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A Fractionated Spacecraft System Assessment Tool Based on Lifecycle Simulation Under Uncertainty

YAO Wen[a] , CHEN Xiaoqian[a,*], ZHAO Yong[a], Michel van TOOREN[b]

[a] *College of Aerospace and Materials Engineering, National University of Defense Technology, Changsha 410073, China*
[b] *Faculty of Aerospace Engineering, Delft University of Technology, 2629HS Delft, the Netherlands*

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Abstract

To comprehensively assess fractionated spacecraft, an assessment tool is developed based on lifecycle simulation under uncertainty driven by modular evolutionary stochastic models. First, fractionated spacecraft nomenclature and architecture are clarified, and assessment criteria are analyzed. The mean and standard deviation of risk adjusted lifecycle cost and net present value (NPV) are defined as assessment metrics. Second, fractionated spacecraft sizing models are briefly described, followed by detailed discussion on risk adjusted lifecycle cost and NPV models. Third, uncertainty sources over fractionated spacecraft lifecycle are analyzed and modeled with probability theory. Then the chronological lifecycle simulation process is expounded, and simulation modules are developed with object oriented methodology to build up the assessment tool. The preceding uncertainty models are integrated in these simulation modules, hence the random object status can be simulated and evolve with lifecycle timeline. A case study to investigate the fractionated spacecraft for a hypothetical earth observation mission is carried out with the proposed assessment tool, and the results show that fractionation degree and launch manifest have great influence on cost and NPV, and generally fractionated spacecraft is more advanced than its monolithic counterpart under uncertainty effect. Finally, some conclusions are given and future research topics are highlighted.

Keywords: fractionated spacecraft; lifecycle simulation; assessment; uncertainty; lifecycle cost; net present value

1. Introduction

Aiming to enhance spacecraft flexibility (in terms of scalability, maintainability and adaptability) and responsiveness (the capability to rapidly respond to uncertain events), Mathieu and Weigel proposed a new concept of fractionated modular spacecraft in 2005 [1]. In contrast to traditional monolithic spacecraft, fractionated spacecraft decomposes spacecraft into a set of separate heterogeneous free flying modules which incorporate various payload and infrastructure functions. They interact with each other through wireless communication and power transmission, so as to form a wireless network and perform as a virtual holistic spacecraft. With the separate module architecture, incremental deployment is allowed as modules can be launched in different batches so that risk of launch failure can be diversified. Once the fractionated spacecraft is on orbit, its performance can be enhanced or mission can be renewed by deploying additional modules in the cluster. In case of module failure, a replenishment module can be quickly deployed to replace the failure one and resume the normal function, thus technical and environmental uncertainties can be handled responsively. Detailed analysis of monolithic spacecraft drawbacks and fractionated spacecraft value propositions is thoroughly discussed in Ref. [2].

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*Corresponding author. Tel.: +86-731-84573111.
E-mail address: chenxiaoqian@nudt.edu.cn

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With the merits of flexibility and responsiveness, fractionated spacecraft has attracted great research interest both in academia and industry. In 2007, the Defense Advanced Research Projects Agency (DARPA) commenced an initiative entitled F6 (Future Fast, Flexible, Fractionated, Free-Flying Spacecraft united by Information eXchange) to develop the related methodologies and technologies [3]. F6 sparks several space industry primers to participate in this field. In recent five years, there is a burst of literature in this field, most of which is devoted to quantitative assessment of fractionated spacecraft in terms of non-traditional attributes (e.g. flexibility, responsiveness, etc.) along with the traditional ones (e.g. mass, cost, etc.), and comparison against the traditional monolithic counterpart. To address the assessment problem with multi-attributes which are of totally different types and measured with different units, approaches in literature can be generally classified into two types. One is to translate the values of the attributes in terms of revenues or cost expressed in monetary units, such as stochastic lifecycle cost metric which incorporates lifecycle uncertainties as cost impact on the overall mission [4], and net present value (NPV) which measures the merit of a design as the stochastic value (benefit) delivered to the user minus the total stochastic cost expenditure over the entire lifecycle of the system considering uncertain risks [5-8]. The other one is based on multi-attribute utility theory (MAUT) [9] to translate the value of each attribute corresponding to each criterion in terms of utility with single utility functions, and use a multi-attribute utility function to evaluate all the attributes in terms of a single synthetic utility value [10-12]. Considering single utility and multi-attribute utility functions should be elicited from the decision makers through interview which usually results in biases with subjective experience and judges, the first type of assessment approach is utilized in this paper, and risk adjusted lifecycle cost and NPV are chosen as assess- ment metrics. This type of design approach, which guides design and optimization based on the values of the multi-attribute assessment criteria, is called value-centric design methodology (VCDM), which is pervasively adopted in the F6 project research [5-8] and advocated as a more advanced systems engineering method by better utilization of optimization to improve design compared to the traditional requirement-centric or cost-centric methods [13-14].

Up to now, several assessment software tools have been developed. Georgia Institute of Technology developed the Georgia Tech F6 Architecture Synthesis Tool (GT-FAST), which can be either used as a point design tool for rapid, automated sizing and synthesis of candidate F6 architectures, or as an optimization tool for trade space exploration [15-16]. Orbital Sciences Corporation developed a VCDM tool suite named PIVOT (Pleiades Integrated VCDM Optimization Tool) which can objectively quantify the net value of any space system (both fractionated and monolithic) subject to a range of perturbations [8]. Boeing developed an F6 VCDM tool RAFTIMATE (Risk Adjusted, Flexible, Time Integrated Multi-Attribute Trade Exploration) to estimate the risk-adjusted cost and performance of candidate systems [6]. Lockheed Martin Corporation developed system value modeling (SVM) tool to support value-centric systems engineering and decision-making based on NPV and its standard deviation [7]. Northrop Grumman Corporation also developed an SVM tool to facilitate fractionated spacecraft sizing and multi-attribute utility calculation based on lifecycle simulation [17]. The latter four researches are funded by F6 project and summarized in Ref. [5].

In the aforementioned assessment tools, there are myriads of simplifications and assumptions, and the sizing and cost models are mainly based on the existing methods and past experience in space engineering, such as small satellite sizing models and cost models, which may be inaccurate or even obsolete for the fractionated architecture. Thus it is very important to invest the assessment tool with the capability to be updated flexibly and evolve with the development in fractionated spacecraft research. In this paper, we develop a fractionated spacecraft assessment tool based on modular evolutionary stochastic models which can drive lifecycle simulation under uncertainty to estimate the assessment metrics, namely risk adjusted lifecycle cost and NPV. Herein the modular evolutionary stochastic simulation models are programmed as classes with object-oriented methodology for each primitive constitutive element of the fractionated spacecraft system (e.g. module, fractionated component, etc.) and its related launch vehicles. In these classes, features, operation functions, and uncertainty characteristics of the object being modeled are programmed. The object status simulated by the operation functions can evolve with timeline according to the internal timer of the lifecycle simulation considering uncertainty effect, which earns the name of evolutionary stochastic models. By integration of these constituent classes as bricks, a complete fractionated spacecraft system and its associated launch vehicles can be composed and its lifecycle simulation can be performed.

