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Cost Analysis for Mass Customized Production of Satellites Based on Modularity

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ABSTRACT In this paper, the cost model of mega-satellite constellation based on modularity is investigated. The aim of this work is to analyze the cost contributions in the development of satellite constellation, which include design cost, manufacturing cost, launch cost and operation cost. Simulation examples are given to demonstrate the cost savings and advantage of mass customized production of satellites based on modularity.

INDEX TERMS Modularity, cost model, satellites constellation, mass customized production.

I. INTRODUCTION

Recently, many plans have been proposed to provide global internet services with hundreds and even thousands of satellites as the new market demand growth of global communication. SpaceX has launched 650 satellites to configure the Starlink system and its final target is to launch 42000 satellites. Amazon has proposed to set up a constellation with 3236 satellites for Kuiper satellite plan. Compared with traditional constellation, there are differences in satellites production, launch and operation. Considered such huge scale of constellations, the economics plays a more and more important role on the deployment of satellite constellations above.

Mega-constellations of communication satellites provide various available application scenarios of Internet of Things aiming at different requirements, but as the proliferation of IoT, the current fifth generation of mobile cellular networks, i.e. 5G, could not give more technical support. It's necessary to pay more attention on the investigation and research on 6G. Reference [1] analyzed the features of 6G and identified the important technologies in the application process of 6G from the perspective of communication, computing and caching. Meanwhile, Reference [2] presented an overview on key aspects for LEO satellite systems. It not only introduces the system architectures and the coverage models of satellites communication systems with ISL, but also makes an contribution on the coordination schemes and resource management in order to decrease the interference with the GEO systems.

Modularity has a substantial impact on many areas of high technology, but concerted efforts have been made to apply modular design philosophies to satellites platform recently [3]–[7]. Traditionally, science and military applications have favored the big centralized mission. But it is unrealistic to the development of mega-constellation because the numbers of satellite are so unprecedented. Reducing the satellites platform cost allows these limited funds to be used most effectively; a higher fraction of the mission budget can be devoted to the payload [8]–[11]. Consequently, a cheap, modular platform design that delivers adequate, but not optimal performance to all of the envisioned payloads, may lead to more effective missions overall [12]–[17].

A modular satellite platform design is defined which is composed of standardized, reconfigurable components, and should not be confused with common platform designs (identical, non-reconfigurable components) or heritage designs (a new design based on a previous old design). A theoretical model has been developed to gauge the benefits of adopting such designs [18]–[24].

For the research and development of mega-constellation of communication satellites, this paper gives the quantitative cost analysis for mass customized production based on modularity. As is known to all, SpaceX has already launched nearly 900 satellites in 15 stages, and there are other satellite constellation plans consisting of hundreds of satellites [25]–[27]. Thus, it's necessary to analyze the project lifecycle cost and the economic advantage of modularity. The main contributions of this work can be summarized as follows. First, compared with [5], this paper not only pays attention to the qualitative illustration of modularity's influence, but also gives the cost model of satellite constellation

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based on modularity. Second, compared with [17], where the assessment process of PnP satellite's modularity was given without any simulation analysis, and the equation representation of the modularity was also needed in that work, this paper can supplement the above shortcomings, which is an obvious contribution to mass customized production of satellites based on modularity. Third, Reference [19] proposed a detailed introduction of the modular satellites' standard, but there was no quantitative cost analysis of the advantage of customized production based on modularity, which is also an advantage of this paper. In conclusion, this paper has contributed to the quantitative analysis of the lifecycle cost of constellation, especially the mega-constellation based on modularity. The analysis results could provide some reference for designers and managers in the R&D and operation of the satellite constellation.

The remainder of this paper is outlined as follows. Section II presents the principles and significance of modularity, based on which the cost analysis for mass customized production of satellites is formulated. Section III gives a case study between cost savings and the number of satellites and development stage. Section IV develops the cost model in detail, and corresponding numerical simulation is performed. Finally, conclusions are drawn.

II. MODULARITY

Several factors distinguish modular design from heritage and common designs. During the stage of satellites mass customized production, there are two main categories of modules, i.e., common modules and variant modules. Common modules consist of the common components which are generally reused. Standard satellite platforms are the typical common modules with the universal interfaces. Variant modules are the specific components which are designed to meet the various requirements, such as power modules, propulsion modules, communication modules, etc. Not only must the system exhibit encapsulated functionality, but the designers must embrace the reuse of common modules across separate missions. It is the second issue that sets this treatment of modular design apart from previous heritage and common designs.

