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Functional Availability and Constellation Reliability Guidelines for Acquisition and Development of Space Systems

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Abstract

Mission Success Improvement Workshops (MSIWs) are collaborative industry and government efforts to address industry-wide space systems mission assurance challenges. Their charter is to develop recommendations and actionable best practice documentation to improve program execution efficiency and, ultimately, on-orbit mission success. This Aerospace technical report (ATR) is the result of an MSIW that addressed the need for improved reliability modeling methods and guidance required to support the transition from single (or few) satellite procurements to satellite constellation architectures. It builds on work documented in *Functional Availability (FA) Analysis* (ATR-2019-01877) [4]. A "sister" ATR, *Reliability Guidelines on Failure Rates for Space Electrical, Electromechanical, and Electronic (EEE) Parts and Units* (ATR-2024-02067) [2], was also produced by this MSIW to address the need to improve industry guidance for EEE part failure rate prediction methods due to the lack of guidance on the use of existing failure rate calculation tools and the increased use of commercial off-the-shelf parts.

Acknowledgments

This document has been produced as a collaborative effort of the MSIW. The MSIW forum was organized to enhance mission success processes and support disciplines through collaboration between industry and the government across the U.S. space program community utilizing an issue-based approach. The process is to engage the appropriate subject matter experts to share best practices across the community to produce value-added mission assurance guidance documentation. This document was created by multiple authors throughout the government and the space industry. For their content contributions, the following team members are acknowledged for making this collaborative effort possible:

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1. Introduction

1.1 Purpose

The goal of this document is to inform sponsors, acquisition authorities, and developers on the utility of functional availability (FA) and constellation reliability (CR) analyses as tools in delivering diverse missions that are realized by a constellation-level solution.

1.2 Background and Motivation

Historically, FA analyses of satellite constellations have been used to inform the launch scheduling process to plan and schedule satellite launches in both the near-term and out as far as 10 years (e.g. as used in the National Launch Forecast originally maintained by Air Force Space Command). They are also used by various organizations within the U.S. government (USG) to make acquisition schedule decisions and support budget requirements in the Planning, Programming, Budgeting, and Execution process. Key inputs to the development of FA analyses are the key performance parameters of the associated mission that are included in the Acquisition Program Baseline. Satellite initial deployment and replenishment planning is a challenging task. Traditional considerations included balancing just-in-time production or ground storage of spare satellites against the risk of constellation outages due to launch or satellite failures. Heritage acquisition approaches and requirements for high-reliability, space-qualified components have led to long production lead times for satellites and the random nature of launch and on-orbit failures make planning uncertain. This risk is usually mitigated by procuring spare satellites (either stockpiled on the ground or maintained on orbit) and by planning for some degree of overlap between current systems and the successor programs; but large inventories of expensive satellite spares and the overpopulation of satellite planes resulting from significant overlap between programs have been historical barriers within the USG to justify in a budget-constrained environment. This is especially true if heritage systems last longer than predicted. Additionally, the lack of consistent on-orbit updates to reliability data and the lack of relevant data sharing across mission areas, coupled with the lack of modern, up-to-date failure rate data in MIL-HDBK-217FN2 [1] and other handbooks, and lack of standardization across products and interfaces, has degraded the ability to accurately forecast satellite life.

The updated guidance in this document is part of a broader modernization effort targeted at improving and optimizing the utility of reliability and availability tools to meet the evolving landscape of the space industry as it strives to meet new missions with disaggregated, proliferated, or hybrid architectures. As has been demonstrated by some commercial entities (e.g. Starlink), these architectures enable moving away from some of the legacy challenges previously mentioned in this document, such as dependency on expensive individual assets with significant lead times driven by satellite-level component selection requirements and acquisition approaches. They also enable missions to operate in contested environments through fielding constellations with redundant systems and providing the ability for functional disaggregation. As reliability planning and specification migrates from a focus on individual satellites, or assets, to more constellation-availability approaches for providing resiliency (redundancy) to individual satellite loss and better reflects architectures that distribute mission functions across assets, it is important to start by defining FA success criteria for the constellation and then allocate acceptable satellite or CR requirements. A graphical representation of the difference in FA and CR is illustrated in Figure 1. The FA curve illustrates that once a constellation has been established, curves typically follow a sawtooth shape since the assets' reliability is a nonincreasing function, but new assets are added to the constellation via replenishment launches to replace the failed assets (or functions) and ensure the functional success criteria (FSC) are met within the specified probability of success (i.e., 0.90 in Figure 1). The CR curve illustrates a focus on a constellation's likelihood of achieving mission objectives for a specific point in time (e.g., mission life) without replenishment. Implementation of the modernized prediction methodologies contained in *Reliability Guidelines on Failure Rates for Space Electrical, Electromechanical, and Electronic (EEE) Parts and Units* (ATR-2024-02607) [2] enable improved and more accurate asset-level models to be incorporated as part of the overall constellation-level analysis of assessing CR and FA. This will reduce the historically observed over-conservatism of predictions that have made constellation and replenishment planning challenging from a reliability perspective. The purpose of both of these documents, utilized together, is to improve the usefulness of reliability metrics to enable optimized (cost, schedule, and performance) solutions for future space mission requirements.

Another modernization effort, *Mission Assurance Guidelines for Mission Risk Classes and Do No Harm (DNH) for Space Vehicles* (ATR-2023-01889) [3], updated the characteristics of mission risk classes and, relevant to this effort, included the delineation between the overall class of a mission from the class of an individual asset within the architecture (i.e., a constellation of lower mission class assets that can achieve a higher overall mission class at the constellation level). The implementation of this guide will lead to architectures where acceptable mission class (i.e., Class A–D) at both the constellation (or mission) level and asset level is determined by trade studies. These trade studies will determine the most cost- and schedule-effective asset design that meets reliability requirements at design life and in turn meets the functional availability requirement of the constellation (with consideration for launch vehicle (LV) reliability, number of assets per LV, and launch cadence). Any future acquisition, regardless of mission class, should consider leveraging this guideline to achieve mission success.