The rest of this paper is structured as follows. First the system modeling of fractionated spacecraft is introduced. The nomenclature of this new concept spacecraft is clarified, and the assessment criteria are analyzed. Then sizing models are described, based on which risk adjusted lifecycle cost and NPV models are investigated in detail. Second, uncertainty sources of fractionated spacecraft are identified and modeled with probability theory. Based on the preceding models, simulation modules are established and the lifecycle simulation process is expounded, based on which the assessment tool is developed. Finally, a case study to investigate the fractionated spacecraft for a hypothetical earth observation mission is carried out with the proposed assessment tool, followed by discussion of results and conclusion remarks.

2. Fractionated Spacecraft System Modeling

2.1. System architecture

The nomenclature of fractionated spacecraft is firstly clarified with reference to Ref. [16].

Component (or **fractionated component**) A fractionated subsystem or device (e.g. payload) which can be developed separately and integrated into different modules according to mission requirements.

Module A single free flying vehicle consisting of a compilation of components and a module bus with supporting subsystems, e.g. structure, thermal, etc., to accommodate components onboard.

Cluster (or **architecture**) An independent spacecraft system consisting of a compilation of modules.

The architecture is graphically illustrated in Fig. 1. The pyramid shape presents the bottom-up design methodology, wherein items of each layer are built up based on its lower level items, and components of the bottom layer are the basic units. The top is a fractionated spacecraft design, which includes two parts: one is the composition of the cluster, and the other is the launch scheme indicating the manifest as on which vehicle each module is launched.

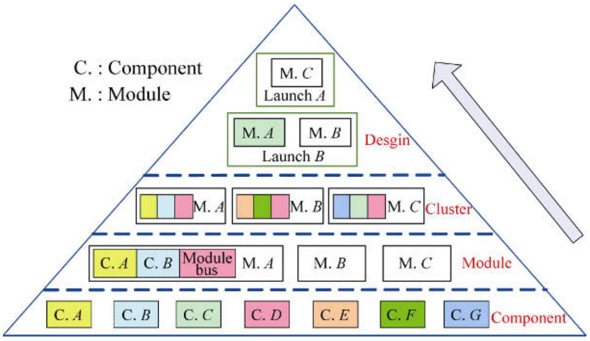

Fig. 1 Architecture of fractionated spacecraft system.

Research on fractionated component in literature is mainly based on the scheme proposed by Orbital Sciences Corporation for the F6 project [15-16, 18], which includes: a) payload, e.g. earth observatory electro-optical (EO) imager; b) tracking telemetry and command transceiver providing nearly continuous communications through tracking and data relay satellites (TDRSS transceiver); c) high-bandwidth downlink (HBD) component providing high-volume downlinks especially for the payload data; d) solid state recorder (SSR) providing high-volume data storage; e) mission data processor (MDP) providing onboard high-speed computing. These five components are also considered in this paper, and the main parameters, including mass, power, cost, technology readiness level (TRL), and mean time to failure (MTTF), are listed in Table 1.

As the cluster can be launched in different batches with different launch vehicles, a list of optional launch vehicles is provided in this paper, which includes six US expendable launch vehicles. The launch mass capability (to low earth orbit), reliability, and unit launch cost (FY08) are listed in Table 2 [19].

Table 1 Fractionated component parameters

Component	Mass/kg	Power/W	Cost/$M	TRL	MTTF/month
EO	40	15	15	9	72
TDRSS	4	25	5	5	84
HBD	10	25	2	9	72
SSR	8	100	2	7	72
MDP	8	18	1	6	84

Table 2 Launch vehicle parameters [19]

Launch vehicle	Capacity/kg	Unit launch cost/$M	Reliability
Pegasus XL	450	22	0.935
Minotaur I	580	23	0.951
Taurus Standard	1 130	28	0.944
Taurus XL	1 390	31	0.944
Athena II	1 700	44	0.888
Delta II	2 500	48	0.988

2.2. Assessment criteria

To comprehensively assess fractionated spacecraft with emphasis on its advantages in flexibility and responsiveness compared with monolithic spacecraft, non-traditional attributes, e.g. maintainability, scalability, robustness, responsiveness, etc. [1-3], should be evaluated in addition to the traditional ones. These attributes can be measured by assessing their impact on the system lifecycle cost and benefit which are subject to uncertainties, e.g. launch failure, module failure, etc. [4]. The lifecycle cost and benefit can be modeled as stochastic variables in terms of monetary units, and the probability distributions thereof can be analyzed with Monte Carlo simulation (MCS) considering uncertainties. The stochastic cost and benefit lead to a risk adjusted NPV [5-6] which is the benefit delivered to the user minus the total expenditure over the entire lifecycle of the system [12-13]. Considering that lifecycle cost under uncertainty (risk adjusted lifecycle cost) and risk adjusted NPV are very important issues in making decision and raising funding for one project, these attributes are chosen as assessment metrics in this paper, and the criterion is that smaller mean and standard deviation of risk adjusted lifecycle cost (lower expected cost with lower risk) and larger mean and smaller standard deviation of risk adjusted NPV (more expected net value with lower risk) are preferred. The estimation method of these assessment metrics is discussed in Section 2.4.

2.3. Sizing models

As risk adjusted lifecycle cost and NPV estimation are based on space system characteristics, e.g. orbit, mass, module cost, etc., the system sizing models of fractionated spacecraft are firstly discussed as follows.

1) Orbit. For arbitrary orbit, input variables include six classical orbit elements, namely semi-major axis,

eccentricity, inclination, right ascension of ascending node, argument of perigee, and true anomaly. The default orbit type for earth observation is circular, sun-synchronous low-earth orbit, and the input variables are orbit altitude, right ascension of ascending node, and true anomaly, based on which the other orbit parameters, eclipse and ground coverage characteristics (e.g. access to ground stations or observation time on target areas) are calculated. The orbit calculation equations can be referred to Refs. [20]-[21].

2) Fractionated components. It is assumed that the fractionated components are developed as standard products supporting mass production, long time stock, and rapid integration. The components considered in this paper are listed in Table 1.

3) Modules. A module includes several fractionated components to perform specific tasks and a module bus with supporting subsystems to accommodate these components. The module bus and module sizing models are developed based on the existing small satellite design models by treating the module bus as satellite bus and the on-board components as satellite payloads. The models are mainly empirical relationships in the conceptual design phase and detailed in Refs. [20]-[21] to estimate module mass, power, and cost according to the fractionated components onboard.

2.4. Risk adjusted lifecycle cost and NPV models

2.4.1. Risk adjusted lifecycle cost models

The risk adjusted lifecycle cost of fractionated spacecraft mainly includes five parts: space segment cost, launch segment cost, ground segment cost, operations and support cost, and risk effect cost. Assuming that the existing ground facilities can be applicable to fractionated spacecraft, the ground segment cost is ignored. To develop these cost models, the widely used parametric estimating method based on cost estimating relationships (CERs) is utilized, and the fiscal year 2008 dollars (FY08$) are used as constant-year dollars.

