A Value-Centric Design and Certification Architecture for Space Systems

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The rapid development of emerging concepts and technologies, e.g., modularity, standardization, and fractionation, has resulted in the miniaturization of satellites and simplification of mission design, as well as a move towards more responsive and economical systems. However, the current customized and labor-intensive design philosophy is not naturally appropriate for enabling the application of these concepts and technologies. Therefore, a value-centric architecture for spacecraft design and certification is proposed in this paper to address this need. Firstly, the characteristics of different types of spacecraft are compared and summarized. In parallel, a survey on the current design and certification frameworks of large and complex systems is carried out. Taking in the experience of the frameworks, a generic design and certification architecture is developed from a value-centric perspective. Apart from keeping the critical advantages from the traditional methodologies, the new approach is capable of solving the problems inherent themselves. The results of a preliminary case study clearly show that the approach proposed can effectively capture, analyze, and optimize the value of different system designs, appealing to the growth of the space market.

Key Words: Value-Centric Design, System Design and Certification

1. Introduction

The rapid development of emerging design concepts and technologies such as modularity, standardization, and fractionation, has contributed to the miniaturization of spacecraft and simplification of mission design, as well as a move towards more responsive and economical systems. However, the current space design philosophy, one of complex structure, long lifecycle, and high cost does not naturally fit with the advancement of these concepts and technologies.

Due to small quantity and customized design, certification by production has become one of the outstanding characteristics of the traditional design and development process. To ensure reliability, a large amount of time and money is invested on testing and evaluating. Such a tedious and inefficient process has incurred many problems, especially cost overruns and schedule delays.

As the US Government Accountability Office (GAO) pointed out, the overall cost of the current defense programs increased nearly 47% from the initial estimates. In terms of space programs, the US Congressional Budget Office (CBO) revealed that the average cost growth of the National Aeronautics and Space Administration (NASA)’s past programs was approximately 50%, wherein 20% of them experienced a cost growth above 90%. One of the most convincing cases is the well-known Space Shuttle Program. The demonstration and estimate work started early in 1972, when it was estimated at $43 billion in total, but it ended up an incredible $196 billion during the 30-year service life. Meanwhile, the cost per flight also boomed from $0.4 to $1.5 billion over time.

On the other hand, the average delay of the current defense programs was over 29 months, or more than 36%, as declared by the US GAO. Regarding NASA’s space projects, the schedule was delayed 11 months on average. Many reasons contribute to schedule delays, where most are intertwined with cost growth. Despite a medium mission with an initial cost of $650 million, the Mars Science Laboratory was estimated at $1.63 billion for preliminary design in 2006. Subsequently, its cost rose to $2.5 billion, and its launch was delayed for two years.

Therefore, a new value-centric approach for space system design and certification is proposed in this paper. It addresses the need of enabling the application of emerging concepts and technologies and overcoming common problems inherent in traditional design and certification methodologies.

The rest of this paper is organized as follows. Firstly, the characteristics of different types of spacecraft are compared and summarized. In parallel, a survey of the current design and certification frameworks of large and complex systems is carried out. Taking in the experience of these frameworks, a generic design and certification architecture is developed from a value-centric perspective. Apart from keeping the critical advantages from the traditional methodologies, the new approach is also capable of solving the problems inherent themselves. The results of a preliminary case study conducted show that the approach proposed can effectively capture, analyze, and optimize the value of different designs. In conclusion, this architecture appeals to the growth of the space market, embracing “smaller, faster and cheaper” spacecraft in the future.
2. System Characteristics

An overview of different system characteristics, such as mass, size, lifetime, cost, and flexibility, is summarized in Table 1, where the up green arrow denotes good, the horizontal yellow one denotes medium, and the down red one denotes bad. Please note that instead of showing an increase or decrease in tangible value, the directions of arrows indicate the direction of performance enhancement or degradation for different characteristics. The three types of space systems to be discussed are defined as follows:

1) Monolithic spacecraft are generally space systems with all functionally independent subsystems integrated on a single physical platform.

2) Constellations of identical spacecraft are clusters of near identical satellites flying in a certain formation, which can function independently from each other.\(^1\)

3) Fractionated spacecraft\(^2\) are heterogeneous clusters of wirelessly-interconnected modules, each capable of sharing and utilizing resources throughout the network.