In many areas, especially the technical areas, principles of modularity are so popular. It can be easily found obvious examples in the fields of computer systems. One of the basic tenets of object-oriented-programming is that of encapsulation. The interfaces for programming libraries are established, and the underlying coding is left to the designer [28]–[30]. Modularity gives the rights for engineers to choose the optimal design architectures and it provides a prevent mechanism which can guarantee the code blocks not influencing with changes from other modules. The lifecycle cost (LCC) could be decreased by establishing a series of standards for power, propulsion, communication modules in space systems.

Not only the interfaces, but actual hardware design is reused, savings can be even greater. For instance, satellite platforms are the typical common modules which are designed as universalization, standardization and seriation. Therefore, the platforms could be applied to various scenarios easily and be compatible with the new design architectures. Considering the large scale of production and existence of learning curve, the scheme of mass customized production based on modularity could be a design choice which has the properties of high performance and low cost. The potential for cost savings arising from modular satellites platform design is twofold. First, interface modularity allows satellite design, integration, and testing to be simplified and expedited. Second, hardware modularity provides a second tier of design, manufacturing and integration savings. Although the opportunity for savings is great, the potential applications for modular design are not limitless: risks and inefficiency limit their acceptance for both technical and political reasons.

The design effort of projects could be decreased by the use of modular design components at the disposal of engineers. A simple case would involve the adoption of a series of pre-existing hardware modularity. In a more modular method, designers would have a design library of pre-existing modules (components) that could be chose, used, and assembled as needed. In both of these scenarios, the development schedule could be shorten which is the one of advantages given by design efforts decreased. This could have direct financial influence on commercial systems in turn.

Satellites manufacture could also benefit from the adoption of a modular design philosophy. Units in mass production show learning curve cost reductions. When modules are manufactured off the same line and integrated into various projects and missions, there are several progressive types of benefits existed. The learning curve represents the fact that as workers become more familiar with a particular product, they could produce it more and more efficiently. If hardware modularity is adopted manufacturing cost savings could become significant. In fact, there is a similar design logic in hardware virtualization and satellite modular design, that's to say, satellite modular design is one of general forms for hardware virtualization. According to the commonality of components and the various functional requirements, we could get the common modules and variant modules, then we could adjust the scheme or customized portfolio of modules to meet the various requirements and scenarios.

III. COST MODEL BASED ON MODULARITY

In order to evaluate the influence of modular satellites design, an attempt must be made to quantify the effect of implementing modular approach. Cost savings analysis comparisons must be made between common customized design method and the modular method. The cost behavior examined in this paper is the effect of varying the number of satellites and the number of development stages. Standing on a general point, modularity could be considered. The most direct parallel is to consider a satellite platform designed to accommodate various payloads.

The total lifecycle cost is broken down into component costs. The breakdown chosen for the study is shown in

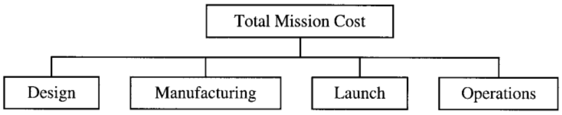

FIGURE 1. **Total mission cost breakdown.**

Figure 1. The nature of each component cost has been examined and attempts have been made to characterize its behavior in response to changes in the number of satellites and the number of development stages. It has been assumed that both modular and common customized satellites are equally capable.

A. DESIGN COST

The design stage of a space mission involves several efforts. A preliminary systems design must be done to evaluate the mission requirement and requirements must be allocated to subsystems.

First consider the total customized design costs incurred over M development stages, is:

$$C_{D1} = M \cdot C_{ref\_D} \tag{1}$$

where C_{D1} is the total cost of customized design and C_{ref_D} is a reference satellite design cost.

Over the total project of M development stages, each of N satellites, the amortized design cost per satellite is found by dividing Equation (1) by the total number of satellites in the project:

$$C_{D2} = \frac{C_{ref\_D}}{N} \tag{2}$$

A modular design requires an up-front investment in the initial design followed by a recurring cost to integrate the modules into each subsequent stages or missions. It is expected that the cost of the first unit will be higher than for the customized scenarios.