1) Space segment cost

The CERs provided by the publicly available small satellite costing model (SSCM) [21] is used considering the free-flying modules are of the small satellite scale. Assume the spacecraft cluster cost is the sum of the module cost. The module cost includes non-recurring and recurring parts. The non-recurring cost mainly consists in research, develop, test and evaluation (RDT&E) cost. Recurring cost is related to flight hardware production phase, and covers theoretical first unit (TFU, the first flight-qualified satellite off the line) cost or the cost of unit production thereafter with learning curve factor applied to TFU cost due to multi-unit production effect.

For the first unit of type i module, the module cost C_{M}^{i1} includes both non-recurring and recurring parts.

$$C_{\mathrm{M}}^{i1} = \mathrm{NRE}_{\mathrm{M}}^{i1} + \mathrm{REC}_{\mathrm{M}}^{i1} \tag{1}$$

where $\mathrm{REC}_{\mathrm{M}}^{i1}$ is the TFU cost of type i module, and $\mathrm{NRE}_{\mathrm{M}}^{i1}$ as well as $\mathrm{REC}_{\mathrm{M}}^{i1}$ can be estimated with CERs in Ref. [21] based on the module sizing models. For the jth (j >1) module of type i, only the unit recurring cost is applied and module C_{M}^{ij} is calculated as

$$C_{\mathrm{M}}^{ij} = \mathrm{REC}_{\mathrm{M}}^{ij} = \mathrm{REC}_{\mathrm{M}}^{i1} \cdot j^{(\ln L/\ln 2)} \tag{2}$$

where L is learning curve slope defined as 0.85 [8].

Considering yearly inflation against FY08$, the cost should be adjusted as

$$C_{\mathrm{M\_inflated}}^{ij} = C_{\mathrm{M}}^{ij}(1+R_{\mathrm{inflation}})^{(\mathrm{lateryear-2008})} \tag{3}$$

where $R_{\mathrm{inflation}}$ is yearly inflation rate defined as 4% [8], and "lateryear" the year when the module is developed. For simplicity, the subscript "inflation" is dropped and module costs in later discussion are all inflation adjusted.

2) Launch segment cost

The unit launch cost is considered in this paper, and the total launch cost for all the modules is

$$C_{\mathrm{L}} = \sum_{i=1}^{N_{\mathrm{L}}} C_{\mathrm{L}}^{i} \tag{4}$$

where N_{L} is the total launch number, and C_{L}^{i} the cost of the ith launch. The optional launch vehicles in this paper are listed in Table 2.

3) Operation and support cost

Operation and support cost covers personnel, hardware, material and facility costs [22] which are unrealistic to estimate in this conceptual design phase. For ease of calculation, we consider these costs in a lump as a fixed annual cost for each module. For low earth orbit observation mission, we assume 2$M per year [4] for the first batch of modules in orbit, and a 50% increment each time a new batch of modules are integrated. The total operation and support cost is

$$C_{\mathrm{O}} = \sum_{i=1}^{N_{\mathrm{L}}} 2(1+50\%)^{i-1} T_i \ \$\mathrm{M} \tag{5}$$

where T_i is the operation time after the ith and before the (i+1)th launch.

So far the cost estimated with deterministic CERs can be summed up as

$$C_{\mathrm{E}} = C_{\mathrm{L}} + C_{\mathrm{O}} + \sum_{i=1}^{N_{\mathrm{M\_type}}} \sum_{j=1}^{N_{\mathrm{M\_type\_}i}} C_{\mathrm{M}}^{ij} \tag{6}$$

where $N_{\mathrm{M\_type}}$ is the number of module types in the cluster, and $N_{\mathrm{M\_type\_}i}$ the number of type i modules.

4) Risk effect cost

There are various uncertainties during spacecraft RDT&E, launch, and on-orbit operation contributing to risks of mission delay, launch failure, and on-orbit failure. In this paper, only the extra cost due to launch failures and on-orbit module failures is considered.

A) Launch failure

If a launch fails, all the modules onboard as well as this launch vehicle are redeveloped and the launch is rescheduled. Without considering insurance, the additional cost due to launch failure is

$$C_{\mathrm{L\_fail}} = \sum_{i \in \boldsymbol{I}_{\mathrm{L\_fail}}} (C_{\mathrm{L}}^{i} + C_{\mathrm{M}}^{\mathrm{L\_}i}) \tag{7}$$

where $\boldsymbol{I}_{\mathrm{L\_fail}}$ is the index vector which includes the indices of the failure launches, and $C_{\mathrm{M}}^{\mathrm{L\_}i}$ the total cost to reproduce all the modules onboard the ith failure launch vehicle.

B) On-orbit module failure

If one module fails during on-orbit operation, a replenishment module will be developed and launched to replace the original failure one so as to realize on-orbit repair. In this repairing mode the cost of on-orbit module replacement is the sum of the module cost and the launch cost, stated as

$$C_{\mathrm{O\_fail}} = \sum_{i \in \boldsymbol{I}_{\mathrm{O\_fail}}} C_{\mathrm{L}}^{i} + \sum_{i \in \boldsymbol{I}_{\mathrm{M\_O\_fail}}} C_{\mathrm{M}}^{i} \tag{8}$$

where $\boldsymbol{I}_{\mathrm{O\_fail}}$ is the index vector of replenishment launches, and $\boldsymbol{I}_{\mathrm{M\_O\_fail}}$ the module index vector to be replenished.

Then the total cost due to risk effect is

$$C_{\mathrm{R}} = C_{\mathrm{L\_fail}} + C_{\mathrm{O\_fail}} \tag{9}$$

Sum up all the single cost items discussed above, and yield the total risk adjusted lifecycle cost as

$$C = C_{\mathrm{E}} + C_{\mathrm{R}} \tag{10}$$

2.4.2. Risk adjusted NPV models

The benefit is measured with cumulative service amount the spacecraft has delivered, i.e. benefit is only related to the total recorded service amount and the detailed information as whether the spacecraft has encountered malfunction during lifetime is not needed.

Lockheed Martin proposed to calculate the revenue based on the data volume downloaded to the ground [7]. Boeing proposed to estimate revenue in accordance with the cost with a specified profit ratio [6]. The Orbital Science Corporation proposed to calculate the profit according to the dynamic market need, market share, and spacecraft service price [8]. In this paper, the model proposed by Lockheed Martin is used for its simplicity and reasonable assumptions. The revenue model is

$$R = N_{\mathrm{Payload\_Data}} \cdot P_{\mathrm{Data\_price}} \tag{11}$$

where $N_{\mathrm{Payload\_Data}}$ is the total amount of payload data downloaded, e.g. number of images for earth observation mission, and $P_{\mathrm{Data\_price}}$ the data price which is determined by resolution and size. The downloaded data amount, resolution, and size are calculated according to the orbit and the performance of payload and communication capacities [20-21].

