate system to achieve the functionality that a given mission requires. Cellularization is a measure of how functions are distributed among satlet types.ⁱ An initial demonstration mission for the Phoenix project is to retrieve and use an antenna from a retired commercial communication satellite (referred to as the retired candidate asset (RCA)). The servicer/tender is expected to retrieve the aperture from the non-functioning satellite and place the satlets in the necessary configuration to provide pointing and orbit maintenance. The aggregation of multiple satlets then provides all of the functionality of a traditional satellite using the harvested aperture.

The initial RCA mission is being used as the concept mission to define requirements and evaluate trades between different levels of cellularization. The cost advantage of the satlet strategy is based on cost-savings gained from producing a large volume of space-capable elements from a design set for a variety of missions. For that reason, the capability provided by satlet cellularization to conduct different types of missions is explicitly considered and sought after. Therefore two missions based on a representative communications satellite (for the purposes of this study we chose the US Tracking and Data Relay Satellite (TDRS)) demonstration mission as well as a mission based on a general attitude determination and control subsystem (ADCS). The first two missions involve harvesting a 12-meter dish and a 2-meter dish from a TDRSS, respectively (as a

proxy to a commercial communications satellite). The third mission is to provide a new or supplementary ADCS to an existing satellite, via robotic servicing from a Servicer/Tender with satlets. This mission was chosen because of the possibility of failure of ADCS subsystems, creating a likely mission for Phoenix to undertake.ⁱⁱⁱ

There are several reasons why a satlet-based strategy is attractive. First, the cost of designing, launching, and manufacturing a satlet-based aggregate system are all expected to be lower than traditional monolithic satellite missions. Using a set of pre-defined satlets to accomplish a variety of missions reduces the average design cost for each of these missions substantially. Additionally, the manufacture of large numbers of a standard set of satlets numbers is expected to be much more cost-effective than building a custom satellite for each mission. This effect is known as the learning curve and is explicitly considered in this analysis.

A team of graduate students from the Massachusetts Institute of Technology (MIT) has conducted the study described in this paper. DARPA is the lead for the Phoenix project with David Barnhart as the program manager. Aurora Flight Sciences (AFS), along with the Jet Propulsion Laboratory (JPL) and MIT, is one of the satlet providers in Phase 1. The MIT team was tasked with creating an analysis of satellite cellularization. Specifically, the it has provided AFS and JPL with a measure of financial return appeal for a set of aggregate systems based on the predominantly bottom-up satlet cellularization of each aggregate system. A market analysis and discussion of key design aspects such as heterogeneity, or the level of fractionation, conveys this information.

Before progressing into the specifics of the model, the requirements must be defined which govern the satlets and the scope of this analysis.

II. REQUIREMENTS

DARPA created a set of requirements that govern the designs of the different mission elements. These mission requirements flow down to requirements for the MIT/JPL/AFS team.

II.I Phoenix Programmatic Mission Statements and Requirements

DARPA created two overarching mission statements that outline the objectives of the project, as listed below:^{iv}

- Mission Statement 1: The goal of the Phoenix program is to develop and demonstrate technologies to cooperatively harvest and re-use valuable components from retired, non-operating satellites in geostationary orbit (GEO).
- Mission Statement 2: The program aims to demonstrate the ability to create new space systems at greatly reduced cost by leveraging morphological reconstruction and cellularization.

Because this mission is so drastically different from any previous one, these mission statements provide a unique high-level framework. The first mission statement flows into requirements that concern the development of new technologies, most notably the concept of a satlet, the small, highly fractionated space element that relies on morphological reconstruction to create a new satellite or augment existing capability on-orbit. No existing cost models are applicable to such a system architecture (further explained in Section IV). The second mission statement addresses this cost issue, flowing down into requirements that govern the development of new cost estimation tools and the need to develop all new technologies effectively at minimal expense. In addition, in order to maximize the project's value proposition, profit was chosen as the proxy, where the statement flows into requirements governing the analysis of possible markets for satellite repurposing, starting with the demonstration mission of repurposing the aperture of an RCA.

II.II MIT Team Requirements

The mission statements flow into requirements for the MIT team in its mission to provide the JPL team with a profit analysis for JPL-optimized aggregate systems. A total of four requirement levels were written to direct the requirements on the MIT team's analysis.

The single MIT Level 1 requirement states that the MIT team shall provide JPL with a profit analysis for use in determining the optimum satlet architecture from an expansive aggregate system trade-space. This profit analysis allows the team to meet the two DARPA mission statements by ensuring that the optimum aggregate system will be able to conduct its missions in the most cost effective manner possible.

As shown in Figure 1, the four levels of requirements are all based on the satlet components database that is provided by the JPL team. This database consists of an initial set of 46 components of which the AFS candidate satlets could be composed.

A satlet may consist of an integer number of these components. Similarly, aggregates are made of integer numbers of satlets.