The total cost of M development stages is:

$$C_{D3} = (\alpha + \beta \cdot M)\, C_{ref\_D} \tag{3}$$

where C_{D3} is the total design cost over M missions for the modular design; α represents the cost impact factor due to the initial cost investment; β is impact factor from the recurring cost.

The amortized cost per satellite is found by dividing (3) by (MN):

$$C_{D4} = \frac{C_{D3}}{M \cdot N} = \frac{\alpha + \beta \cdot M}{M \cdot N} C_{ref\_D} \tag{4}$$

The net cost savings from design modularity could be written as:

$$\begin{aligned} S_D &= \frac{C_{D2} - C_{D4}}{C_{D2}} \\ &= \left(\frac{1}{N} - \frac{\alpha + \beta \cdot M}{M \cdot N}\right) \cdot N \\ &= \frac{(1-\beta) \cdot M - \alpha}{M} \end{aligned} \tag{5}$$

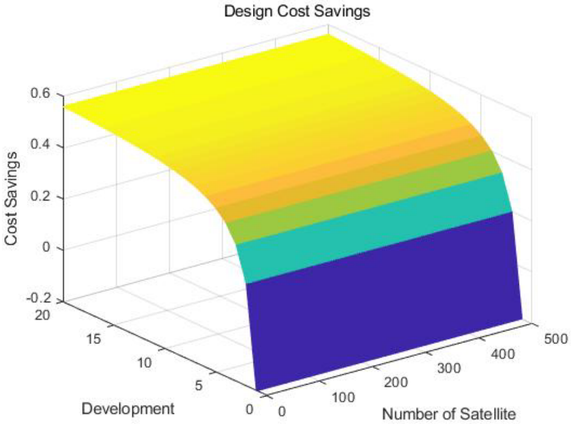

FIGURE 2. **Design cost savings.**

TABLE 1. **The relationship of N and S.**

Number of units, N	Learning curve factor, S
1<N<10	0.95
10≤N<50	0.9
50≤N	0.85

As shown in Figure 2, the most dramatic savings improvements could be made within the first few missions and there is a cost advantage by modular design method over a customized one.

B. MANUFACTURING COST

Following the design of the system, the space vehicle components must be produced and assembled. During this period of development, many opportunities exist for substantial savings. Three phases are typically encountered during manufacturing: production and qualification testing

1) PRODUCTION COST

One of the advantages enjoyed by distributed space architectures is the learning curve. Learning curve savings can include many aspects of mass customized production. For small numbers of units, they represent a worker's growing familiarity with the hardware. For larger runs of products these savings can include various methods of mass customized production.

The learning curve is typically represented by:

$$Cost = TFU \cdot N^{(1+\log_2 S)} \tag{6}$$

where TFU is the Theoretical First Unit cost, N is the number of units produced, and S the learning curve factor. The relationship of N and S is shown in Table 1.

Without losing generality and computing easily, the relationship between N and S could be approximated as:

$$S = 1 - 0.05 \log_5 N \tag{7}$$

The total production cost of the system can then be estimated. The essential difference between modular and custom components is the total number of identical units produced. In the customized design, the learning curve is not as steep with each mission. The learning process of modular systems could bring more benefit over many missions.

The total production costs are then:

$$\begin{aligned} C_{P1} &= C_{ref\_P} \cdot M \cdot N^{(1+\log_2(1-0.05\log_5 N))} \\ C_{P2} &= \rho \cdot C_{ref\_P} \cdot (M \cdot N)^{(1+\log_2(1-0.05\log_5(M \cdot N)))} \end{aligned} \tag{8}$$

where ρ is an arbitrary factor to reflect any difference in T FU cost between the modular and customized designs. Assumed that the value is 1.3. The average costs per satellite are then:

$$\begin{aligned} C_{P3} &= C_{ref\_P} \cdot N^{(\log_2(1-0.05\log_5 N))} \\ C_{P4} &= C_{ref\_P} \cdot \rho \cdot (M \cdot N)^{(\log_2(1-0.05\log_5(M \cdot N)))} \end{aligned} \tag{9}$$

The net cost savings from design could be written as:

$$\begin{aligned} &S_P \\ &= \frac{N^{(\log_2(1-0.05\log_5 N))} - \rho \cdot (M \cdot N)^{(\log_2(1-0.05\log_5(M \cdot N)))}}{N^{(\log_2(1-0.05\log_5 N))}} \\ &= 1 - \frac{\rho \cdot (M \cdot N)^{(\log_2(1-0.05\log_5(M \cdot N)))}}{N^{(\log_2(1-0.05\log_5 N))}} \end{aligned} \tag{10}$$

2) QUALIFICATION TESTING COST

Generally the qualification of a satellite system design would be included as a module of the manufacturing costs, it presents different types of behavior depending on whether modularity exists or not.