Considering that the value of money can increase with time regardless of inflation as it can be invested to gain return, the time value of money should be used as a standard to measure the monetary value of cost and benefit [21]. The present value of both cost and benefit invested or gained at different schedule time of lifecycle can be obtained by multiplying the original value with the factor PV defined as

$$\mathrm{PV} = 1/(1+d)^{n-1} \tag{12}$$

where n is the year of the money measured relative to the constant dollar year, and d the discount rate which is defined as 10% for study purpose [21].

Based on the preceding cost model and revenue model, the risk adjusted NPV can be estimated as

$$\mathrm{Net} = R - C \tag{13}$$

3. Uncertainty Modeling

All the uncertainties are treated as random variables, and probability theory is used for uncertainty modeling and propagation.

3.1. Uncertainties of components and modules

Failure profiles are defined in the traditional “bathtub” shape to describe the performance uncertainties of fractionated components and module bus, with more likelihood of failure in the infant periods at the beginning and in the wear-out periods at the end of the spacecraft lifetime. In the middle operation period, the failure rate keeps stable and relatively low, and the exponential model is used to characterize the distribution of failure probability with failure density function defined as

$$f(t) = \lambda \mathrm{e}^{-\lambda t} \tag{14}$$

where λ is the constant failure rate and $\theta = 1/\lambda$ is MTTF. The MTTF of each component is listed in Table 1. The module bus is considered as a holistic item with several subsystems, and the MTTF is assumed to be 60 months (5 years). For ease of calculation, infant mortality rate and wear-out failure rate are both assumed to be 5%.

The components and module bus failures determine the module failure status, which influence the cluster operation status and module replacement decisions. There are four scenarios considered in this paper.

1) If the bus of the module fails, this module is assumed to completely lose function. If there is no other module in the cluster which can replace this failure module to carry out required task, then a new one should be deployed.

2) If the module has only one component which encounters failure, this module is assumed to completely lose function. If there is no other module in the cluster which can replace this failure module to carry out required task, then a new one should be deployed.

3) If the module has two or more components of the same type, these components form a parallel system, i.e. the module fails only when all the components fail. If there is no other module in the cluster which can replace this failure module to carry out required task, then a new one should be deployed.

4) If the module has two or more types of components, the components of each type form a parallel system, i.e. one of the module functions fails when all the components of this type fail. Assume that the different functions performed by different types of components onboard are independent. If one function fails and there is no other module in the cluster which can replace this module to carry out required task, then a new one should be deployed.

The uncertainties of components and modules are monetized as extra cost $C_{\mathrm{O\_fail}}$ induced by on-orbit failure risks.

Regarding the variation of orbit altitude resulting from Earth oblateness, atmosphere effect, and orbit insertion accuracy, the truncated normal model is used to describe the fluctuation of orbit altitude [23]. The uncertainty of orbit altitude contributes to the variation of payload resolution and communication access time for data download, which further influences the service delivered and benefits gained.

3.2. Uncertainties of cost model

The cost models to estimate C_{E} are based on parametric CERs which rely on a statistical analysis of past data to project future costs, so the models per se have statistical uncertainties which are called cost-risk. The major sources of cost model uncertainties include three parts: a) uncertainties of fractionated component cost and unit launch cost which are taken from literature reference. Assume the distributions of both fractionated component cost and unit launch cost are normal with mean values listed in Tables 1-2 respectively and the coefficient of variance is 1%; b) CERs estimation uncertainties which are quantified by the standard errors specified in the SSCM model [21]; c) cost growth uncertainties due to unforeseen technical difficulties, which are quantified with standard errors with respect to TRL, e.g. TRL of 6 represents low risks and the associated cost growth standard error is approximated as 10% (or lower) of the original estimated product cost. The TRL and corresponding standard error ratio are referred to Ref. [21]. The root sum square of the standard errors of all the component or subsystem costs is taken as the standard error of the module or cluster estimation cost assuming that the uncertainties are uncorrelated.

3.3. Uncertainties of launch vehicle

Assume each launch is an independent random event with corresponding reliability of the launch vehicle listed in Table 2. The uncertainties of launch vehicles are monetized as extra cost $C_{\mathrm{L\_fail}}$ induced by launch failures.

4. Lifecycle Simulation Under Uncertainty

To assess the fractionated spacecraft which features flexibility and responsiveness in responding to various uncertainties through the lifecycle operation, a lifecycle simulation should be implemented to observe its performance under uncertainties.

4.1. Chronological lifecycle simulation

The lifecycle simulation is carried out in a chronological way exactly following the real lifecycle process of the fractionated spacecraft. A schematic illustration of the chronological simulation through the lifecycle is depicted in Fig. 2 which takes a cluster with two launch batches for example. The simulation process mainly includes the following five phases.

1) Module development and production

After the project kick-off, the modules to be launched on the first batch are developed concurrently, followed by integration and test when all the modules are ready. Meanwhile the launch vehicle procurement for the first launch is processed. During the development of the first batch modules, the modules of the second batch also gradually enter the development phase and second launch vehicle procurement begins to be under process according to the schedule. The concurrent development is reasonable as the modules can be developed separately and signed to different subcontractors. In this paper, the delay of development time and launch vehicle procurement cycle is not considered.

2) First launch and initial performance operation

When both the modules of the first batch and the launch vehicle are ready, the first launch is carried out to insert the modules into predefined orbit. After the initial adjustment and health check, the first batch begins to perform tasks with predefined initial performance. The first launch is subject to launch uncertainty. If launch failure occurs the modules onboard are redeveloped and launch is rescheduled with the same launch vehicle. Considering that the time for incremental deployment of modules is very short and negligible compared to the whole operation life, it is presumed that there is no component or module failure for on-orbit operation until the whole cluster is established.

3) Incremental deployment

When both the modules of the second batch and the corresponding launch vehicle are ready, the second launch is carried out to insert the modules into orbit to join the first batch. After the initial adjustment, health check and integration with required configuration, the cluster begins to perform full performance mission operation. For cluster with more batches, the same procedure as this step is repeated for each batch until the last batch is deployed and the cluster is finally formed to enter the full operation phase.

4) Full performance operation

During the full performance operation, the operation status of each component and module bus is monitored. If a component or module bus failure occurs, the module failure status and replacement strategy are defined according to the four module failure scenarios discussed in Section 3.1. If a module should be replaced, the decision maker makes the decision to replace the failing module if the revenues over the rest of the spacecraft lifetime are expected to be larger than the repair cost, otherwise not. The risks associated with repair are not taken into account. The cluster begins to operate in degraded level. Once a decision for module replacement is made, the replenishment module development and corresponding replenishment launch vehicle procurement are conducted. The replenishment module development cycle is shorter than that of the first module development, as the TRL is improved and standard off-the-shelf products can be employed. The quick replenishment embodies the responsiveness of the fractionated spacecraft. After the replacement module is launched and integrated, the normal full performance is resumed. In later period of operation, the process to handle component and module failure is the same as this step.