It is also worth noting that there are two assumptions made before the subsequent analysis:

1) The analysis stands from the overall system level.
2) There is a similar subsystem technology level across different architecture types.

2.1. Mass & size

Mass and size are two basic physical properties playing an important role in the design and certification process of any category of space systems.\(^3\) Generally, traditional spacecraft are smaller and lighter than distributed systems at the system level, although individual subsystems might be larger or heavier. Distribution or fractionation leads to dual effects on the system characteristics of mass and size. On one hand, distributed systems suffer the mass penalty from the interfaces of power, communication, and so on. On the other hand, some individual modules of distributed systems tend to be smaller and lighter, as each module does not need to perform full capabilities to cover the entire system. For instance, the fractionation of payloads will probably result in significant shrinking of the attitude and orbit control system.\(^4\)

The different characteristics of mass and size represent different design philosophies and system requirements. Monolithic spacecraft are typically complex with a long development cycle, which used to be the trade-off for higher returns on investment and lower risk throughout the mission lifecycle. Distributed systems can increase the possibility of low complexity, a rapid design-build-test development cycle, and the use of advanced technologies, which are the enabling factors of the responsive space paradigm.\(^5\)

2.2. Lifetime

Lifetime is the length of time for which a device, vehicle, or system is intended to perform its function.\(^6\) The three types of lifetime discussed are defined as follows, and the characteristics for different types of systems are compared in Table 2:

1) Mission lifetime is the duration of a space mission.
2) Orbit lifetime is the length of time for a spacecraft to stay in its mission orbit.
3) Subsystem lifetime is acceptable period of use in service for a subsystem.

System design philosophy also plays a significant role in the mission lifetime characteristic. Driven by stakeholders’ desire to maximize the return on investment, extending the design lifetime is popular in the space industry.\(^7\) The surveys conducted by Futron Corporation have shown that\(^8\) the average lifetime of communication satellites increased by 38% from 1990 to 2002, as well as another 25% excess of their actual service lifetime.

In monolithic spacecraft, reliability is strengthened by the prevention and duplication of critical components. Each subsystem has a rather long lifetime, no less than the mission lifetime. Meanwhile, monolithic systems tend to be launched into a relatively high attitude orbit for long-term rewards.

Constellations of identical spacecraft are likely to have a longer mission lifetime. This is because each satellite can be replaced by a new one to progressively achieve system updating; for example, GPS II has been updated into GPS III while maintaining continuous service.

Thanks to the fractionation of different functionalities, different modules of fractionated systems are not physically interconnected anymore. Under this condition, subsystems can be designed, developed, tested, and launched separately, reducing the development and deployment of each module. Thus, replenishment and updating activities can be effectively and economically performed to keep the mission lifetime of distributed systems prolonged from a technical perspective.

2.3. Cost

The lifecycle cost of a space mission architecture, which represents the total mission cost from planning to the end of life, can be divided into three major segments\(^9\); the characteristics of which are compared for each type of system in Table 3.

1) The research, development, test, and evaluation (RDT&E) cost consists of analysis, design, and test in the nonrecurring phase, conventionally including prototype
flight units and one-time ground station costs.

2) The production and deployment (P&D) cost incorporates the cost of producing flight units and launching them, realizing the first flight-qualified satellite with full operational capabilities.

3) The operations and maintenance (O&M) cost covers ongoing operation and maintenance costs including spacecraft unit replacement and software maintenance.

The traditional system design enlarges the system scale to maximize the value/cost ratio and extends the system lifetime to minimize the annual running cost, making the system larger, more complex, and more expensive. Consequently, mistakes are extremely costly for traditional systems, and any potential failure or technology obsolescence may incur the disastrous breakdown of an entire system or imply the requirement of on-orbit servicing. For example, the Space Shuttle Challenger disaster is believed to have cost $12 billion and taken 32 months to recover the flight service.20

Constellations of identical spacecraft turn system redundancy from the component level to the satellite level. This change increases the development cost but decreases the lifetime operations cost.