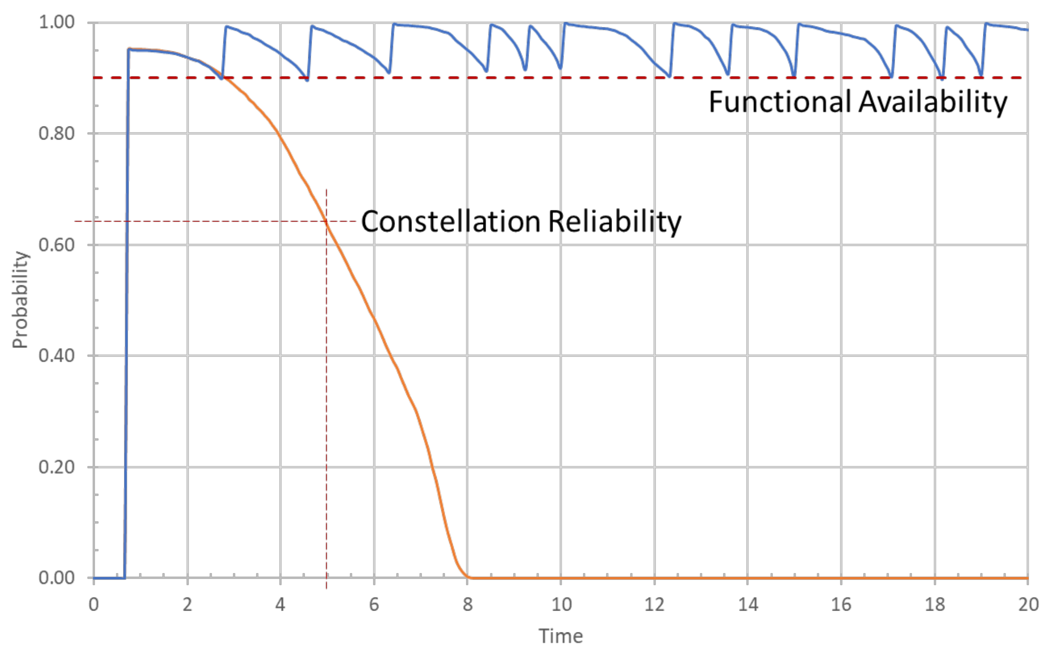


Figure 1. Comparison of functional availability (FA) and constellation reliability (CR).Both CR and FA measure the probability of a constellation meeting its functional success criteria (defined below). FA can be thought of as the extension of CR through replenishment launches.

1.3 Overview

Definitions are provided for all the key terminology and context is provided to ensure alignment of nomenclature throughout the guide. Section 2 of this document introduces the front end of the FA and CR processes related to the trades and decisions required to inform the initial constellation architecture. CR uses are introduced when looking at the constellation without considering replacement of failed satellites. FA is also introduced as a means for using CR as a driving requirement in constellation and asset design.

Examples of both FA and CR approaches are discussed in Section 3 of this document. They include examples of how the CR and FA may be used to optimize an architecture at either the asset design level or by reconsidering number or asset replenishment rate. Section 4 provides a summary and recommendations for the future.

1.3.1 Out of Scope

This document is not a detailed discussion of FA modeling tools available to help define satellite reliability requirements, launch schedule, and necessary satellite spares. See *Functional Availability (FA) Analysis* (ATR-2019-01877) [4] for a detailed discussion of FA. It does not address LV reliability or make recommendations on LV contributions to availability. Operational availability (A_O) is also often specified for individual assets and focuses on recoverable downing events such as single event upsets, calibration, redundancy switching, etc. This document does not address guidelines for developing A_O. See AFI 10-602, *Determining Mission Capability and Supportability Requirements*, Attachment 9 – Space, Space Surveillance, and Missile Warning Systems [5] for a detailed discussion.

1.4 Definitions

1.4.1 Availability

Availability is the probability that a system is in an operable and committable state when called upon at an unknown time. Availability differs from reliability primarily through the inclusion of maintainability considerations. For space systems, availability is assessed with two distinct metrics: functional availability (FA) and operational availability (A_O). Maintainability in the context of FA constitutes acquisition and launch of replenishment spacecraft or spares, assessed over time scales from years to on the order of decades. Maintainability in the context of A_O constitutes autonomous or ground-commanded recovery from outages (e.g., transient events), usually assessed over a smaller window of time (e.g., 30-day period).

1.4.2 Constellation

A constellation is a mission composed of two or more assets (which can be homogeneous or heterogeneous) placed into a specific orbit(s) for the purpose of serving a common objective.

1.4.3 Constellation Availability

Constellation availability is synonymous with functional availability (FA).

1.4.4 Constellation Reliability (CR)

CR is the probability that a related collection of assets, or specific features of those assets (e.g., sensors), will perform its intended functions adequately for a specified period of time without failure. CR could be assessed at the specific mission function level across the constellation (i.e., not assessing as a Boolean asset, functional or not functional) and is expected to degrade over time at some nonuniform rate. A viable CR metric is a subset of FA and is the appropriate probabilistic aggregation of a collection of asset probabilities acting together to achieve mission objectives. When CR lacks a closed-formed expression, Monte Carlo simulations are often implemented. Single-asset system-level reliability (often both the bus and payload inputs for a satellite) is an essential input to the CR analysis. Assets often degrade over time, so it is imperative to define what constitutes functioning adequately. It is also imperative that the period of time considered for CR be well-defined.