5) When the cluster reaches its end of life (EOL), it is deorbited and the mission is ended.

According to the preceding chronological procedure, the flowchart of lifecycle simulation is illustrated in Fig. 3. In the block diagram, the blocks shaded with diagonal grains represent there are uncertainty models incorporated, including launch uncertainties and on-orbit operation uncertainties.

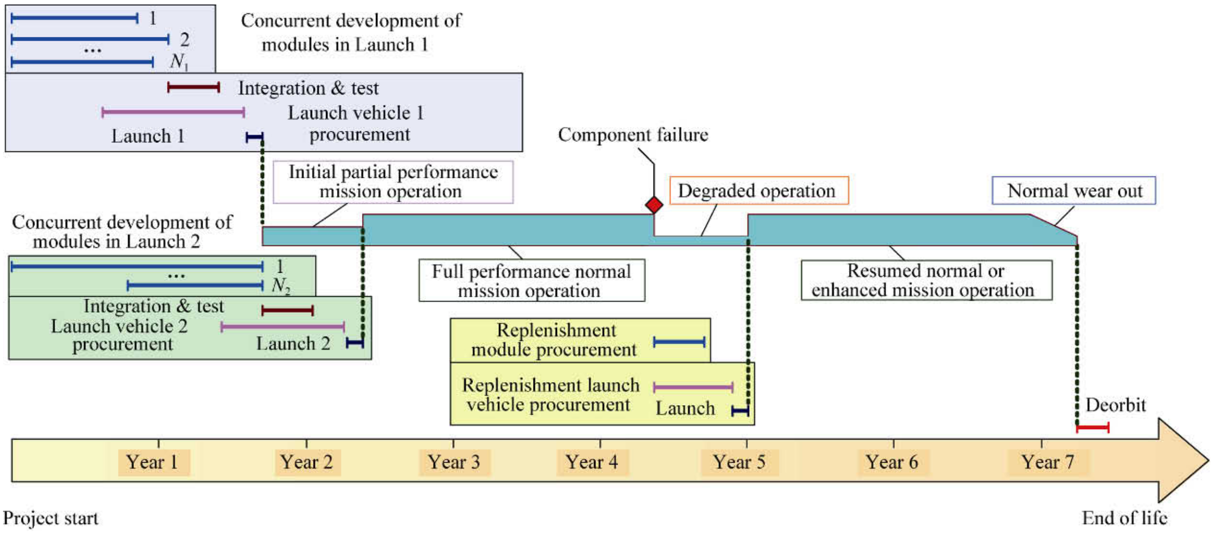

Fig. 2 Schematic illustration of chronological simulation along fractionated spacecraft lifecycle.

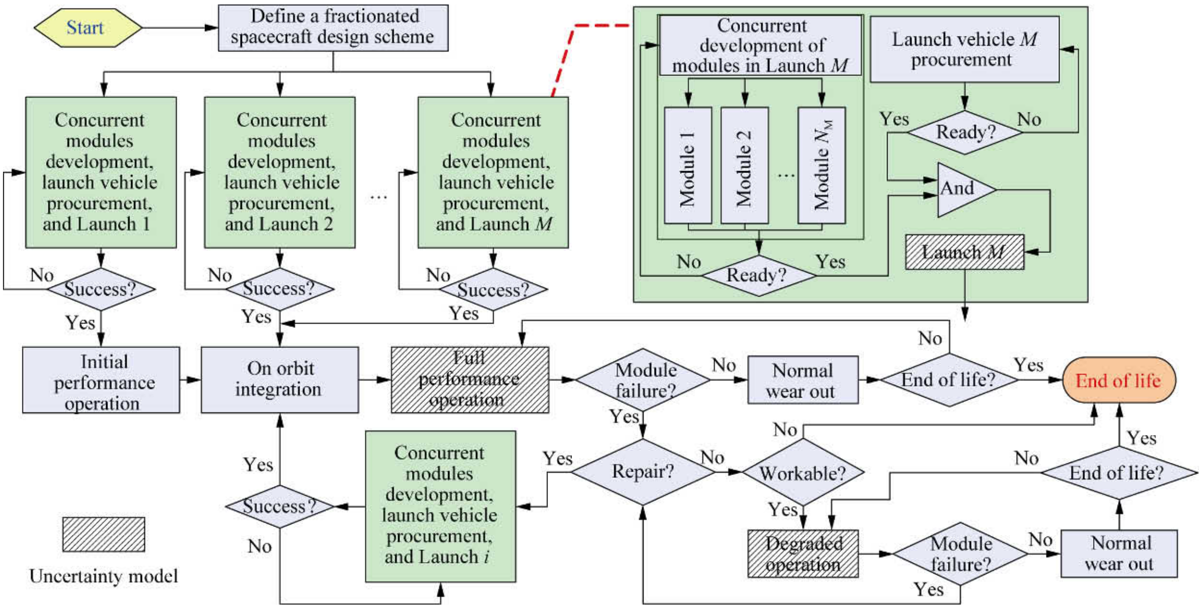

Fig. 3 Flowchart of fractionated spacecraft lifecycle simulation.

After a lifecycle simulation, the risk adjusted lifecycle cost and NPV can be calculated. Under the uncertainty effects, the simulation output values of risk adjusted lifecycle cost and NPV are random as well, which vary each time the lifecycle simulation runs. MCS method is utilized to analyze the uncertainty characteristics of assessment metrics with propagation of uncertainty effects. The flowchart of the MCS method-based uncertainty analysis of the assessment metrics is depicted in Fig. 4.

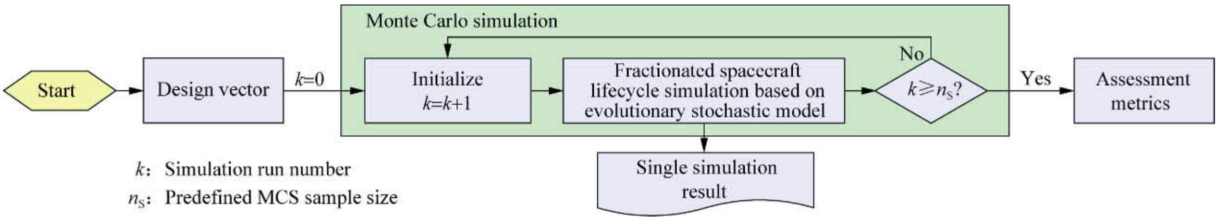

Fig. 4 MCS method-based uncertainty analysis of assessment metrics.