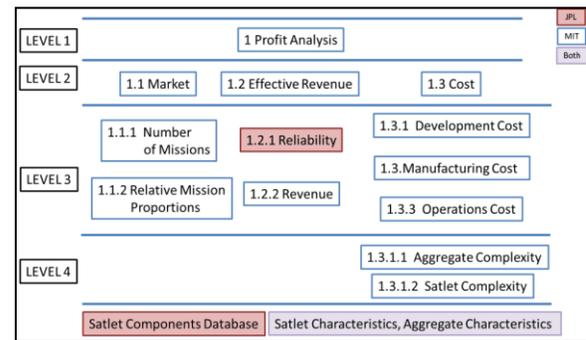


Figure 1. Requirements flow for conceptual analysis development phase (MIT).

Both the market and effective revenue are calculated by analyzing the three sample missions stated earlier in this paper. The number of total missions and the relative distribution of each mission type determine the market. Each mission type corresponds to a specific revenue value, thus market assumption has profound impacts on the overall valuation of the satlet enterprise in the Phoenix project, as identified in this analysis.

Each market requires different capabilities from the aggregate systems. Consequently, an aggregate, specified by the number of set satlet types, can change the number of satlets of each type to meet the requirements for each mission, but not the types themselves. The MIT team has analyzed three mission types, i.e. large aperture, small aperture, and ADCS on-orbit servicing.

With the types of satlets and the numbers of each type provided by JPL's initial architecture, the MIT team can compute the complexity and other characteristics of each aggregate system in order to create the profit analysis and fulfill the MIT team's Level 1 requirement. The following section describes this bottom-up process.

II.III Bottom-Up Approach

The creation of a profit analysis requires knowing the market to be exploited by the Phoenix architectures, as well as the aggregate systems that will perform the missions themselves. The MIT team has identified the three mission types that constitute the Phoenix market, while JPL has identified a suite of possible aggregate systems. Figure 2 shows how the requirements in Figure 1 correspond to calculations in the MIT MATLAB codes. As can be

seen in the figure, the envisioned missions and characteristics of both the satlets and aggregates lead to the calculation of profit that JPL can use to conduct its tradespace optimization.

The MIT team utilized a bottom-up approach to conduct the profit analysis. The JPL inputs, described in Figure 1, allow for the MIT code to calculate the characteristics of both the satlets and aggregates as determined by the JPL optimizer and provided to the MIT team, including volume, mass, power requirements, power generation capabilities, and thermal losses; as well as the cost to purchase the components that comprise the satlets. Additionally, the MIT-developed Design Structure Matrix allows the MIT code to compute a level of complexity of satlets based on the interactions between the different components (described in Section IV). The MIT cost estimator, which is described later in this paper, then uses the components in the satlets to compute estimated development, manufacturing, and operations costs associated with each satlet and, subsequently, each aggregate system.

The costs combined with the effective revenue allow a simple representative profit to be computed. As shown in the boxed equation in Figure 2 in the next section, the profit equation takes as inputs the envisioned number of missions performed, the number of mission types, the revenue for each mission type, the reliability of the aggregate system, and the costs of the aggregate. Consequently, the MIT code allows for the JPL inputs to be analyzed in a bottom-up manner, starting from components for an envisioned market and working towards a complete profit analysis.

III. PROFIT

In the bottom-up approach just described, a variety of activities converge into the profit analysis, which is the ultimate goal for the MIT project. The calculation of profit is comprised of three main components: (1) the total cost associated with the given aggregate system, (2) a market projection, and (3) the (effective) revenue produced by the system in the specified market. Equation 1 shows the major dependencies of profit on the aforementioned components.

$$P = [\sum_{i=1}^n m_i (R_i r_i - C_i^O) - C_i^M] - C^D. \quad [1]$$

In Equation [1]:

- n is the number of different mission types performed by the aggregate system. In the context of this paper, three different missions are considered ($n = 3$): small aperture, large aperture, and ADCS.
- m_i is the number of repurposing/servicing missions envisioned to be carried out by all manufactured satlets, for the given mission i where $i = 1$ corresponds to the small aperture mission, $i = 2$ to large aperture, $i = 3$ to ADCS (e.g., $m_1 = 2$ indicates conducting two small aperture repurposing missions).
- R_i is the approximated revenue income associated with the performance of mission i .
- r_i is the reliability factor (i.e., probability of success) associated with the performance of mission i . Reliability depends also on the given aggregate system of interest and has been computed by JPL and AFS (based on the initial component set chosen only).
- C_i^O is the operations cost associated with the performance of mission i by the aggregate system of interest. A model has not been constructed yet for the calculation of this cost type. In the context of this paper, only launch cost is computed as part of the operations cost.
- C_i^M is the cost associated with the manufacturing of the part of the aggregate system that is going to perform mission i . This cost is a function of m_i , as it takes into account “learning curve” effects.
- C^D is the one-time, upfront cost of the initial research and development associated with the design of the specific satlets that compose the aggregate system of interest.