1.4.5 Functional Availability (FA)

FA is the probability of a constellation meeting its functional success criteria (FSC), expressed as a function of time. FA is also known as constellation availability. FA is distinct from operational availability (A_O). FA is driven by the risk of permanent satellite failures, quantified in satellite reliability predictions, that require activation of a spare on-orbit satellite or launch of a replenishment satellite to restore constellation success, while A_O is driven by temporary (i.e., transient) downing events (e.g. side swaps for redundant sides, ground intervention to resume mission function) impacting an assumed fully-populated constellation. As the complexity or number of assets and launch cadence increase in a constellation, the analysis effort (i.e., time and resources) to determine an FA value increases. FA often lacks a closed-formed expression and is typically executed via Monte Carlo simulations due to the complex nonlinear nature of the competing constraints. System-level reliability (often both the bus and payload inputs for a satellite) of each constellation asset and the replenishment cadence for failed constellation assets are essential inputs to the FA analysis. In computing FA, it is important to consider modeling degraded capabilities of assets and how they contribute to meeting the FSC. Due to the complexity of the FA analysis, it is often performed by the constellation control authority or through entities independent from the constellation asset providers. Probability of launch success is an essential input to FA analysis.

1.4.6 Functional Success Criteria (FSC)

FSC are usually determined from operational mission objectives often defined by the constellation control authority (i.e., the customer or sponsor), in consultation with the contractor, and simply are the number of assets required to meet constellation functions or mission objectives that are desired (i.e., these criteria must be met to classify the constellation as operational). FSC (e.g., number of assets required in each plane) are normally determined by the performance of assets in a constellation to meet a functional (e.g., coverage) requirement from a customer. FSC can be defined at various levels including at the constellation (typical), at a subconstellation characteristic (e.g., for a particular plane), for the asset itself, for a set of payloads or an individual payload, or possibly for a vehicle subsystem. There can be multiple levels of FSC to satisfy users with differing degrees of priority (see ATR-2019-01877 Section 3.1.1 [4] for a detailed example). Examples of possible summary-level FSC by mission-type are as follows:

- Navigational FSC – percent of global coverage to achieve mission objectives and this coverage
- Surveillance FSC – specific number of contacts within 24 hours in a particular area of interest
- Communication FSC – sufficient capability to meet desired communication throughput
- Weather FSC – the average revisit time for a number of sensors

It is imperative that FSC be well-defined to ensure viable assessment of the FA metric.

1.4.7 Heterogeneous Constellation

Assets can either have different designs, provide different functions, or provide the same functions with different designs.

1.4.8 Homogenous Constellation

All assets are the same design and can provide redundant functions.

1.4.9 Monolith

A monolith is a mission composed of a single asset capable of meeting objectives.

1.4.10 Proactive Replenishment

Proactive replenishment is a scheme in which assets are added to a constellation on a predetermined cadence. The cadence is independent of current constellation health. The scope can range from a single asset to an entire constellation replacement.

1.4.11 Reactive Replenishment

Reactive replenishment is a scheme in which the launch cadence of a constellation is adjusted as on-orbit assets fail. In this reactive case, constellation proposals must address the assumed response time between an observed on-orbit failure and its replacement.

1.4.12 Reliability

Reliability is the probability that an element will perform its intended function for a specified period of time under stated operational and environmental conditions.

1.4.13 Satellite

A satellite is an individual asset within a constellation.

2. Selection of the Functional Availability or Constellation Reliability Approach

2.1 Trade Space for Constellations

Space mission architectures can be characterized as either constellations or monoliths. Evaluating the optimum architecture for a mission requires developing the specific success criteria factors required to achieve a successful mission. From an asset-level reliability perspective, these success criteria have historically prescribed design and performance requirements in the context of meeting a probability of success at a specific design life. This includes driving specific redundancy schemes into the asset-level design. Asset-level analysis is a cornerstone of all constellation-level analysis discussed in this document. FA and CR are modeling tools that enable architects to trade relative risk and design concepts for constellations to achieve the necessary functions to accomplish the mission. This includes using the related modeling framework to trade the number of assets from one mission class baseline (with related design and reliability details) with another to assess candidate architectures (e.g., Can a large constellation of Class C assets better achieve mission objectives than a small constellation of Class B assets within the allocated budget and schedule?). A detailed and insightful discussion of this trade process including examples trading from monoliths to constellations, trading across mission class, and sizing constellations using FA is captured in *A Methodology for Reliability Assessments of Arbitrary Satellite Constellations* by B. Merrel et al. [6].

Once a constellation solution is identified (versus a monolith) from the initial mission architecture process, the work to define the related mission requirements at the constellation level begins. Early on in concept and initial requirement generation for a mission, it is important to focus more on the mission-level (constellation) performance instead of the individual asset performance. Constellation FA analysis allows for vastly different architectures to meet similar requirements at the mission level. This is a significant benefit of using constellations of assets to complete a mission that FA analysis takes advantage of and offers predictive outcomes. For this reason, focusing on the performance of an individual asset (e.g., individual asset probability of success requirements) in the requirements space constrains the constellation trade space, and reduces some of the advantages of constellations.