With predefined number of MCS, a statistical sample set of risk adjusted lifecycle cost and NPV values can be calculated, and their means and standard deviations for the given fractionated spacecraft design can be obtained. With abundant samples, the accurate mean and standard deviation of the population can be estimated by the mean and standard deviation of the MCS samples. Hence, although the real distribution models of the risk adjusted lifecycle cost and NPV are unknown, the unbiased estimation of the mean and standard deviation of their distributions can still be obtained with statistical approaches. The median static can also be used to represent central tendency which is not discussed here. The mean values are estimated as

$$\begin{cases} E(C) \approx \dfrac{1}{n_{\mathrm{S}}}\displaystyle\sum_{i=1}^{n_{\mathrm{S}}} C_i \\ E(\mathrm{Net}) \approx \dfrac{1}{n_{\mathrm{S}}}\displaystyle\sum_{i=1}^{n_{\mathrm{S}}} \mathrm{Net}_i \end{cases} \tag{15}$$

where C_i and Net_i are the risk adjusted lifecycle cost and NPV of the ith sample. The standard deviations can be estimated as

$$\begin{cases} \sigma_C \approx \sqrt{\dfrac{1}{n_{\mathrm{S}}-1}\displaystyle\sum_{i=1}^{n_{\mathrm{S}}} (C_i - E(C))^2} \\ \sigma_{\mathrm{Net}} \approx \sqrt{\dfrac{1}{n_{\mathrm{S}}-1}\displaystyle\sum_{i=1}^{n_{\mathrm{S}}} (\mathrm{Net}_i - E(\mathrm{Net}))^2} \end{cases} \tag{16}$$

The MCS estimation accuracy can be quantified with the standard error defined as

$$\begin{cases} \mathrm{err}_C = \sigma_C \big/ \sqrt{n_{\mathrm{S}}} \\ \mathrm{err}_{\mathrm{Net}} = \sigma_{\mathrm{Net}} \big/ \sqrt{n_{\mathrm{S}}} \end{cases} \tag{17}$$

It can be seen that the estimation accuracy is not related to the problem dimension, which is very useful to solve large scale spacecraft problems. Besides, it is proportional to root square of sample size, which means the improvement of accuracy by one order will result in the increase of samples by two orders. To maintain the standard error of estimation to be within 10% of the standard deviations of risk adjusted lifecycle cost and NPV, it is recommended that the sample size should be at least 100.

4.2. Simulation module architecture

The fractionated spacecraft assessment tool based on lifecycle simulation is programmed with object-oriented methodology to provide flexibility, maintainability and extensibility. The modular simulation architecture is described in Fig. 5 with united modeling language (UML) class blocks and relationship connections therein [24]. There are five classes describing the main objects in lifecycle simulation, namely cluster, module, module bus, fractionated component, and launch vehicle. Inheriting from fractionated component as parent class, there are five child classes namely EO, TDRSS, HBD, MDP and SSR. The features and operation functions incorporated in classes embody the characteristics and behavior of the object being modeled, e.g. the operation function “develop status” and “operation status” are in charge of managing progress of development or operation according to the internal clock along the lifecycle timeline. For fractionated components and module bus, the function “operation status” generates the object performance and status with probability theory according to the corresponding reliability and MTTF. Furthermore, there is a class of clocks which act as the internal timer, and a class of assessment metrics which encapsulate risk adjusted lifecycle cost and NPV models.

The class relationships are illustrated with connection lines. One cluster is composed by one or more modules, which includes one module bus and one or more fractionated components. And, one cluster is related to one or more launch vehicles for multiple launch batches. Clock controls the time of all the objects, and the class of assessment metrics is related to cluster and launch vehicle to estimate assessment outputs.

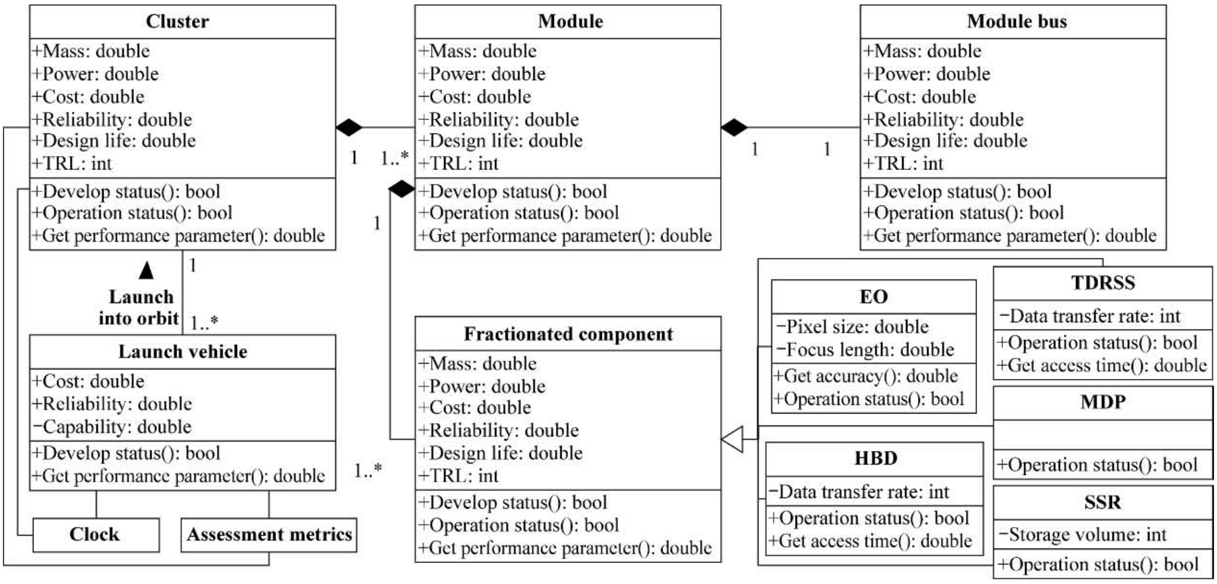

Fig. 5 Simulation model architecture with UML.

4.3. Simulation input and output

The simulation inputs include the fractionated spacecraft design and its mission orbit. A fractionated spacecraft design includes the composition of the cluster and the launch manifest. The cluster composition is stated as

$$\begin{cases} N_{\mathrm{M}} = \sum\limits_{i=1}^{N_{\mathrm{M\_type}}} N_{\mathrm{M\_type\_}i} \\ \boldsymbol{x}_i = [n_{i1} \quad n_{i2} \quad n_{i3} \quad n_{i4} \quad n_{i5}] \quad (i = 1, 2, \cdots, N_{\mathrm{M}}) \end{cases} \tag{18}$$

where N_{M} is the total module number, and $\boldsymbol{x}_i$ is the fractionated component composition of the ith module with n_{ij} indicating the number of fractionated component j (numbered in the same sequence with the components listed in Table 1) integrated in module i. Launch vehicles for all the launch batches are stated as

$$\boldsymbol{l} = [l_1 \quad l_2 \quad \cdots \quad l_{N_{\mathrm{L}}}] \quad l_i \in \{1, 2, 3, 4, 5, 6\} \tag{19}$$

where l_i is the launch vehicle serial number (numbered in the same sequence with the launch vehicles listed in Table 2) for the ith launch. The launch batch manifest is stated as

$$\boldsymbol{s} = [s_1 \quad s_2 \quad \cdots \quad s_{N_{\mathrm{M}}}] \tag{20}$$

where s_i indicates the batch in which the ith module is launched. The mission orbit input includes six classical orbit elements.