The three major components that make up profit (mentioned at the start of this section) are described by the above factors. The total cost is approximated by the sum of the development, manufacturing and operations costs; effective revenue is the revenue associated with the given mission, corrected by the reliability factor (systems with larger numbers of low reliability components are penalized in terms of the revenue they can generate); the market projections are modeled by the number of specific missions envisioned to be performed by the system across its lifecycle. More details about the calculation of certain factors (such as development cost) are presented in the next section. The relation between the factors that go into equation [1] and all the activities performed throughout the project are shown in Figure 2.

It is important to note that Equation [1] assumes that all aggregate systems for which profit is evaluated are able to meet the mission requirements, and therefore generate revenue. In the analysis shown in this paper, the aggregate systems considered have been provided by JPL, which has designed them (in terms of the number and type of satlets included) so that they meet the requirements associated with all three missions. Another important consideration is that no present value analysis has been included in the profit model: future revenues and costs are not subject to a discount rate.

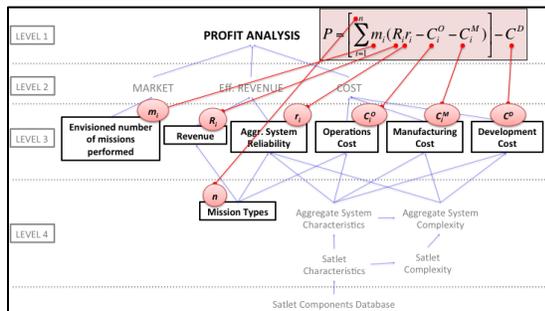


Figure 2. Relation between the equation parameters and the activities performed throughout the project.

III.I Description of Profit Equation Factors

This section briefly describes the calculation of the parameters that define revenue and cost (see Equation [1]): reliability, operations cost, development cost, manufacturing cost, and revenue for Missions 1, 2, and 3. The reliability code takes into account component reliability at the satlet level and redundancy of functionality at the aggregate level. This information was provided by JPL and AFS. Operations cost is a function of mass at the satlet level as well as the resulting launch costs at the aggregate level. Another important driver of operations cost is the concept of operations, which has not been fully defined so far. In our analysis, we assumed a concept of operations in which a large number of satlets are initially launched to satisfy m envisioned missions over time, even before the demand has been established.^v This assumption implies that satlets will already be in space waiting to be used, possibly before a customer has paid for service.

On the satlet level, development cost is predicted by the satlet structural complexity (via a power law relationship described in Section IV), as well as software cost. Adding up the satlet development costs, along with an additional aggregate system PMSE estimate of \$500K modified by the satlet

complexity, gives the final development cost. This \$500K baseline PMSE cost represents the funds that AFS reports was initially provided by DARPA for early-stage PMSE costs to AFS and JPL.^{vi} Lastly, each satlet's manufacturing cost is a function of the cost of components present and the AIT cost (calculated from a power law relationship with complexity – see Section IV – and a baseline satlet AIT cost that is estimated from the labor hours of CubeSat test cases). Labor hours were translated into AIT cost using Level 1, Level 2, and Level 3 engineer salaries estimated by AFS.^v On the aggregate system level, AIT cost is also subject to a learning curve.^{vii}

The revenues for Mission types 1, 2, and 3 are as follows per year-long mission:

- Mission type 1 Revenue: \$71.4 million
- Mission type 2 Revenue: \$14.3 million
- Mission type 3 Revenue: \$380 million

The revenue for mission type 1 is equal to the total cost of a typical high end communications satellite, of approximately \$500 million, divided by an average life (seven years), as the repurposed system would make the launch of a new satellite unnecessary.^{viii ix} The revenue for mission type 2 is equal to the total cost of a DirecTV satellite (as another commercial reference), or \$100 million, divided by the average life of the DirecTV asset (seven years).^{viii ix} The revenue for mission type 3 is assumed to be the operating profit that DirecTV makes from one of their 12 satellites annually.^x For mission 3, it was assumed that the profit made by DirecTV is based off of their satellites.

III.II Complexity Analysis

AIT and PMSE cost are typically estimated with parametric models such as the Small Satellite Cost Model (SSCM). The SSCM uses cost-estimating relationships (CERs), which are developed using historical data from completed satellites. Many models use CERs for each of the major subsystems (Attitude Determination and Control, Propulsion, Power, Telemetry, Tracking and Command, Structures, and Thermal),^{xi} and individual Phoenix satlets may not contain all of these subsystems. Simply leaving out the contribution of a particular CER is not prudent as satlets may contain various numbers of components related to a particular subsystem (for example, all satlets may have rate sensors but not actuation devices). For this initial analysis (and for lack of any suitable reference in space) candidate satlets can be approximated as CubeSats for use with CERs, but one has not been developed yet. Because of the expected size of

Phoenix satlets, as well as the fractionated nature of the Phoenix aggregate systems, SSCM estimates are unrealistic for Phoenix satlet cost estimation.