When more than one satellite is produced, qualification remains distinct from acceptance testing, which need to meet the specifications issued for its architecture.

Although qualification is extensive and time consuming, it is a task that would be performed only once on a particular design. The cost could be evenly spread out over the entire series of satellite manufactured if using the same method of design. This would give total qualification costs as:

$$\begin{aligned} C_{Q1} &= M \cdot C_{ref\_Q} \\ C_{Q2} &= C_{ref\_Q} \end{aligned} \tag{11}$$

The amortized cost per satellite is :

$$\begin{aligned} C_{Q3} &= \frac{C_{ref\_Q}}{N} \\ C_{Q4} &= \frac{C_{ref\_Q}}{M \cdot N} \end{aligned} \tag{12}$$

The net cost savings of the qualification of the satellite could be found as:

$$S_Q = \frac{M-1}{M} \tag{13}$$

C. LAUNCH COST

Launch cost is one of the main problems in the space industry that is at the center of heated debates. In order to decrease the launch costs, there is generally a fixation with reducing system mass. The financial benefits of reducing mass are dependent on the particular application. So if the satellites launched at one time is more, the amortized cost could be lower. The ratio of customized to modular launch costs is equal to the ratio of satellite mass:

$$\frac{C_{L1}}{C_{L2}} = \frac{M_{Mod}}{M_{Cus}} = \tau \tag{14}$$

where C_{L1} is the cost of a modular launch, C_{L2} is the cost of a customized launch, M_{Mod} and M_{Cus} are modular and customized launches, respectively.

D. OPERATION COST

Just because there is difficulty existed in valuing the operational requirements from design parameters, so operations costs could be neglected in cost analysis.

E. LIFE CYCLE COST

After analyzing the contribution of the component costs, the remaining task is to assemble them into a lifecycle cost model for the entire system. The individual costs are treated as basic functions. The averaged costs for modular and customized satellite are integrated as :

$$\begin{aligned} &C_{Cus} \\ &= f_D \cdot \frac{C_{D2}}{C_{ref\_D}} + f_P \cdot \frac{C_{P3}}{C_{ref\_P}} + f_Q \cdot \frac{C_{Q3}}{C_{ref\_Q}} + f_L \cdot \frac{C_{L2}}{C_{ref\_L}} \\ &C_{Mod} \\ &= f_D \cdot \frac{C_{D4}}{C_{ref\_D}} + f_P \cdot \frac{C_{P4}}{C_{ref\_P}} + f_Q \cdot \frac{C_{Q4}}{C_{ref\_Q}} + f_L \cdot \frac{C_{L1}}{C_{ref\_L}} \end{aligned} \tag{15}$$

Each component cost is normalized with respect to its reference cost. The resulting term is multiplied by factors, f_i. These factors describe the distribution of cost between components and the reference. Thus, each term in Equation(15) represents the cost per satellite, expressed as a fraction of the total reference cost. Net savings are then computed by:

$$S = \frac{C_{Cus} - C_{Mod}}{C_{Cus}} \tag{16}$$

IV. CASE STUDY

The plot shows the relation between the number of satellites per development stage, the number of missions in a project and the average modular cost savings per satellite. Mission sizes of up to 500 satellites were considered along with projects of up to 20 development stages. Negative values of cost savings indicate that the modular system was more expensive than the customized design.

In this parameterization, design costs are setting to be the largest component costs. Launch costs represent the next largest amount; manufacture and qualification the remaining

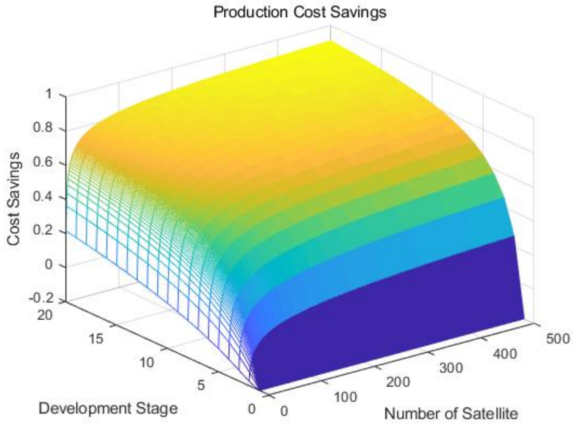

FIGURE 3. Production cost savings.