The effects of fractionation on cost characteristics are threefold. Firstly, the initial production cost of fractionated spacecraft is typically high as a result of the mass penalty of extra wireless transceivers, as Mathieu and Weigel have demonstrated.21,22) Secondly, complex integration, assembly, and test problems do not exist in fractionated spacecraft since all of the modules are manufactured and tested independently. Finally, large quantities of distributed systems make it necessary for mass production or commoditization, which in turn cuts down the total production cost of the mission.

Furthermore, operating and launching a cluster are two cost characteristics yet unknown for distributed systems. On one hand, separate launches may increase the cost. On the other hand, new concepts such as small and responsive launch vehicles,21) piggyback, and rideshare launches can also prevent the launch cost from sharp growth.

### 2.4. Flexibility

Flexibility refers to the ability of a system to change on demand or adapt to diversification. It represents the scope of options to alter a current system in response to multiple unforeseen circumstances. The flexibility of a spacecraft consists of four main attributes, exhibited in Table 4,23) and their characteristics are compared in Table 5.

The long research, development, and production cycle of traditional spacecraft is doomed by its customized design and certification process, which draws the essential impact on system flexibility in two ways. Firstly, it prevents a space system from reusing the elements already launched, showing limited maintainability, scalability, and upgradeability with the serious waste of substantial in-orbit infrastructure resources. Secondly, it restricts adaptation to potential changes in user demands, mission requirements, available technology, and space environment, which may cause a catastrophic outcome for the spacecraft.

Constellations of identical spacecraft enable the capability to reconfigure the system or replace the failed satellite, in contrast to the nearly unchangeable monolithic spacecraft.

The fractionation of system functionalities, allowing the design of some elements to be postponed to later in the lifecycle, provides fractionated spacecraft more degrees of freedom to unpredictable changes or risks.24) Throughout the lifetime, it is easier to scale up or down capabilities by adding or removing individual payloads or resource modules according to changing demands. When any technology becomes obsolete or a certain module fails, only the relative module needs to be replaced. Moreover, a single module failure will not likely destroy the entire service, and only degrade system capability to some extent.

### 3. Survey of Design & Certification Frameworks

A survey of current design and certification frameworks for large and complex systems was carried out (i.e., structure shown in Fig. 1), which can be utilized as a significant reference for developing a generic design and certification architecture for innovative space systems associated with the studies of system characteristics.

Overall, the International Council on Systems Engineering (INCOSE) design and certification framework is described as a general baseline of these frameworks. NASA and European Space Agency (ESA) frameworks are tailored for spacecraft, providing the comprehensive understanding of space engi-

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Table 3. Comparison of cost characteristics for monolithic spacecraft, constellations of identical spacecraft, and fractionated spacecraft.

| Characteristics | Monolithic | Identical | Fractionated |
|-----------------|------------|-----------|--------------|
| RDT&E cost      | ↓          | ↓         | ↑            |
| P&D cost        | ↑          | ↓         | ↑            |
| O&M cost        | ↓          | ↓         | ↑            |
| Total cost      | ↓          | ↓         | ↑            |

Table 4. Breakdown of the flexibility characteristics of spacecraft.

| Characteristics | Monolithic | Identical | Fractionated |
|-----------------|------------|-----------|--------------|
| Maintainability | ↓          | →         | ↑            |
| Scalability     | ↓          | →         | ↑            |
| Upgradeability  | ↓          | →         | ↑            |
| Adaptability    | ↓          | →         | ↑            |
| Flexibility     | ↓          | →         | ↑            |

Table 5. Comparison of flexibility characteristics for monolithic spacecraft, constellations of identical spacecraft, and fractionated spacecraft.

| Characteristics | Monolithic | Identical | Fractionated |
|-----------------|------------|-----------|--------------|
| Maintainability | ↓          | →         | ↑            |
| Scalability     | ↓          | →         | ↑            |
| Upgradeability  | ↓          | →         | ↑            |
| Adaptability    | ↓          | →         | ↑            |
| Flexibility     | ↓          | →         | ↑            |
neering and an excellent reference for spacecraft design process. The Department of Defense (DoD) and the Ministry of Defense (MoD) frameworks are generally used in defense acquisitions for medium-scale production, offering another systematic perspective for system design and certification. While all of the above processes are internal (certification and design organization are joint), the subsequent Federal Aviation Administration (FAA) and European Aviation Safety Agency (EASA) processes are external examples (i.e., certification organization is independent from design organization), particularly for large-scale manufacturing, which are appropriate references for innovative concepts and technologies.