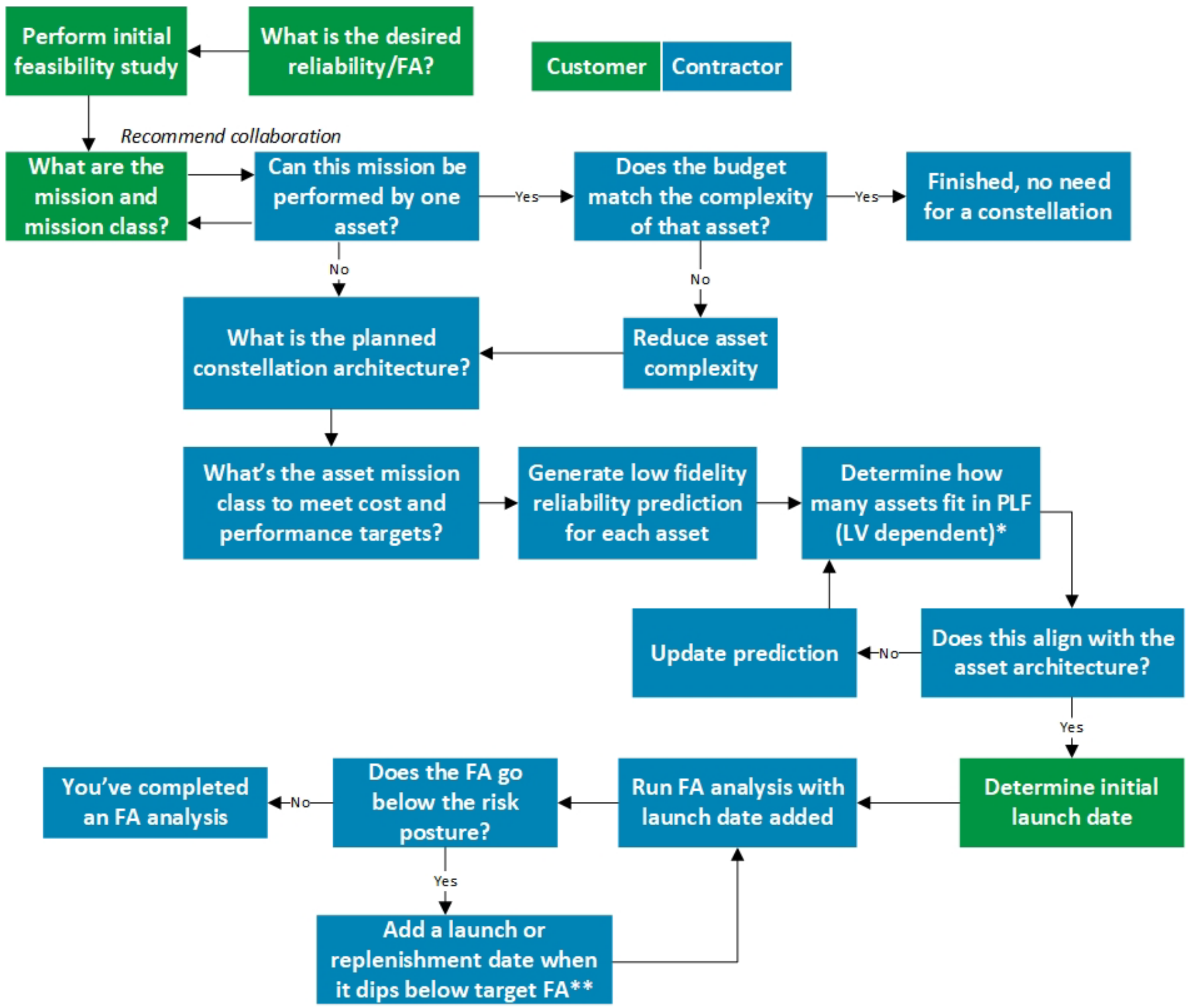
CR and FA analysis involves an iterative process that includes involvement of the contractor and customer reliability subject matter experts (SMEs), systems engineering SMEs, and other SMEs across engineering disciplines. Since these analyses are an iterative process, constant communication is needed between these parties to ensure that the proper assumptions are captured and effectively used in the analysis. As a reference, the constellation design process is further detailed in chapter seven of *Space Mission Analysis and Design* by J. Wertz and W. Larson [7].

The trade space for CR and FA calculations involves the reliability of the individual assets that comprise the constellation, FSC (e.g., how many assets and which orbits are needed for the constellation to achieve performance goals), the concept of operations (CONOPS) of the mission (which factors in how downed assets are replaced), the launch cadence of the establishment and replenishment of the constellation, mission funding, and the overall risk posture of the mission. Table 1 shows a more detailed layout of the various components that make up the CR and FA trade space.

Table 1. Functional Availability Trade Space

Aspect of Mission	Trade Space Considerations	
	Mission Inputs	**Functional Availability Inputs**
Mission class of individual asset	• Asset complexity • Mission significance • Mission lifetime • Acquisition costs • Launch constraints • Available budget	• Reliability prediction per asset • FSC
Constellation make-up	Different types of assets in the constellation (homogenous or heterogenous asset architecture)	Reliability prediction per asset or asset type
Planes these assets are distributed across	CONOPS	Number of assets required per plane for mission requirements (number of homogenous or number of each type of heterogenous asset)
How are downed assets replaced	CONOPS	• Which assets can replace the downed assets • Relevant replenishment plan
Establishment/ Replenishment schedule	• Lead times for asset development and production • Funding (customer and contractor inputs) • Launch constraints	• Number of assets per launch • Change to asset function (i.e., retasking) • Launch dates • Launch vehicle used
Constellation FA required	Mission risk posture	Target threshold for analysis

These inputs are implemented in the FA and CR process flow at various stages. The iterative nature of the FA and CR analysis process is captured in Figure 2.



Notes:
*Constellation assets can be homogeneous or heterogenous. FA and CR analyses apply to both configurations.
**Launch date factors in many different facets, including but not limited to: funding limitations, production lead times, supplier lead times, AI&T schedule (with margin), etc. Replenishment could occur at the functional level without a new launch (e.g., if there is on-orbit sparing).

Figure 2. Functional availability (FA) and constellation reliability (CR) process flow.

As the trade space is more fluid (i.e., understanding importance of and sensitivity to the various elements being considered as captured in Table 1), more FA and CR trades are performed until the trade space solidifies. For this reason, it is very important that FA and CR analyses be performed during the early stages of a program to help define the optimal (cost, schedule, and technical) system architecture.

The FA process has three main iterative loops in the development of the analysis. These are a design iteration loop (i.e., size, weight, and power [SWaP] trade) to determine how many assets can be launched at a time with a given asset architecture, an FSC loop to iterate over alternative asset architectures (orbits and the minimum number of operational assets to achieve constellation performance requirements), and a loop to determine the replenishment schedule needed to meet the target mission FA.

As SWaP trades begin on a program, it's recommended that the engineer performing the FA analysis be involved with these trades, as asset architecture plays a large role in the generating an FA analysis. When generating the replenishment schedule, there are many factors that are involved to determine the next available launch date, including funding limitations; production lead times; and assembly, integration, and test schedule. It is recommended that the launch schedule be developed hand in hand with the systems engineering team for the missions, such that the replenishment schedule is feasible given these constraints.