Structural complexity has been found to scale with both AIT and PMSE cost with a power law relation^{xii}. The team chose to implement a structural complexity metric because it has been shown to be a predictor of development cost across several types of complex systems.^{xii} The structural complexity metric used in the cost analysis contains three complexity factors:^{xii}

$$C = C_1 + C_2 C_3. \quad [2]$$

C_1 represents the complexity due to the number and flight readiness of the components, C_2 represents the complexity due to pair-wise component interactions, and C_3 represents the complexity due to the topology of the system architecture and the associated complexity of system integration.^{xii} A more detailed description of each factor is shown in Equation [3].

$$C(n, m, A) = \sum_{i=1}^n \alpha_i + \left[\sum_{i=1}^n \sum_{j=1}^n \beta_{ij} A_{ij} \right] \gamma E(A). \quad [3]$$

In Equation [3], n is the number of components, m is the number of interfaces, A is the Design Structural Matrix, α is a function of Technology Readiness Level (TRL) as described by Equation [4], β is the complexity of each connection between pairs of components, γ is $1/n$, and $E(A)$ is the graph energy of the DSM.^{xii} In our complexity analysis, items such as star trackers and thrusters were given higher values of β in comparison to those assigned to batteries, structural interfaces, etc. to reflect their required extra software and integration effort.

$$\alpha = 5 \left(\frac{TRL_{max} - TRL}{TRL_{max} - TRL_{min}} \right). \quad [4]$$

The power law relationship between complexity and development cost is denoted in Equation [5].

$$Y = aX^b. \quad [5]$$

This relationship was shown to predict development costs of MotherCube (AFS) and Armadillo (University of Texas). Figure 3 shows the predicted versus the actual PMSE costs for the two CubeSats, with \$500K as a baseline PMSE cost for the aggregate system. For AIT cost, a power law relationship is also used, but with a fixed AIT cost estimate of \$60K based on CubeSat case studies, as previously described.

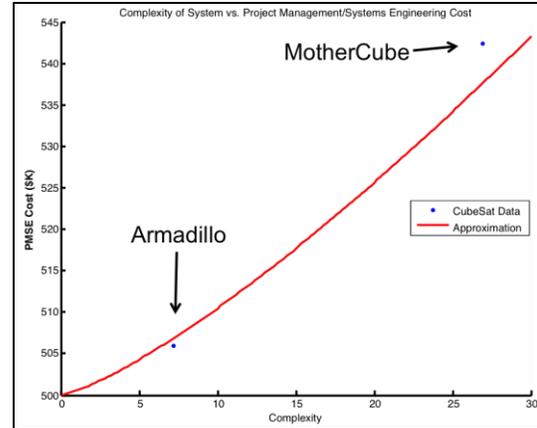


Figure 3. Relationship between complexity factor and PMSE cost.

The method used to estimate the development and manufacturing cost for each aggregate is an amalgamation of a bottom-up approach as well as estimation by analogy. As mentioned before, elements such as bus cost are computed in a bottom-up manner; the price of the individual components is simply summed. The baseline figures for AIT and PMSE are drawn from the most comparable projects, but they are each adjusted based upon the complexity of the constituent satlets as well as the system as a whole. The learning curve is applied for AIT cost estimation at both the satlet and the aggregate level because the production process is expected to become more efficient as the numbers increase. Before presenting the results from the implementation of the model, it is prudent to delve more deeply into the particulars of how the aggregates will be implemented to meet the main requirements of the Phoenix program

IV. VERIFICATION AND VALIDATION

IV.I Verification

Verification and validation are essential aspects of any type of modeling, cost modeling included. The process of verification examines the model's internal consistency as well as the consistency of the model's function with the original intent of the team. Validation is an outward-looking process meant to justify the various inputs (component costs, for instance), relationships (such as the learning curve), and outputs (such as single small satellites analogous to satlets) of the model. Once the cost model was verified to produce results in accordance with the respective inputs and relationships defined, it was then partially validated before attaining the present results.

Several levels of the model were verified with similar methods. The first level to be verified was the satlet level, which included the component costs for each satlet, the complexity values for each satlet, the power and thermal characteristics for each satlet, and the learning curve for a given satlet type. The second level verified was the aggregate system level, which included aspects such as the cost of an aggregate system, its power requirements, and its calculated complexity value. Similar methods of verification were used at this level as in the satlet level.

The third (and highest) level verified was the mission level, including the mission requirements and revenue gained from each mission. The calculations and baseline numbers used were verified in the code, and single and multiple missions' results were compared with manual summations of the quantities in question.

IV.II Validation

Several external cost comparisons were performed to begin the process, and several attempts at gathering data on small satellites were made. Only two sets of data were able to be obtained: the data from the University of Texas ARMADILLO and AFS MotherCube projects. In addition, the difficulty in validating any part of the cost of a novel architecture in an advanced domain cannot be understated; however, reasonable assumptions and input from subject matter experts allowed some preliminary conclusions regarding the validity of the results. Parts of the model to be validated fall largely into the same three levels as with verification: satlet, aggregate, and mission levels. At this time, validation has only been performed at the satlet level, including component costs, complexity values, and satlet cost.