3.1. General design & certification framework

Specific design and certification processes vary according to different missions or products, but one of the widely used generic frameworks is explicitly described by INCOSE. This framework is summarized below.

In the exploratory research phase, the critical outcome is to acquire a clear understanding of the users’ needs, an accurate evaluation of the current technology readiness level, and a rough estimation of the mission cost and schedule. A large amount of creative work is executed to develop new concepts as a starting point of the project.

Alternative designs and the corresponding demonstration of systems, subsystems, and key components are identified in the concept phase, and associated with the users’ expectations and requirements. The baseline design selected for the system, subsystems, and key components is further modified, built, verified, and validated throughout the development phase. Meanwhile, the management strategies of the mission cost and risk are also optimized and refined.

Subsequently, the system-of-interest based on the baseline design is manufactured in the production phase. Sometimes product modifications may be applied to resolve manufacturing problems, reduce manufacturing cost, or improve system capabilities.

Maintenance and support to keep the system offering continuous services in nominal circumstances are carried out in the utilization and support phase. Upon reaching the retirement phase, the system and corresponding services are safely removed from operation.

Throughout the development and modification of a system, verification and validation are two critical technical activities performed to examine the satisfaction of system requirements. System verification is conducted to comprehensively demonstrate that the system capabilities satisfy all of the requirements before the production and utilization phase. System validation is conducted to confirm the mission requirements and system implementation as an appropriate solution to the users’ requests.

3.2. Space design and certification framework

3.2.1. NASA design and certification framework

NASA has developed a typical framework for space de-
sign and certification, and applies it for both human flights and robotic missions. Under this framework, two major phases are defined as “formulation” and “implementation,” with a system approval gate between them. They are further divided into seven incremental phases, as shown in Fig. 2.

Prior to concept and technology development, various feasible mission concepts are explored in the Mission Concept Review (MCR), and feasibility verification and programmatic assessment are conducted as well.

In the concept and technology development phase, activities are performed to completely identify the functional, performance, and schedule requirements for the system in the System Requirements Review (SRR), undertake the required technical responsibilities, and make engineering management plans for the project downstream processes as the System Design Review (SDR) or Mission Definition Review (MDR).

During the preliminary design and technology completion phase, the major efforts focus on establishing the preliminary alternatives with the complete functions satisfying mission objectives and requirements, and culminate in the Preliminary Design Review (PDR). Both technical and engineering readiness of the system design are reviewed, assessed, and improved at the end of the design and fabrication phase (i.e., in the Critical Design Review (CDR) or the Production Readiness Review (PRR)). Before entering into integration, all of the preparations are examined in the System Integration Review (SIR).

In the system assembly, integration, test, and launch phase, the assembly, integration, testing, and launch activities are assessed during the following four reviews.

1) Test Readiness Review (TRR) confirms the system is ready for testing, and arranges the data acquisition, filtration, and governance.

2) System Acceptance Review (SAR) validates the completeness and maturity level of the entire system to satisfy the mission needs and expectations.

3) Operation Readiness Review (ORR) evaluates characteristics of the system and the procedures of the project.

4) Flight Readiness Review (FRR) analyses, tests, and verifies the readiness of the system for a successful and reliable flight, as well as subsequent flight operations.

In the operation and sustainment phase, the Post-Launch Assessment Review (PLAR) is performed to observe the status, characteristics, and capabilities of the spacecraft. The Critical Events Readiness Review (CERR) deals with the readiness of a project for critical mission activities, and the Post-Flight Assessment Review (PFAR) identifies and solves all of the anomalies appearing in the flight and operations tests. In the closeout phase, a system decommissioning plan is formulated and conducted, and a data analysis is presented in the Decommissioning Review (DR).

### 3.2.2. ESA design and certification framework

In parallel with NASA, ESA has also defined its own design and certification process consisting of six phases, offering another traditional paradigm.

Initially, the proposed system performance and relevant risk of alternative mission options are identified and assessed in the mission analysis/needs identification phase.