3. Implementation Functional Availability and Constellation Reliability Analysis: Examples

The execution of a CR or FA (or both) analysis can be nuanced and complex, so a number of examples follow to illustrate the common analysis inputs and hurdles to achieve a viable CR or FA metric. See *Functional Availability (FA) Analysis* (ATR-2019-01877) [4] for a detailed discussion on performing FA calculations and associated tools. This section will explore various CR and FA examples that reflect the closed-loop nature of the decision flow diagrams illustrated in Section 2.1. The concept of mission class is introduced in these examples to illustrate that all constellation missions can realize benefit from FA and CR analyses (i.e., these tools hold value across the spectrum from operational to demonstration missions). While these examples are notionally characterized as conventional Class A/B or Class C/D programs with associated risk profiles [3], the process execution of a CR or FA analysis is agnostic to the program class designation.

3.1 CR Analysis Examples

CR is the probability that a related collection of assets will execute its intended functions adequately for a specified period of time without failure. The CR metric is generally measured at a particular time of interest, which is often the desired nominal mission length. Four CR examples help to illustrate how a CR requirement might be achieved, which implies how that same requirement could have been originally derived. In the examples, considerations are made to improve the CR when needed that include both asset-level design changes and constellation composition (size). It is important to factor in the ramifications of cost, schedule, mass, etc. that could result in threats to the constellation launch cadence or capacity per launch in executing the trades (i.e., if the SWaP increases beyond the available capacity per launch). These examples are meant to delve into the various aspects of a typical CR analysis effort, but given all the possible nuances associated with the development and deployment of a constellation of assets, they are notional and not meant to be exhaustive (e.g., other considerations include fuel limitations and mission functions with different design life requirements).

3.1.1 Notional Program Class A/B Examples

For the mission, a single asset could not achieve the mission goals while a constellation of five fairly large geostationary Earth orbit (GEO) assets could consistently meet the mission objectives. Given that each asset is substantial and requires its own launch vehicle to achieve orbit, this example likely represents the Class A/B program risk spectrum. This example has the desired design attributes delineated in Table 2. The objective is to determine if the CR requirement of ≥0.70 at five years can be met and if not, determine likely asset or constellational design changes to ensure the CR metric is achieved.

Table 2. Class A/B CR Initial Design Attributes

Attribute	Criteria
CR requirement	≥0.70
Desired mission length	5 years
# of planes	1
Assets per plane	5
Total # of initial assets	5
# of launches to initialize	5
# of replenishment launches	0
# of assets needed	5
Asset checkout time	3 months

The assets are assumed to be identical and a critical input to the CR analysis will be the asset reliability, which is illustrated as Figure 3. This reliability model likely was derived from reliability analysis, empirical data, or estimated via comparison to similar vehicles (i.e., surrogacy). Analysis by The Aerospace Corporation in *2019 Satellite Lifetime Study* (TOR-2019-02620) [8] has shown that satellite lifetimes typically follow a quantifiable distribution. This high-level example uses a Weibull-Gaussian reliability model to represent the reliability risk of a single asset. The Weibull portion of the model (blue line within Figure 3) accounts for the likely random failures that may occur during the mission while the Gaussian portion (orange line within Figure 3) represents wear-out failures (e.g., battery cells or photovoltaic cells decreasing their efficacy over time). The green line within Figure 3 is a composite reliability model of the likely random (Weibull) and wear-out (Gaussian) failure modes.

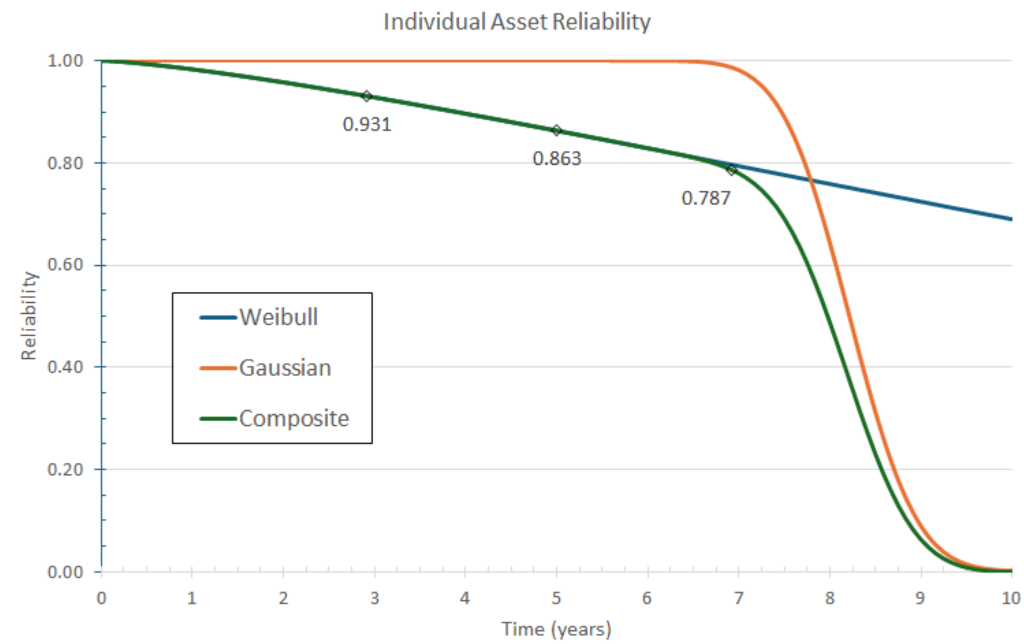


Figure 3. Class A/B asset initial reliability.

Commonly, a Monte Carlo simulation is utilized to assess the CR metric because even though the five assets are identical (i.e., all have the same reliability attribute illustrated as Figure 3), they are launched individually three months apart (represented by orange triangles in Figure 4). This launch initialization distinction means that each asset has three less months of life exhausted on them once the constellation is established. The assets are identical but are at different points on the reliability chart. While a closed-form mathematical solution can be derived for this example (i.e., identical 5-out-of-5 topology with phased timing of the assets), a Monte Carlo simulation was developed and executed for a sufficient number of trials (i.e., convergence is achieved) and the result are shown in Figure 4.