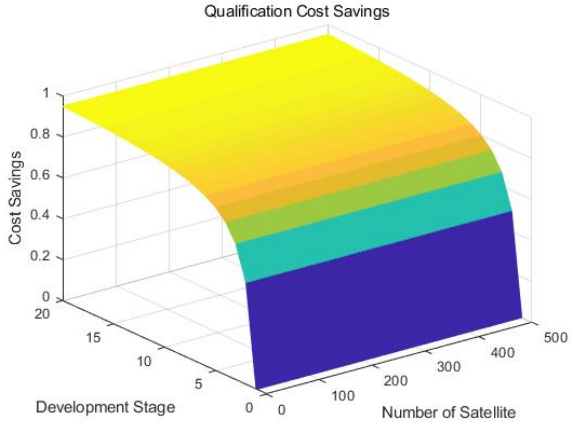

FIGURE 4. Qualification cost savings.

portions. It could be shown that the savings increase monotonically with increasing M. The interesting phenomenon is that the cost savings decrease with increasing N.

As the number of satellites per development stage increases, the component costs for design, qualification and manufacture decrease. Although cost savings remain constant or increase with N, this represents only the relative proportions between the two. The fractional costs of both the modular and customized systems become so low that the other components such as launch become the dominant costs. Since for the modular case launch costs are actually more expensive than the customized system, the overall savings decreases.

High cost savings appearing at low values of N represent advantages due to design savings. As the number of satellites increase, the customized system is able to rapidly amortize its cost of design. Most of the remaining cost savings could occur due to the learning curve existence.

Starting from high initial values, the cost savings drop sharply as the number of satellites per development stage increases. Shortly after this the cost savings rise, reach a local maximum and then taper off again.

The impact of the degree of modularity is an important issue of the cost model. This is represented by the values of

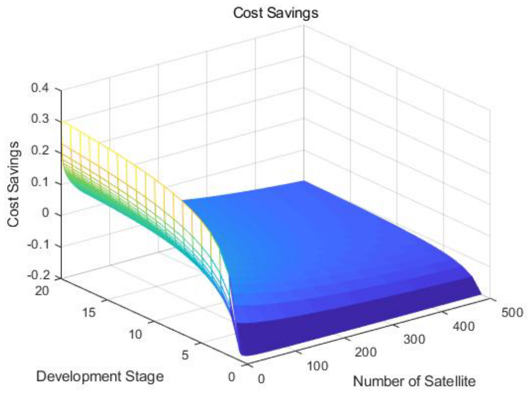

FIGURE 5. Total cost savings.

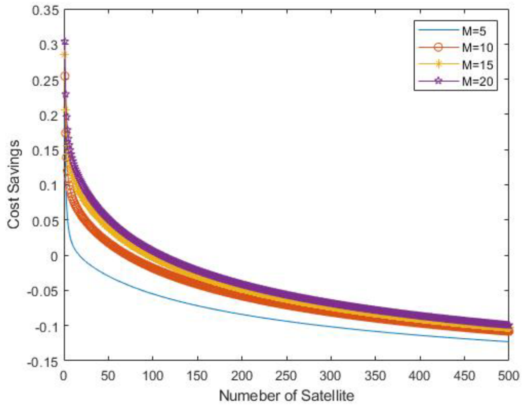

FIGURE 6. Development stage dependence.

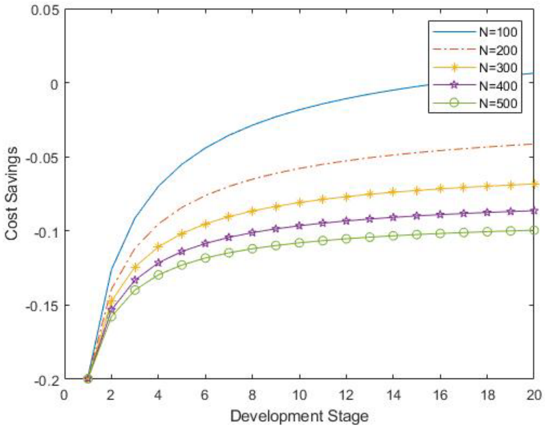

FIGURE 7. Effect of development stage.