After maximizing the lifecycle value and minimizing the risk level, system architectures and mission operations are designed in greater detail in the preliminary definition phase, and further technical requirements and applicability are confirmed. This design is later optimized and confirmed in a detailed definition, production, and qualification testing phase. The relative technical implementation and risk level are also evaluated to support design modifications, resource allocation, and management strategies.

Throughout the utilization phase, mission operations are implemented within the acceptable risk level, and mission data is collected, transferred, and analyzed to meet mission objectives. Near the end of this phase, unless an extended

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[Fig. 2. NASA design & certification framework] (image reference)
mission is proposed, the disposal plan is formulated, demonstrated, and executed.

3.3. Acquisition design and certification framework

3.3.1. DoD design and certification framework

The US DoD has authorized an official design and certification framework for defense acquisitions.28 Based on the potential military application needs identified, the user needs and technology opportunities phase explores alternative concepts, available technologies, and resource constraints in a broad and collaborative way, thereby enabling development of a feasible and affordable system with the desired capabilities.

Starting from analyzing the selected concepts, system realization, and cooperative opportunities, the preliminary concepts are refined, the Technology Development Strategy (TDS) is developed, and the Analysis of Alternatives (AOA) plan is approved in the concept refinement phase. The complex and iterative process of technology identification, development, and demonstration is fulfilled and evaluated during the technology development phase, after system requirements have been refined. An Independent Cost Estimate (ICE) is prepared and an assessment of initial maturity of critical technologies is made to minimize cost and maximize effectiveness. System Development and Demonstration (SDD) needs to be sufficiently studied before reaching an affordable, useful, and mature technology.

In the SDD phase, the detailed system with required capabilities is developed, system integration, safety, and operability are demonstrated, and both simulation-based and hardware test and assessment are executed to reduce integration and manufacture risks. Furthermore, the operations and capabilities proposed are assessed against the designed Key Performance Parameters (KPPs), associated with the corresponding design maturity in the Design Readiness Review (DRR). This review evaluates design deficiencies, testing sufficiency, risk assessment, failure effect analysis, and system reliability estimation.

After the capability to adequately and efficiently manufacture under low-rate production conditions is confirmed, full-rate production is achieved in the production and deployment phase, with the effectiveness and applicability verified by operational testing and assessment.

Meanwhile, a support program is carried out to satisfy the operational and performance requirements and keep system capabilities under the most cost-effective circumstances throughout the operations and support phase. At the end of its lifetime, the defense system needs to be disposed of following legal, regulatory, safety, and environment-friendly requirements and policies.

3.3.2. MoD design and certification framework

The MoD’s CADMID cycle describes the lifecycle design, certification, and management of acquisition systems from the initial identification of a gap in capability to the development, manufacture, usage, and disposal of the capability.29,30 This cycle consists of six major phases (concept, assessment, demonstration, manufacture, in-service, and disposal) and two key approval points (initial gate at the end of concept phase and main gate at the end of assessment phase).31,32

In contrast to the DoD, the MoD’s concept phase covers both user requirement identification and procurement option exploration, with the initial gate passed before moving to the next phase. In the assessment phase, the system assessment and project decision are made, ending up with approval for the main gate after iterative design and evaluation.

As the stage immediately before production, the demonstration phase turns the concept into reality, serving as the subsequent manufacturing phase that delivers the solution to the mission requirements within the cost and time limits. After system acceptance, the system is put into service, and the maintenance and update activities are performed during the in-service phase and until the disposal phase is reached.

3.4. Aviation design and certification framework

3.4.1. FAA design and certification framework

The FAA formulates one of the standard product design and certification frameworks for the aviation industry,33 which consists of five main phases, as shown in Fig. 1. It is noteworthy that this framework is an external process in that the certification organization is independent from the design organization, whereas those discussed above for the space industry are joint.

In the concept design phase, the applicants get to the point of developing a new feasible concept, and the FAA conducts the certification fundamentals covering methods of demonstrating compliance and preliminary risk estimation, as well as corresponding policies and research materials; all contributing to formation of the initial Project-Specific Certification Plan (PSCP).

Subsequently, the definition of the new product is identified with potential risks, and a mutual agreement to perform the product certification process is reached in the requirements definition phase. The compliance planning phase completes the final PSCP, enabling the responsible organizations to possess and take advantage of it when arranging the entire product certification process.