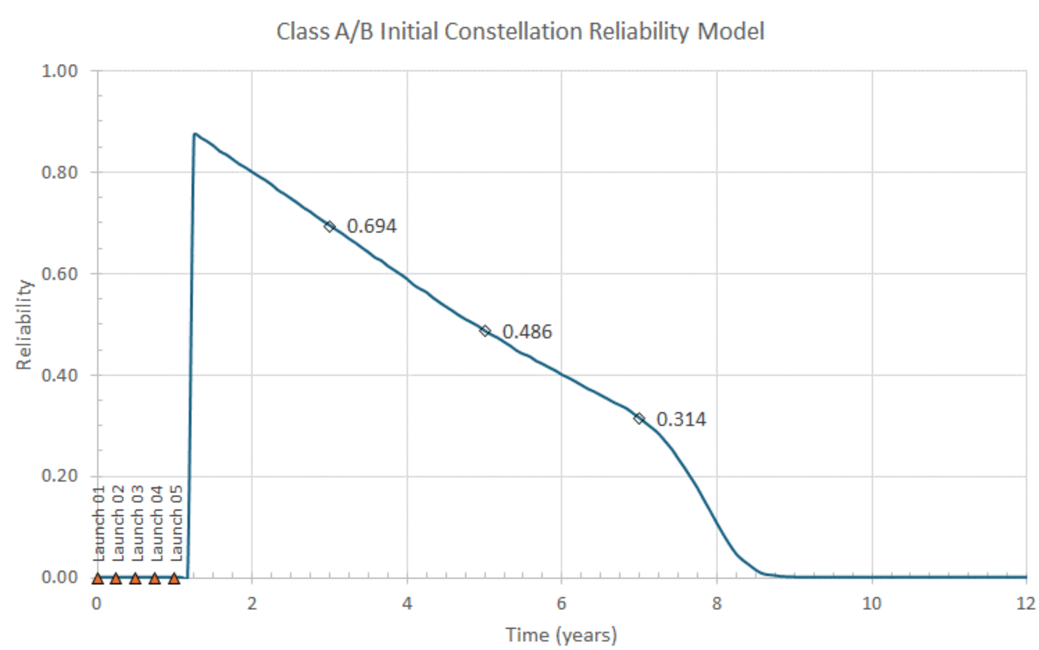


Figure 4. Class A/B asset initial constellational reliability.

Figure 4 clearly illustrates that at the five-year mission length objective, the current CR value of 0.486 is significantly less than the requirement of 0.70. This CR value is so much less than customer's CR requirement that a different tactic needed to be considered. A first approach to improve the CR metric was to consider improvements to the overall reliability of each individual asset. Pareto graphs showing the top risk drivers for each subsystem and the vehicle were reviewed in detail amongst the design team, the specialty engineering team, management, and the customer. Improving the redundancies within the Electrical Power Subsystem and Guidance, Navigation, and Control Subsystem were deemed to be viable design opportunities given mass, cost, and schedule constraints. Figure 5 illustrate the improved Weibull-Gaussian asset reliability.

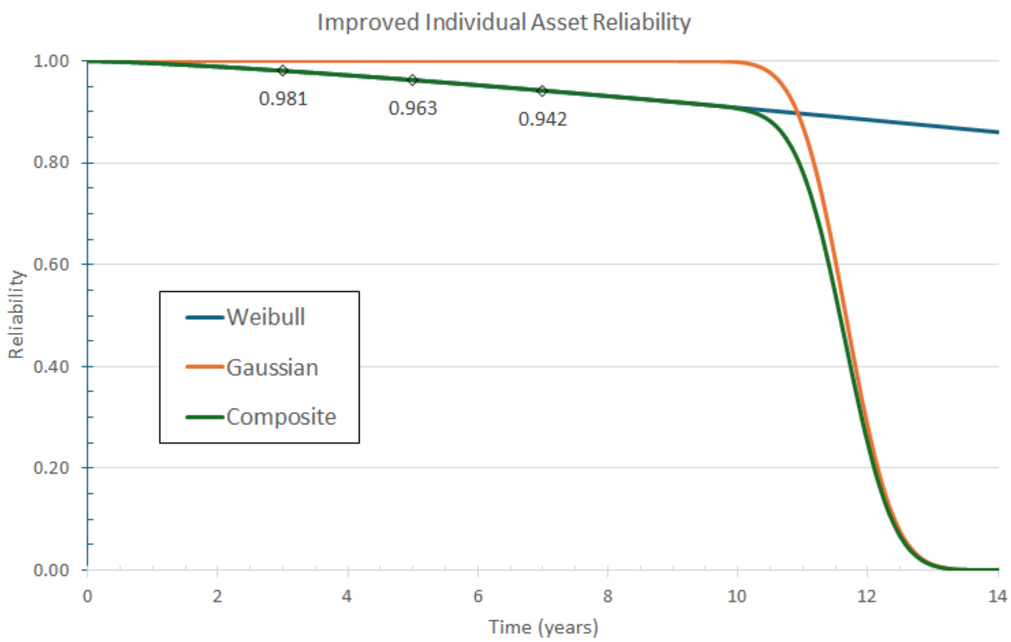


Figure 5. Class A/B asset improved asset reliability.

Figure 6 illustrates the improved CR metric due to the increased asset reliability as a green line, respectively for a single asset. With these design changes, the CR value is now 0.786, which exceeds the customer's requirement with healthy margin.