α and β. A low value of α combined with a high value of β would represent the case reusing a component not specifically designed to be modular. Assumed that values of $\alpha = 0.7$ and $\beta = 0.4$. Thus the first mission design cost would be 1.1 times the cost of a customized design. Subsequent missions would have an incremental cost of 0.4 of the reference cost.

The above example assumes that an existing design is simply adapted to meet the needs of various missions. A truly modular method would likely devote more up-front investment to the initial design in the interest of decreasing

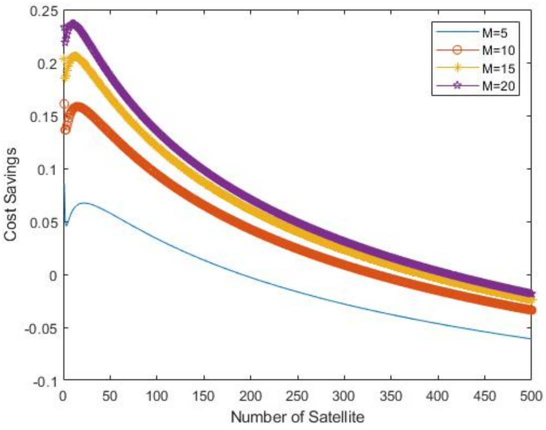

FIGURE 8. Effect of Number of Satellite.

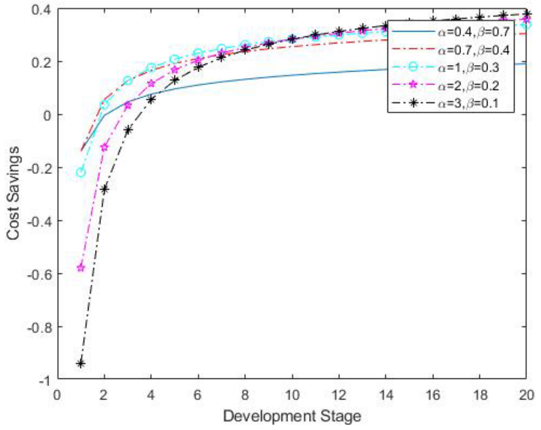

FIGURE 9. Degree of Modularity and Stages.

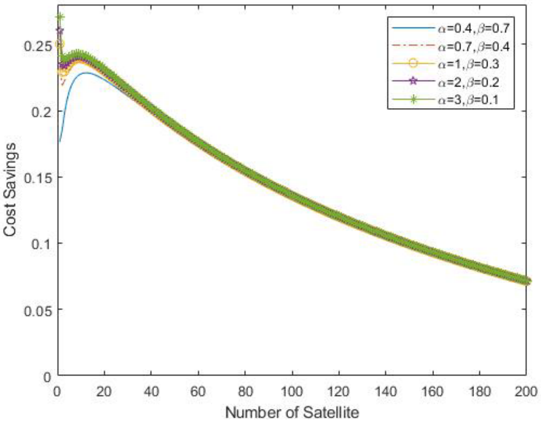

FIGURE 10. Degree of modularity and number of satellite.

the incremental cost. Fig. 8 and Fig. 9 show the effect of several choices of different α and β. As the number of missions increase, the cost curves cross at around 6–8 missions. Differences in cost savings are not very great after the break-even point. For a quadruple increase in initial cost, the savings increase after 20 stages is only about 13%.

In conclusion, customized designs are optimized for performance, but at the expense of a higher total system cost. Modular satellite platform designs may be suboptimal in terms of performance and mass, but lead to significant cost savings. Finally, use of the modular satellite platform design could decrease the lifecycle costs of system.

V. CONCLUSION

The insights which are given by the analysis of cost model based on modularity are following. When the number of satellites is not so large, the cost savings is highest if the design cost gives the main contribution. These trends help to formulate some general rules that might be applied to the strategic planning for a space mission. At present, the model is most effective in identifying trends in the future of a certain technology. If, however, a reference design was chosen, the model parameters could be configured to give more accurate predictions of costs, break-even points and sensitivities. LEO communication satellite constellations are becoming increasingly popular as architectures due to the inherent reliability-driven cost advantages, hat they display in many classes of missions. Upon model benchmarking and validation, the cost analysis based on modularity would help designers, faced with a number of missions to plan, determine the appropriate investment in modularity that the program should adopt.

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