The simulation outputs are assessment metrics, including the means and standard deviations of risk adjusted lifecycle cost and NPV.

5. Case Study

The fractionated spacecraft for a hypothetical earth observation mission is investigated with the proposed assessment tool.

5.1. Problem description

The description of the fractionated spacecraft for the earth observation mission is listed as follows.

1) The mission life is five years.

2) The mission orbit is assumed to be a circular, sun-synchronous low-earth orbit. For simplification, the right ascension of ascending node and time of perigee passage are fixed as constants, and only orbit altitude is taken as orbit input of simulation.

3) Assume that there is at least one module of the cluster carrying an EO component with the following parameters: pixel size 8 000 × 8 000, single charge coupled device (CCD) pixel size 8 um, and 2 bits data per pixel for storage; the field of view is 1.9°. The downloaded picture data amount is a function of the orbit and communication link capacity. The module with EO component is termed as payload module.

There are four modes to transmit the payload data to the ground.

A) If the payload module comprises an EO, an SSR and an HBD, the data is transmitted to the ground directly from this module.

B) If the data cannot be all dumped by means of Step A) because of component failure, capability limit, etc., or if the payload module only comprises an EO and an SSR, then the modules with HBD in this cluster are identified and the payload data is transmitted to these modules to be dumped to the ground.

C) If the data cannot be all dumped by means of Step A) and Step B), or if the payload module only has an EO, then the modules with SSR and HBD in the cluster are identified and the payload data is transmitted to these modules to be dumped to the ground.

D) If the data cannot be all dumped by means of the preceding three steps, or if the payload module only has an EO, then the modules with SSR and the modules with HBD in the cluster are identified and the payload data is dumped to the ground through cooperation with these modules.

4) In this case study, the uncertainty issues of schedule slip, market uncertainty, funding change, etc., are not considered.

5.2. Assessment results and discussion

Five design schemes are assessed separately with the proposed assessment tool, and the details of the schemes as well as the assessment results are listed in Table 3. These five schemes represent five different fractionation degrees. Scheme 1 is a single module design, which is essentially a monolithic design to be compared with the fractionated architecture. Scheme 5 is a fully fractionated design with each component being carried by a separate module. The orbit altitudes of all the schemes are defined the same as 500 km. MCS sample size is 100 for each design scheme.

Table 3 Assessment results of five fractionated spacecraft design schemes with different fractionation degrees

	Variable	Scheme 1	Scheme 2	Scheme 3	Scheme 4	Scheme 5
Input	Module 1 $\boldsymbol{x}_1$	[1 1 1 1 1]	[1 1 1 0 0]	[1 1 0 0 0]	[1 0 0 0 0]	[1 0 0 0 0]
	Module 2 $\boldsymbol{x}_2$		[0 0 0 1 1]	[0 0 1 1 0]	[0 0 1 1 0]	[0 1 0 0 0]
	Module 3 $\boldsymbol{x}_3$			[0 0 1 1 1]	[0 1 0 0 0]	[0 0 1 0 0]
	Module 4 $\boldsymbol{x}_4$				[0 0 0 1 1]	[0 0 0 1 0]
	Module 5 $\boldsymbol{x}_5$					[0 0 0 0 1]
	Lauch vehicle $\boldsymbol{l}$	[2]	[1 1]	[1 1]	[1 1]	[1 1]
	Lauch batch $\boldsymbol{s}$	[1]	[1 2]	[1 1 2]	[1 1 2 2]	[1 1 2 2 2]
	Altitude h / km	500	500	500	500	500
Output	μ_{Net} / \$M	110.012 5	146.802 1	263.113 8	300.329 8	325.350 1
	σ_{Net}/ \$M	44.973 2	75.995 6	80.539 1	94.887 7	102.711 7
	μ_C / \$M	140.474 6	200.515 9	242.668 5	269.824 6	302.436 9
	σ_C/ \$M	31.759 8	28.368 2	37.637 3	48.281 2	49.574 6

The distribution scatter plots of MCS simulation for each scheme are depicted in Fig. 6. The scatter points with different marks represent simulation outputs for different schemes. The ellipses are constructed according to the statistical analysis results of the MCS samples. For a specific scheme, the center of the ellipse is located at the point with the sample mean values. The semi-axis lengths are equal to the standard deviations. The orientation of the ellipse is defined by the eigen vectors of the covariance matrix, and the major semi-axis is set along the direction of the eigen vector of the corresponding standard deviation in the covariance matrix. The results show that generally fractionated architectures are more advanced than the monolithic one, and schemes with higher fractionation degree can provide higher risk adjusted NPV, but lifecycle costs are also more expensive. This observation agrees with the research results in Ref. [1] and Refs. [10]-[11] which give the conclusion that more-fractionated architecture tends to have higher nontraditional attributes which contribute to higher NPV, but mass and cost tend to increase as well. So decision makers have to make trade-off between NPV and cost according to preference. It is also observed that standard deviations of both NPV and cost tend to increase with higher fractionation degree. It is because that more modules and launch batches lead to more chances of failures which contribute to the variation in benefit and cost. Especially the standard deviation of NPV rises quickly with the increase of fractionation degree due to the interrupted service resulting from any module failure.

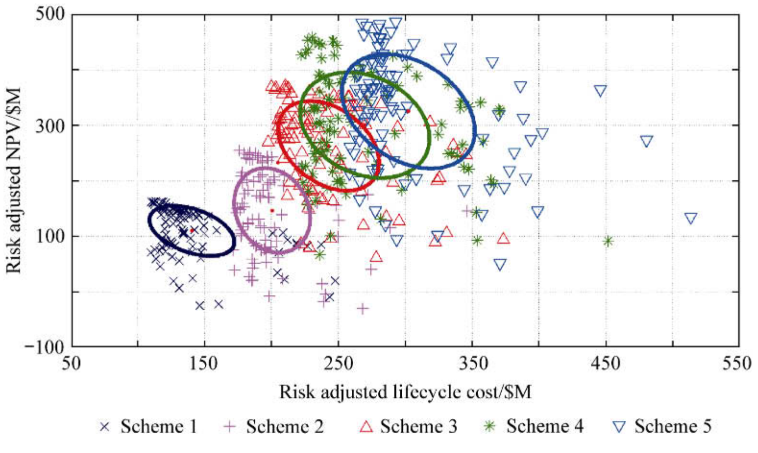

Fig. 6 MCS scatter plots of five fractionated spacecraft design schemes with different fractionation degrees.

The preceding results show that Scheme 3 with three modules can provide a good balance between risk adjusted lifecycle cost and NPV. To investigate schemes with three modules in detail, six three-module schemes with different component compositions and launch manifests are explored. The orbit altitudes of all the schemes are defined as 500 km. Scheme 3A is the same with Scheme 3 in Table 3 for comparison. The results are listed in Table 4, and the sample distribution ellipses of risk adjusted lifecycle cost and NPV of each scheme are depicted in Fig. 7.