Component costs were validated through the use of websites of manufacturers and distributors of small satellite components, such as Clydespace and Novatel, among others. An individual satlet's complexity was validated on an order of magnitude scale by comparison with systems in Sinha and de Weck 2010^{xi}. Even though the systems in the paper are different from satlets, the complexity model is still useful owing to its demonstrated wide applicability. Validation of the learning curve for high-volume manufacturing is outside the scope of this class, and as a result it was not attempted.

Individual satlet costs were validated in two ways. The first was through comparing single function satlets (such as a thruster satlet) with estimates given by subject matter experts from AFS and JPL. The second was by comparing a non-commercial full-function satlet with two known CubeSat projects, UT's Armadillo CubeSat, and the Aerospace Corporation's SSCM. The results are shown below in Figure 4. As the figure shows, the costs estimated by the MIT cost model are well in line with a CubeSat cost; but several important points should be considered.

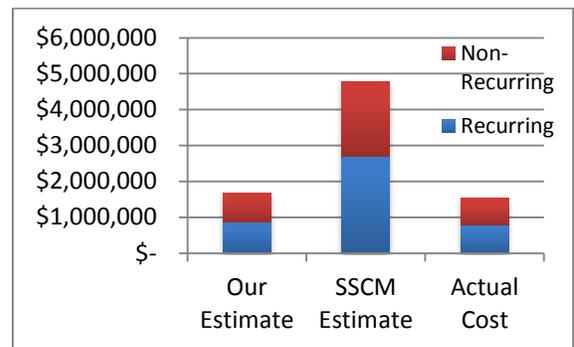


Figure 4. A comparison of cost estimates and actual costs of the UT Armadillo CubeSat.

First, the class of the mission is not taken into account by either the MIT cost model or SSCM. Secondly, the MIT cost model is designed to estimate the cost of an aggregate system, not a single CubeSat. This model design means that certain costs are built into the construction of any aggregate system (even an aggregate consisting of one satlet), so the model predicts average costs that decrease with bigger aggregates and higher volumes, but slightly inflates the cost of a single-satlet aggregate for the same reason. Secondly, this validation is related to only one set of satlet variants and instantiations (from AFS and JPL). Other satlet vendors variants and costs would change this initial comparison.

V. RESULTS

After verifying and validating the model, a profit analysis was performed on data sets (the various aggregates that meet the requirements for each mission) generated by JPL. As mentioned in Section I, market analysis and an analysis of heterogeneity were conducted to explore the impact of design parameters on profit.

V.I Profit Analysis and Robustness to Market Uncertainty

Profit rises from the accumulation of revenue over the completion of several missions and the subtraction of development, manufacturing, and operations costs. Many assumptions are embedded in the current model's calculation of profit. For instance, the total number of missions performed across the lifecycle of the system is purely notional, and new, better-informed predictions (perhaps obtained from more detailed market research or domain experts and stakeholder interviews) need to be included in the analysis. Similarly, the calculation of revenue is an estimate coming from first order market research (see Section III). Furthermore, as mentioned in Section II, no model has yet been developed for the calculation of operations cost, and only aggregate-level launch cost has been quantified as part of the operations cost. Given these assumptions and gaps to be filled, it is not possible at present to obtain an absolute number for profit. Instead, if one assumes fixed, unknown additional costs for operations and the servicer/tender (which are approximately equal for all aggregate systems), it is possible to analyze the relative profit gains for the various aggregate systems.

Nineteen different aggregate systems have been provided by JPL for the profit analysis, each with two to three satlet types. The satlet types vary among aggregate systems, and the number of satlets for each type in each system has been selected to meet the requirements associated with the given mission. Given the characteristics of the provided aggregate systems and a market projection, it is possible to compute development, manufacturing, and launch costs, revenue, and reliability factors associated with each system envisioned in this analysis.

V.I.I Varying Market Projections

As discussed above, relative profit gains can be determined only when the aggregate system's specifications are known and a market projection is made. While the former piece of information is provided by JPL, the latter is estimated with much less certainty.

Given the inability of assessing a defined market projection, it is convenient at this point to analyze the performance of the aggregate systems under different market conditions of interest. In fact, if the analysis is focused only on one market type, certain aggregate systems may be favored. For example, Figure 5 shows a comparison of the results obtained for two different market conditions: Market 1 is mission type 2-heavy, where the number of large aperture missions

performed is much larger than the number of other missions, and Market 2 is mission type 3-oriented.