All of the implementation activities (e.g., demonstrating compliance, verifying conformity requirements, recording compliance findings and documentation, approving type design and product, etc.) are executed in the implementation phase. Finally, the type certification activities are followed up by airworthiness certification, and closure activities are conducted in the post-certification phase.

3.4.2. EASA design and certification framework

The EASA Type Certification process offers another perspective of design and certification processes, especially for products requiring mass production,34 covering the steps shown in Fig. 3. It is worth noting that major certifications by the EASA are completed before fabrication, while the mode of certification through production is widely used in the space industry.

For new Type Certifications (TCs), the Design Organization (DO) submits and application to the EASA, which determines whether or not it is accepted; acceptance of which launches the Certification Program (CP). Once accepted,
the DO can start its own design work and prepare the type design documents. Compliance demonstration, ground and flight testing, data acquisition and analysis, and technical content, completeness, and readiness are all examined in the compliance, demonstration, and testing phases. The process ends with final approval from the EASA and the declaration and summary of compliance.

3.5. Summary

Due to the small quantity and customized design, certification by production has become one of the major characteristics of the current design and development processes in the space industry. In this design philosophy, much time and money is invested in testing and evaluating to ensure system reliability, which in return, incurs many problems in such tedious and inefficient processes; especially, cost overruns and schedule delays. On the other hand, this customized and complex design process does not fit with the rapidly expanding space market and the latest trend of the Operationally Responsive Space (ORS) proposed by the DoD.\(^3\)\(^5\)

Other design and certification frameworks such as the defense and aviation industries have offered different perspectives of design and certification processes, particularly for products requiring mass production. Under these frameworks, major certification of the system to be designed is completed before final manufacturing begins, which is the key distinguishing factor from the philosophy of certification through production in the space industry.

Since emerging concepts and technologies (e.g., modularity, standardization, and fractionation) have led satellites into the era of smaller, faster, and cheaper, a new design and certification architecture is urgently required to manage the problems inherent in traditional design methodologies and respond to growth of the space market. In the desired architecture, major phases of the typical space design and certification processes should be kept, associated with the design philosophy of manufacture after certification learned from other industries.

4. Value-Centric Design and Certification Architecture

4.1. Basic requirements and capabilities

In order to solve the problems inherent in traditional design methods and promote the application of emerging concepts and technologies, a new architecture for spacecraft design and certification is required to deliver the necessary capabilities such as the following.

1. Meet the design and certification requirements of both traditional and innovative systems

Instead of a customized and labor-intensive requirement-centric process focused on traditional systems, a generic design and certification process for both traditional and innovative systems needs to be developed. It should promote the use of innovative concepts and technologies (e.g., modularity, standardization, and fractionation). In this design architecture, the type of spacecraft will not be determined before the design and certification process starts, but it will be optimized based upon different requirements, leaving more degrees of freedom in the later detailed design.

2. Decouple mission, orbit, and component lifetimes

The coupling of component, orbit, and mission lifetimes is one of the bottlenecks of traditional design and certification methodologies. The design lifetime of any component or orbit is forced to be no less than that of the mission in this design philosophy. When coming to innovative systems, not all of the components need to remain active throughout the lifecycle thanks to the concept of fractionation. This enables the design lifetime of mission, orbit, and component to be optimized independently, according to different requirements. Therefore, the decoupling of these three types of lifetimes should be one of the key capabilities of the desired method.

3. Minimize cost overruns and corresponding schedule slippage

Problems such as cost overruns and schedule slippage result from the requirement-centric design philosophy of small quantity and customization, especially when system require-
ments fluctuate. Therefore, the desired design architecture should be driven by a quantitative system value that is proposed to prevent the problems inherent in traditional methodologies.

4.2. Description of architecture proposed

The potential growth of the space market is being stimulated by emerging design concepts and technologies such as modularity, standardization, and fractionation, which have lowered the difficulty of spacecraft design. To embrace these trends, a new design and certification architecture is developed to deliver the necessary capabilities and solve the problems inherent in traditional design methodologies. This has been realized based on the design philosophy of manufacture after certification, which was learned from other industries.