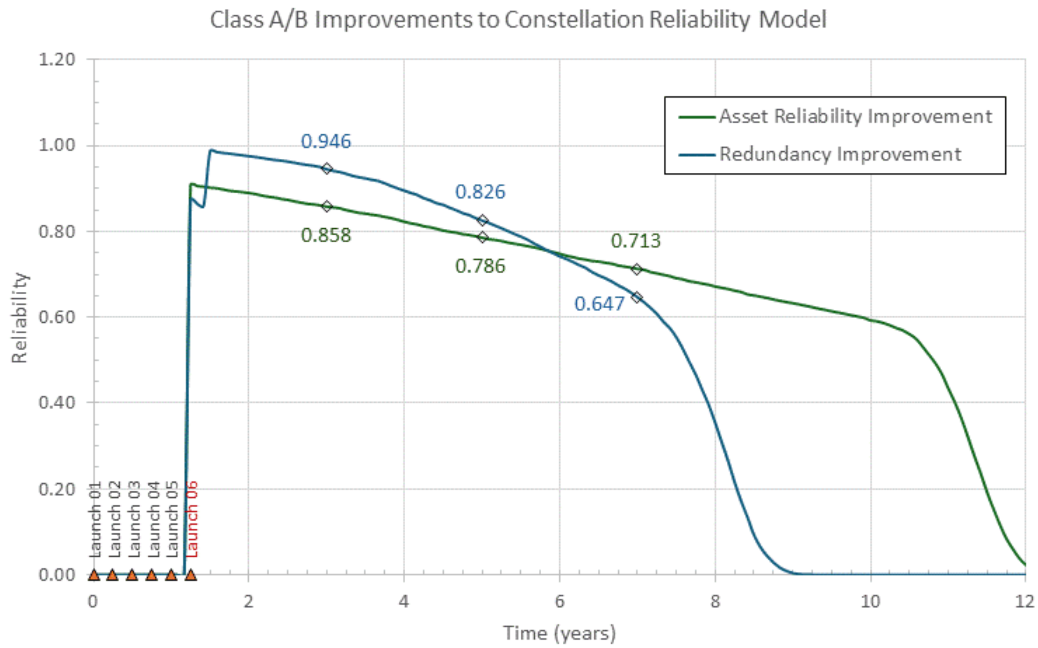


Figure 6. Class A/B constellational reliability improvements.

A second approach is to focus on constellation size and constellation redundancy, not the individual asset, to achieve the CR requirement. After detailed reviews by the design team, the specialty engineering team, management, and the customer, it was determined that changing the asset design at this point in the acquisition would significantly delay the deployment of the constellation and place in jeopardy the objectives this very constellation was meant to mitigate.

It was determined that there was sufficient time, resources, and available funds to construct an additional sixth asset and deploy it three months after the fifth asset was launched. This CR analysis utilized the same original asset reliability model shown in Figure 3 but now, instead of a serial 5-out-of-5 design, the constellation can achieve mission objectives if 5 out of 6 assets are viable. Again, Figure 6 illustrates the improved CR metric with this constellational redundancy design change as a blue line. The CR value is now 0.826, which also exceeds the customer's requirement with significant margin.

There are numerous other design changes that could be considered (e.g., shorten the number of initialization launches by obtaining a more capable launch vehicle, maybe four out of five assets can achieve nearly all mission objectives, a shorter mission objective, a new asset that is inherently more reliable), but the two examples illustrated above are conventional constellational design considerations to achieve a CR objective for a Class A/B program. It should be noted that a cost trade between the two approaches (adding redundancies within each asset or adding a sixth baselined asset) may also have resulted in the final design choice.

3.1.2 Notional Program Class C/D Examples

For this mission, a single asset could not achieve the mission goals while a constellation of thirty small low Earth orbit (LEO) assets distributed amongst three planes could consistently meet the mission objectives. The small nature of the assets allows for 10 to be deployed from a single launch vehicle. This example likely falls within the Class C/D program risk spectrum and has the desired design attributes delineated in Table 3. Again, the objective is to determine if the CR requirement of ≥0.70 at five years can be achieved.

Table 3. Class C/D CR Initial Design Attributes

Attribute	Criteria
CR requirement	≥0.70
Desired mission length	5 years
# of planes	3
Assets per plane	10
Total # of initial assets	30
# of launches to initialize	3
# of replenishment launches	0
# of assets needed	8 per plane
Asset checkout time	3 months

The assets are assumed to be identical and again, the critical input to the CR analysis will be the asset reliability, which has already been illustrated as Figure 3. The initial constellation design is 3 planes of 10 assets, each requiring 8 of the 10 to be viable (i.e., a series topology of three 8-out-of-10 redundant configurations). While a closed-form mathematical solution can be derived for this example, a Monte Carlo simulation was developed and executed for a sufficient number of trials and the result are shown in Figure 7.

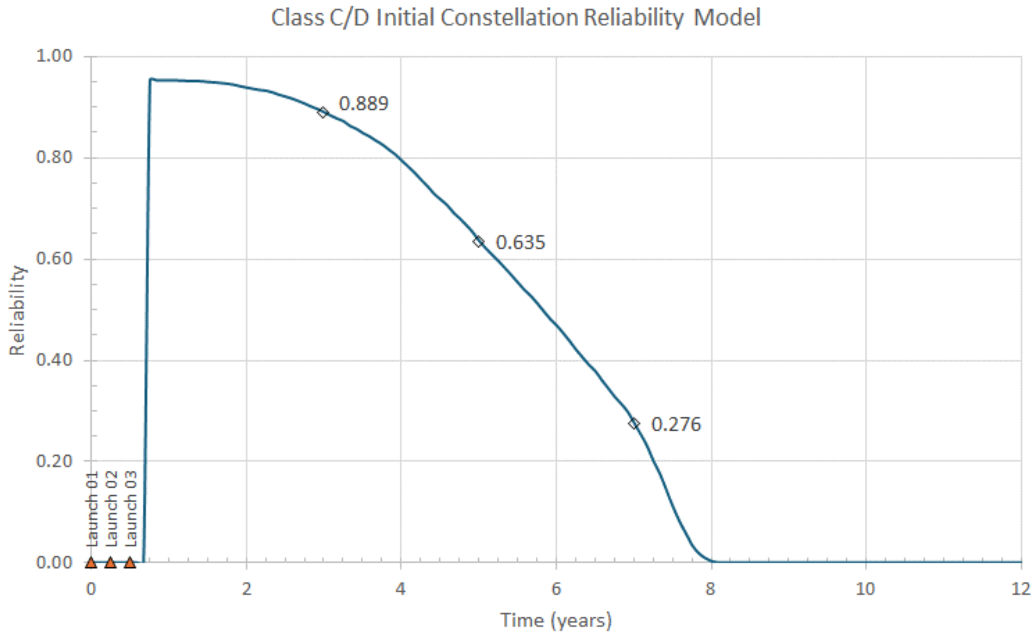


Figure 7. Class C/D asset initial constellational reliability.