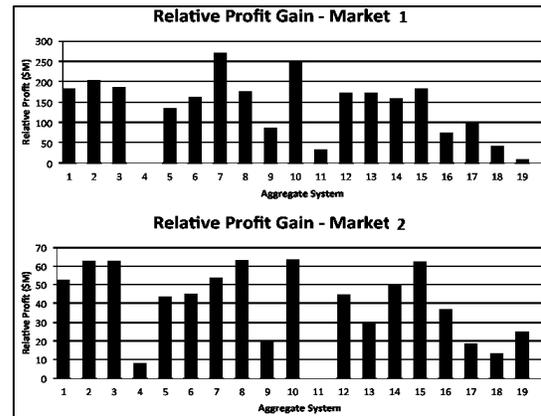


Figure 5: Relative profit results obtained for two different market conditions.

Interesting insights can be derived from Figure 5. As can be seen, the differences in relative profit gain between various aggregate systems are highly market dependent. Therefore, the difference in the results obtained under the two market conditions suggests that it is opportune to explore a large number of markets, rather than focus on a select few.

V.I.II Robustness to Market Uncertainty

As demonstrated in the previous subsection, the market conditions can have a great impact on the final profit results. However, given the complex and highly dynamic environments in which systems operate, great uncertainty is usually associated with market predictions, even when detailed market research has been performed. A way of accounting for this uncertainty is to perform a Monte Carlo simulation, which samples a large variety of different market conditions.^{xiii} Rather than looking at single projections, it is possible to analyze the profitability of aggregate systems for a variety of different market conditions, and then obtain the relative average profit gain across all samples. The relative average profit gain is a measure of *robustness* to market variations: more robust designs have higher relative average profits across all market conditions.

As explained in Section III, market variations are obtained by varying the variable m_i in Equation [1]; m_i is the number of performed missions of a particular mission type envisioned to be carried out by all satlets. To perform the Monte Carlo simulation, three probability distributions are associated with each of the numbers of missions performed for the three mission types. For the

analysis presented hereafter, the following probability distributions (based on preliminary market research) have been assumed for the three varying numbers of missions performed: a uniform distribution over the interval [2, 10] for small aperture (m_1); a uniform distribution over the interval [1, 6] for large aperture (m_2); a uniform distribution over the interval [3, 10] for ADCS (m_3). This assumption corresponds to between 6 and 26 potential missions performed across the lifecycle of aggregate systems. Of course, all assumptions need to be refined after more in-depth market research and domain expert interviews. The probability distributions and ranges used here are initial placeholders that allow for the analysis to be carried out, but both need to be further investigated to reflect more accurately true expectations.

In order to perform the Monte Carlo simulation, three hundred market projections have been sampled, which corresponds to a 5.7% convergence of the resulting profit distribution (by the central limit theorem, the convergence of the outcome distribution is proportional to the inverse of the square root of the number of samples). For all aggregate systems, the resulting profit distribution well fits a Gaussian probability distribution. Figure 6 shows this finding for aggregate system 13, one with smaller thrusters and reaction wheels.

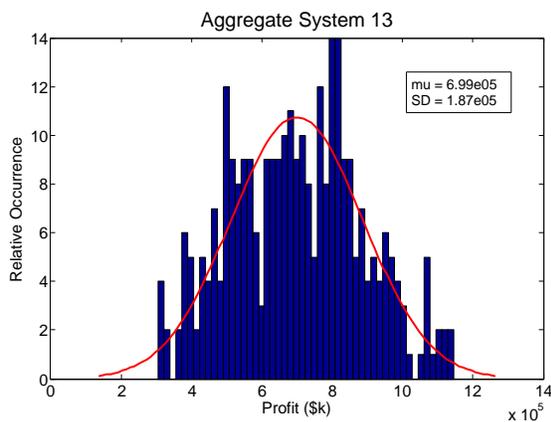


Figure 6: Relative profit across 300 different market scenarios.

The Monte Carlo simulation yielded the relative average profit gains shown in Figure 7. Profits found for a single aggregate system across the three hundred market conditions are averaged and compared to the worst performing system (4, in this case). The histogram shows how aggregate system design 7, another system with small thrusters and reaction wheels, is the most robust to the modeled

market uncertainty, resulting in (approximately) an average 30 million dollars profit gain, as compared to the least profitable design.

Given the time constraints associated with the project, it was not possible to perform a detailed investigation of the nature of aggregate system 7, as compared to others. This task is not a trivial one, given the non-linearities embedded in the model and the high complexity of the aggregate systems. General trends, however, could be determined (such as component density of aggregates based on the number of satlets which comprise an aggregate.

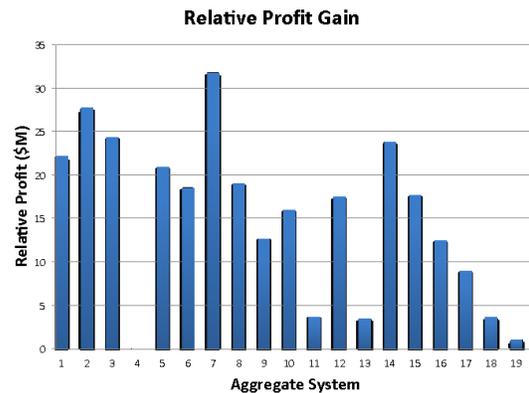


Figure 7: Relative average profit gains of all aggregate systems across the 300 different market scenarios sampled.