To achieve the necessary capabilities presented, the architecture desired is established from a value-centric perspective. The requirement-centric methodologies are sensitive to variations in requirements, while value-centric methodologies meet given constraints in pursuit of the maximum value. This quantitative design process can overcome the common problems incurred by the traditional customized and labor-intensive requirement-centric allocation process (e.g., performance uncertainty, cost overruns, and schedule slippage). The basic phases of the architecture are described in Fig. 4.

The need phase can be considered a pre-design phase in which various preparations for the upcoming design and certification are made. Major achievements in this phase are the same as traditional tasks, such as identifying the needs of users and stakeholders, assessing available space technologies, and estimating the rough cost and schedule.

In the concept phase, extensive research is carried out to develop a baseline mission concept, including various risks and constraints. Multiple concept and technology options are quantitatively assessed in order to refine and select the final solution for further development. Within the constraints of performance, cost, and time, the lifecycle risks are minimized to an acceptable level in support of the feasibility demonstration of the mission.

From this phase, the value-centric design and certification process starts. As shown in Fig. 5, the concept design, selection, and optimization are all driven by system value, which is integrated from the bottom to the top. The properties at the subsystem level (i.e., system level 4), that is, mass and reliability, are integrated into the system level (system level 3), which influences the characteristics of the following activities of system launch (system level 2) and mission operations (system level 1). Such properties or characteristics are later converted into budget dimensions using system value models; for example, mass can be converted into launch cost.

Eventually, the values of the four levels are integrated into system value, acting as the objective function of the selection or optimization process.

In the development phase, the mission solution selected is developed in detail. Key system design drivers are identified and optimized to reach the best solution within the available budget and time. Meanwhile, many trade-offs are made among different subsystems and components. Different from the prior phase, this phase is implemented at more-detailed levels; namely, a more accurate value model is built for system design, assessment, and optimization.

In the testing phase, samples of systems, subsystems, or components are produced for testing and evaluating. Instead of the conventional process of certification through production, testing is carried out to ensure the ability to deliver and manufacture the products. Modifications to the system value model can be made in response to the outcomes of testing, yet any change in the spacecraft requires sufficient assessment and convincing demonstration.

In the manufacturing phase, a process is defined before production of the space system. Modifications concerning manufacturing problems, cost reductions, or capability improvements are also cautiously assessed, demonstrated, and approved.

The utilization phase and retirement phase define all of the activities about maintenance, support, and retirement, keeping the system offering continuous and nominal service until the end of mission life.

4.3. Preliminary case studies

The function of the value-centric architecture proposed is to design the optimal configuration to achieve the best value given the value models. In this section, we conduct a preliminary case study to show how this architecture works, while
the detailed techniques and procedures can be found in other literature reporting our research.36,37) One of the simplest examples of value models can be found in Table 6,19,38) where value is considered as development cost. Adopting this objective function, the development cost of a space system can be minimized. Assuming that the capabilities of different system architecture types can be achieved at a similar level, the minimization of development cost is therefore equivalent to the maximization of overall system value. Other forms of the objective function or value can be launch cost, reliability, lifetime, or any property the users or stakeholders are interested in.

The abbreviations used here are, respectively, PLS for Payload Subsystem, TCS for Thermal Control Subsystem, EPS for Electrical Power Subsystem, TTC for Telemetry, Tracking and Command Subsystem, CDH for Command and Data Handling Subsystem, ACS for Attitude Control Subsystem, OCS for Orbit Control Subsystem, and IAT for Integration, Assembly, and Test.

One of the characteristics of the architecture proposed is enabling the use of emerging design techniques such as fractionation apart from traditional designs.

In terms of fractionation, the exchange of information, power, and force between modules is realized by the devices Wireless Sharing Subsystem (WSS). The mechanism of a WSS is similar to that of TTC but much less powerful since all of the fractionated modules are in the near field. Therefore, the cost fraction of a WSS can be reasonably assumed as 1.5%, far less than the cost of a TTC.

Once more than one WSS is required, a learning curve effect is also considered (i.e., a mathematical technique to account for productivity improvements as the number of units is produced).19) The accumulative average learning curve is typically 0.95 in the aerospace industry, the effect of which is shown in Table 7.