Table 4 Assessment results of six three-module fractionated spacecraft design schemes

	Vbriable	Scheme 3A	Scheme 3B	Scheme 3C	Scheme 3D	Scheme 3E	Scheme 3F
Input	Module 1 $\boldsymbol{x}_1$	[1 1 0 0 0]	[1 1 0 0 0]	[1 1 0 0 0]	[1 1 1 1 0]	[1 1 1 1 0]	[1 1 0 0 0]
	Module 2 $\boldsymbol{x}_2$	[0 0 1 1 0]	[0 0 1 1 0]	[0 0 1 1 0]	[0 0 1 1 0]	[0 0 1 1 0]	[0 0 1 1 0]
	Module 3 $\boldsymbol{x}_3$	[0 0 1 1 1]	[0 0 0 0 1]	[0 0 0 0 1]	[0 0 0 1 1]	[0 0 0 1 1]	[0 0 0 0 1]
	Lauch vehicle $\boldsymbol{I}$	[1 1]	[2]	[1 1]	[2]	[1 1]	[1 1 1]
	Lauch vehicle $\boldsymbol{s}$	[1 1 2]	[1 1 1]	[1 1 2]	[1 1 1]	[1 2 2]	[1 2 3]
	Altitude h / km	500	500	500	500	500	500
Output	$\mu_{\rm Net}$ / \$M	263.113 8	232.594 1	258.813 8	238.443 6	254.342 3	243.579 2
	$\sigma_{\rm Net}$/ \$M	80.539 1	77.563 6	76.039 4	78.617 9	77.747 3	81.285 6
	μ_C / \$M	242.668 5	204.915 0	225.785 8	213.900 4	237.051 1	247.192 4
	σ_C / \$M	37.637 3	35.281 1	31.695 2	31.655 3	42.509 6	32.447 2

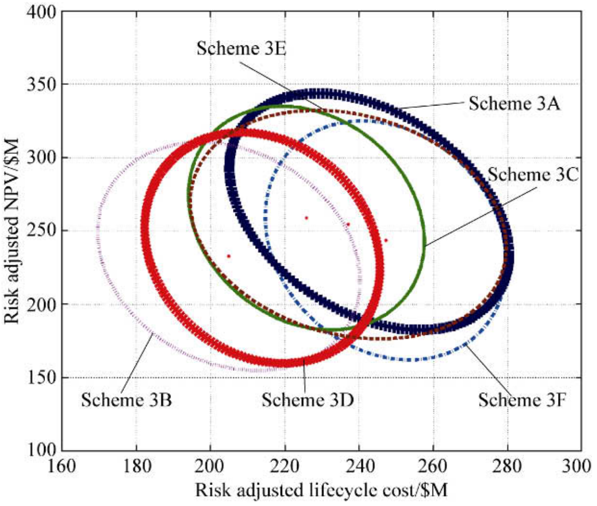

Fig. 7 MCS scatter plots of six three-module fractionated spacecraft design schemes.

The results show that with the same module composition, e.g. the pair of Scheme 3B and Scheme 3C, and the pair of Scheme 3D and Scheme 3E, multiple-launch schemes tend to achieve more risk adjusted NPV than single-launch schemes, but the risk adjusted lifecycle cost increases as well. It complies with the expectation that modules launched in separate batches can reduce launch failure risk and corresponding economic loss. The results also show that the standard deviations of NPV among the six schemes are almost at the same level, but the differences in standard deviations of cost are significant, especially between Scheme 3C and Scheme 3E where the relative difference almost reaches 30%. The same degree of difference is also observed between Scheme 3D and Scheme Scheme 3E. The simulation results show that schemes with more launch batches and more components onboard each batch tend to have higher cost standard deviations, as shown is Scheme 3A and 3E. Although Scheme 3F has the largest number of launch batches, only one or two components are carried on each batch, so the failure of single launch would not lead to large loss of modules/components. As the standard deviation represents the variation/risk degree associated with the scheme, it is straightforward that lower standard deviation is useful to decision makers given the same level of mean cost and NPV. From this perspective, it can be stated that Scheme 3C is preferable to Scheme 3E as the ellipse for Scheme 3C is nearly fully contained within the ellipse for Scheme 3E, meanwhile the mean of risk adjusted NPV of Scheme 3C is larger and the mean of risk adjusted lifecycle cost is smaller. The comparison between Scheme 3C and Scheme 3E indicates that it is possible to find a design scheme which is better than another in all assessment criteria. This is essentially a multi-objective optimization problem with each assessment criterion as an objective, and the non-dominate Pareto optima can be identified and treated as candidates for final decision-making based on decision makers' preference settings.

6. Conclusions

1) The assessment method for fractionated spacecraft is studied in this paper, and an assessment tool is developed based on lifecycle simulation under uncertainty driven by modular evolutionary stochastic models. With the modular classes as bricks, different archit- ectures of fractionated spacecraft can be realized and the corresponding lifecycles can be simulated, based on which assessment metrics, e.g. means and standard deviations of risk adjusted lifecycle cost and NPV, can be obtained to facilitate comprehensive assessment. Furthermore, this assessment tool can also be used to implement trade-off between multiple schemes and design optimization.

2) A case study is carried out to investigate the fractionated spacecraft for a hypothetical earth observation mission with the proposed assessment tool, and the results show that generally fractionated architecture is more advanced than its monolithic counterpart, and schemes with higher fractionation degree can provide higher risk adjusted NPV, but lifecycle costs are also more expensive. The standard deviations of both NPV and cost also tend to increase with higher fractionation degree, which is not desirable as it means that the risks associated with NPV and cost increase under uncertainty effect. This phenomenon can be plausible as more modules and launch batches lead to more chances of failures which contribute to the variation in benefit and cost, but this diverges from the advantages of robustness as the fractionated spacecraft advocators boast of. We presume that with the progress in module standardization and mass production, robustness can be improved by rapid response to uncertainties which can greatly reduce interrupted mission service time. With the strategy that can anticipate module failure and launch replacement module prior to its predecessor's failure, no gaps in service can be assured, so that variation of benefit can be further reduced. The preceding conclusion is drawn from the results of the specific case study in this paper dedicated to a hypothetical earth observation mission. More case studies should be implemented so as to summarize more general rules for fractionated spacecraft design.

3) The sizing models, lifecycle cost and NPV models studied in this paper are fundamentally based on the existing small satellite sizing and cost models with myriads of simplifications and assumptions, which need further rigorous work to improve the model accuracy with development in research of fractionated spacecraft and more information available about the enabling technologies for fractionated architecture. In this paper, only the uncertainties directly related to the spacecraft mission are considered. More uncertainty issues, e.g. schedule slip, market uncertainty, funding change, etc., should also be addressed in the future.

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Biography:

YAO Wen received B.S. and M.S. degrees from College of Aerospace and Materials Engineering, National University of Defense Technology in 2005 and 2007 respectively, and currently is a Ph.D. candidate there. Her main research interests include uncertainty-based multidisciplinary design optimization and its application in spacecraft system design.
E-mail: yaowen@nudt.edu.cn