V.II Heterogeneity Analysis

Another key aspect the MIT Phoenix team sought to analyze was the impact of heterogeneity (the number of different satlet types) on aggregate cost. Preliminary JPL optimization runs based on their 46 component data set produced aggregates with two to three satlet types. Inputs ranged from homogeneous satlets to fractionated, heterogeneous systems with five or more satlet types. The architectures with two to three satlet types generally cost less than those with greater or fewer. After refining the model, the trend remains the same. The analysis performed by the MIT Phoenix team shows that architectures with two to three satlet types generally cost less, based on the previously described assumptions and components selected.

First, one must examine cost estimates for architectures with varying levels of heterogeneity. Based on the 46 initial component set, the trend is immediately apparent in Figure 8; for all three mission types, the minimum cost lies around aggregates with two to three satlet types. This figure only displays the results for the cost of the first

aggregate system. Additionally, one must extend this analysis to account for the number of missions performed. With the learning curve applied at the satlet and aggregate levels as well as the averaging of development cost over all aggregates, it cannot be inferred that this same trend will hold. Figure 9 displays these results.

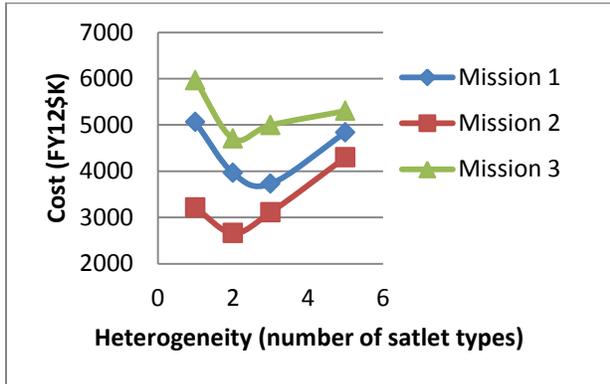


Figure 8. Comparison of heterogeneity (number of satlet types) to mission cost.

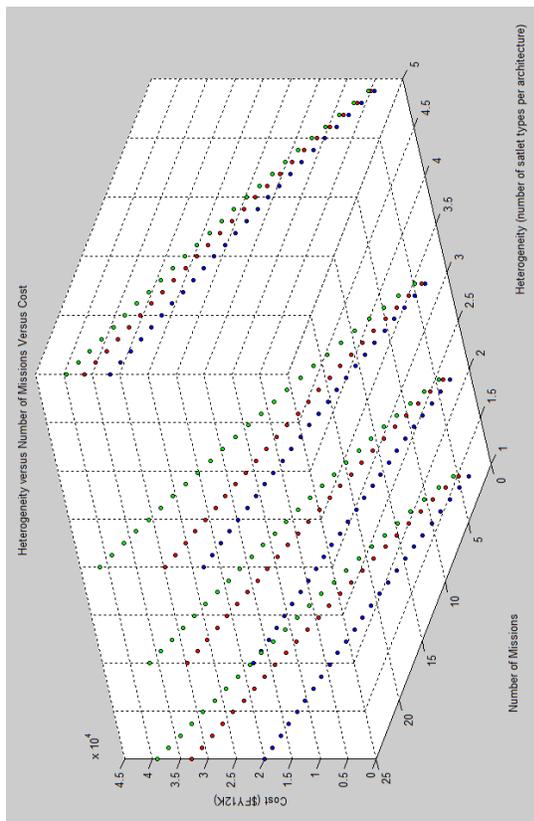


Figure 9. Comparison of heterogeneity to total mission cost for various numbers of missions. Mission types 1, 2, and 3 are indicated by red, blue, and green, respectively.

The trend holds for mission types 2 and 3. The lowest total cost for 25 aggregate systems lies with two satlet types. Mission type 1 differs; the lowest total is at three satlet types, conveying two important points. First, the missions dealing with repurposing apertures can be accomplished most profitably with aggregates composed of two to three satlet types. Secondly, the optimal level of heterogeneity depends on the type of mission to be performed.

After 25 missions, the dip in cost around two to three satlet types does not appear significant, but the difference in profit is not trivial. The disparity between two and five satlet types totals 6.6 million dollars; for mission type 2, the same figure comes out to 13.6 million dollars. This result conveys that heterogeneity makes a noticeable difference. Furthermore, if this is coupled with the profit variability among aggregates with the same number of satlet types in an uncertain market environment (Figure 7), the disparities may become greater. It is valuable to understand the sensitivity of how a cost estimate varies with particular trades.

Another important result is the location of the “elbow” of the curve, critical in determining how many missions must be completed for the profit margin to be high enough. Breaking traditional precepts, Phoenix leverages modularity and large-scale production in reducing cost: the real savings are found when the production numbers are greater and the effectiveness of the engineers and technicians assembling and testing the system increases. The learning curve is applied on both the satlet and the aggregate level, and the development cost averages over the total number of aggregates.