Having established the value models, the architecture proposed can be applied to seek the optimal design with the objective function exemplified by the minimization of development cost. The corresponding results are shown in Table 8, and the detailed techniques and procedures are illustrated in other literature reporting our research.36,37)

It needs to be clarified, first, that the architecture proposed does not force using emerging design concepts or technologies exemplified by fractionation, but introduces the possibility of fractionated design. The final solution is determined by system value regardless of the type of spacecraft, while traditional methodologies empirically design a system to meet the requirements.

The results show that neither monolithic design (1 satellite) nor fully fractionated design (7 satellites with all of the subsystems spatially separated from each other) achieves the best value. The solution with the minimum cost in the development phase is scattering the seven subsystems into three satellites. This is because such a design has a good balance between fractionation penalty (cost of subsystem fractionation) and IAT cost (cost of subsystem integration).

5. Conclusion

This paper proposes a new approach for spacecraft design and certification based on a value-centric architecture, enabling the application of emerging concepts and technologies.

Firstly, the characteristics for different types of space systems were compared and summarized. In parallel, a survey of the current design and certification frameworks of large and complex systems was carried out. Both acted as the references for developing a generic design and certification architecture for traditional and innovative systems.

Taking the experience of other industries into consideration, a generic design and certification architecture was developed from a value-centric perspective. Under the architecture, the design philosophy of certification though production is changed to that of manufacturing after certification. This quantitative design and certification process not only overcomes the common problems inherent in customized and labor-intensive requirement-centric allocation processes (e.g., cost overruns and schedule slippage), but also stimulates the growth of the space market.

Throughout the lifecycle, the value-centric architecture is used to design, analyze, and optimize the space system. Us-

| Subsystem/activity | Fraction of spacecraft bus cost (%) |
|--------------------|-------------------------------------|
| 1.0 PLS            | 40.0                                |
| 2.0 Bus total      | 100.0                               |
| 2.1 TCS            | 2.4                                 |
| 2.2 EPS            | 28.5                                |
| 2.3 TTC            | 15.4                                |
| 2.4 CDH            | 20.9                                |
| 2.5 ACS            | 22.5                                |
| 2.6 OCS            | 10.3                                |
| 3.0 IAT            | 14.0                                |
| 4.0 Total          | 154.0                               |

| Unit number | Total cost | Average cost |
|-------------|------------|--------------|
| 1           | 1.00       | 1.00         |
| 2           | 1.90       | 0.95         |
| 3           | 2.77       | 0.92         |
| 4           | 3.61       | 0.90         |
| 5           | 4.44       | 0.89         |
| 6           | 5.25       | 0.88         |
| 7           | 6.06       | 0.87         |

| Number of satellites | Cost fraction (%) | Type of spacecraft |
|----------------------|-------------------|--------------------|
| 1                    | 154.0             | Monolithic         |
| 2                    | 148.9             | Hybrid             |
| 3                    | 145.9             | Hybrid             |
| 4                    | 146.4             | Hybrid             |
| 5                    | 147.4             | Hybrid             |
| 6                    | 147.9             | Hybrid             |
| 7                    | 149.1             | Fractionated       |

Table 6. The development cost distribution per subsystem.19,38)

Table 7. Effect of a 0.95 learning curve.

Table 8. The development cost fraction of different designs.

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ing the architecture proposed, system value is the driving factor for spacecraft design and analysis, which is integrated from subsystems or more detailed levels. The properties of lower levels are integrated into those of higher levels until the overall system level, which influences the characteristics of spacecraft launch and mission operations. Such properties or characteristics of a space system and the corresponding space activities are converted into a uniform dimension of budget through different system value models; for example, mass can be converted into launch cost. The value of all four levels is eventually integrated into the overall system value, acting as the objective function for the selection or optimization process of system designs.

A preliminary case study was conducted to show how this architecture works, and a simple and typical example of value models presented. The results reveal that the approach proposed can effectively capture, analyze, and optimize the value of different designs.

In conclusion, the value-centric design and certification architecture proposed not only promotes the use of emerging design concepts and technologies, but also absorbs the critical advantages from traditional methods, embracing “smaller, faster and cheaper” spacecraft in the future.10)

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