The market analysis results clearly show that proper selection of architecture, even among a set with the same heterogeneity, is very important and can result in large profit gains over time. The heterogeneity analysis reinforces this point. At this stage in the project, the MIT Phoenix team cannot converge on a single optimal design, but it has helped provide the tools, insight, and analysis necessary for others to make a more informed decision when it comes time to do so.

V.III General Comments

The results of our analysis are subject to specific assumptions and shall not be taken as the only possible instantiation of a satlet architecture. It is not possible to perform a complete market analysis until

solid estimates for launch cost, operations cost, and the cost of the servicer-tender are obtained. If the choice of aggregate system affects these estimates, satlet optimization cannot be performed independently as it is here. Despite the uncertainty, there are valuable conclusions which must be considered as the design progresses. Moving forward with this information will assist in selecting and optimizing the correct parameters to ensure maximum profit for any set of missions.

The views expressed are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

VI. CONCLUSIONS AND FUTURE WORK

To conclude, the MIT Phoenix Team found that a certain level of heterogeneity generally reduces cost by leveraging morphological reconstruction and cellularization. Designs with two to three satlet types were found to be in a region of optimality for the Phoenix mission, based on Cubesat input assumptions with a single satlet developer. The moderately heterogeneous aggregates selected by JPL show improved expected profit over single homogeneous satellites as well as very heterogeneous aggregates. The upfront cost for PMSE (\$500K+) more than pays for the possible \$30 million more in profit that can be made by choosing the most profitable aggregate amongst a set of equally capable aggregates. This information is useful for future satlet providers and developers, who may use these initial findings to narrow their tradespace depending upon the morphology examined.

More work must be completed to validate further the cost and profit models including obtaining additional cost and labor information, as well as refining assumptions made at both the satlet and aggregate levels. Specifically, larger data sets of aggregates employing homogeneous satlets, as well as aggregates with additional satlet types should be analyzed to ensure validity of the robustness to market uncertainty analysis at the lower and higher ends of heterogeneity, beyond the 19 aggregates from JPL. We should also supplement our analysis with a “difference” analysis that quantifies how common satlets are with each other. The addition of a servicer/tender cost estimate would further increase the validity of the profit calculations. In addition, more detailed market research would increase the validity of the profit model by enabling better guesses of the distributions of the numbers of missions performed of each mission type. The profit

equation could also be expanded to include a net present value analysis.

Much work remains to be done, but progress is being made to understand the complex interplay of various factors associated with such a novel project.

VII. REFERENCES

- ⁱ DARPA. 2011. *Broad Agency Announcement Phoenix Technologies Tactical Technology Office (TTO) DARPA- BAA-12-02*. DARPA. Arlington, VA.
- ⁱⁱ David Barnhart, Lisa Hill, Margaret Turnbull, and Peter Will (2012) “Changing Satellite Morphology through Cellularization.” AIAA SPACE 2012 Conference & Exposition: AIAA 2012-5262
- ⁱⁱⁱ Wertz, J., Everett, D., and Puschell, J., ed. *Space Mission Engineering: The New SMAD*. Microcosm Press. 2011. p. 757
- ^{iv} Ramirez, J., Ingham, M., et al., “System Requirements Specifications Document”. Aurora Flight Sciences and NASA Jet Propulsion Laboratory, AR12-361, Cambridge, MA, Sept. 2012.
- ^v Email correspondence with AFS and JPL, 8 November 2012.
- ^{vi} Discussions with AFS, 17 October 2012.
- ^v Berk, Joseph. *Cost Reduction and Optimization for Manufacturing and Industrial Companies*. Scrivener Publishing LLC, 2010. Chapter 9. Web. <<http://onlinelibrary.wiley.com/doi/10.1002/9780470643815.ch9/summary>>.
- ^{vi} Brook Sullivan, John Bergman, and David Barnhart (2012) “Economics of Repurposing In Situ Retired Spacecraft Components.” AIAA SPACE 2012 Conference & Exposition: eISBN: 978-1-60086-940-2
- ^{vii} Discussions with the Jet Propulsion Laboratory, 1 November 2012.
- ^{viii} “Form 10-Q Quarterly Report.” <http://investor.directv.com>. N.p., 03 2012. Web. 10 Oct 2012. <<http://investor.directv.com/secfiling.cfm?filingID=1047469-12-7709>>.
- ^{ix} “SSCM Overview.” *Aerospace: Assuring Space Mission Success*. The Aerospace Corporation, n.d. Web. 10 Dec 2012. <<http://www.aerospace.org/expertise/technical-resources/small-satellite-cost-model/sscm-overview/>>.
- ^x Kaushik Sinha & Olivier de Weck, 2012. De Neufville R., and Scholtes, S., “Flexibility in Engineering Design.” The MIT Press, 2011. pp. 217.