Figure 7 illustrates that at the five-year mission length objective, the current CR value of 0.635 is less than the requirement of 0.70. A first approach to improve the CR metric was again to consider improvements to the overall reliability of each asset itself (i.e., Figure 3). When this design change was considered and the CR analysis updated, the improved constellation reliability metric shown in Figure 8 as a green line indicated a CR value of 0.941, which exceeds the customer's requirement with significant margin.

A second approach to improve the CR metric was again to consider not changing the individual asset reliability (i.e., Figure 3) but to make a design change at the constellational level. It was determined that improved redundancy within the assets would be cost and schedule prohibitive but an augmentation to the constellation's redundancy was viable. It was also determined that with a relatively low-cost improvement in the packing design within the launch vehicle's fairings, 11 assets could be launched instead of 10 (i.e., maintaining 3 launches to achieve initialization of the constellation). Thus, the constellational redundancy would change from each of the three planes requiring 8 out of 10 assets to 8 out of 11 assets to be viable. Figure 8 illustrates the improved CR metric with this constellational redundancy design change as a blue line. The CR value is 0.831, which again exceeds the customer's requirement with significant margin.

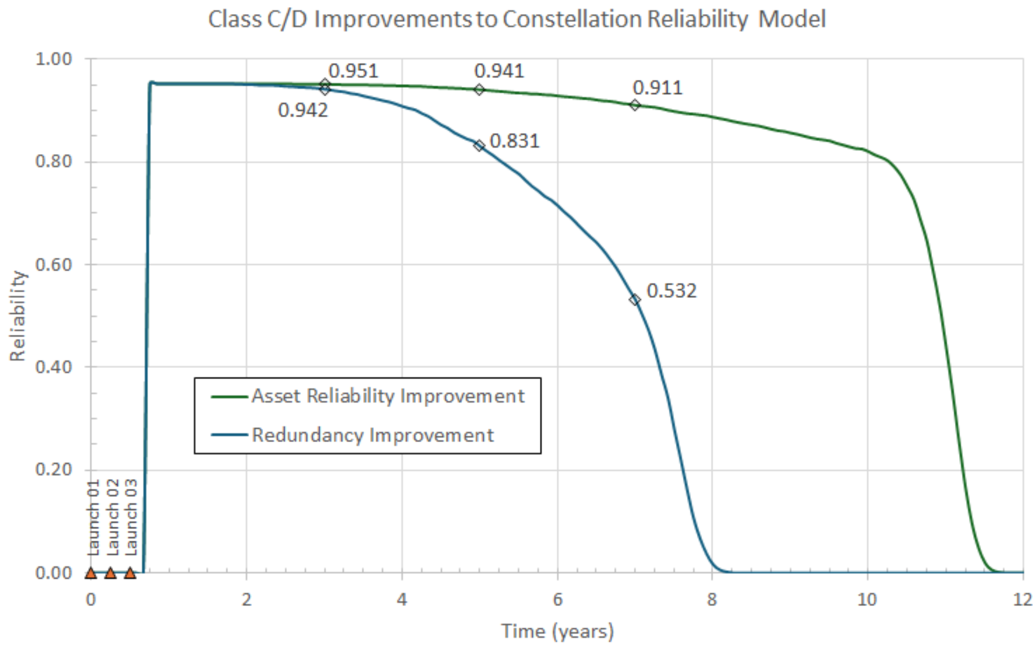


Figure 8. Class C/D constellational reliability improvements.

Again, there are numerous other design changes that could be considered, but the two examples illustrated above are conventional constellational design considerations to achieve a CR objective for, say, a Class C/D program.

3.2 FA Analysis Examples

Recall that the FA metric is the probability that a constellation of assets meets its functional success criteria given the current reliabilities of the constellation's assets and planned replenishment launches. The FA metric is often measured across a spectrum of time, which is usually from constellation initialization to the desired nominal mission length. This section will explore two FA examples to help illustrate how an FA requirement might be achieved, which implies how that same requirement could have been originally derived. These examples are meant to delve into the various aspects of a typical FA analysis effort, but given all the possible nuances associated with the development, deployment, and replenishment of a constellation's assets, these examples are notional and not meant to be exhaustive.

Commonly, a Monte Carlo simulation is utilized to assess the FA metric because of the nearly endless possibilities of various replenishment strategies that could be implemented. In fact, it is this classic queuing modeling complication that makes the development of closed-form mathematical solutions for the FA metric very challenging. The FA analysis effort will consider (and trade) not only establishment launches but also the number and timing of various replenishment launches.

3.2.1 Notional Program Class A/B Examples

This example is similar to the one described in Section 0 of five fairly large GEO assets within a single plane (again, likely the Class A/B program risk spectrum). This example has the desired design attributes delineated in Table 4 and has a single FSC of all pertinent mission functions must be viable for 20 years. The objective is to determine if the FA requirement of ≥0.90 can be consistently achieved across a spectrum of time that encompasses the notional mission duration. The assets, lunched individually three months apart, are assumed to be identical and a critical input to the FA analysis will be the asset reliability, which again is illustrated as Figure 3.

Table 4. Class A/B FA Initial Design Attributes

Attribute	Criteria
FA requirement	≥0.90
Desired mission length	20 years
# of planes	1
Assets per plane	5
Total # of initial assets	5
# of launches to initialize	5
# of replenishment launches	To be determined
# of assets needed	5
Asset checkout time	3 months

A Monte Carlo simulation was developed and executed for a sufficient number of trials and the results are shown in Figure 9. This FA plot clearly shows that the objective of ≥0.90 was achieved for 20 years given a robust replenishment strategy. The FA plot further illustrates the additional replenishment launches (one asset per launch vehicle) as blue triangles advantageously spaced to ensure the FA requirement is achieved while attempting to minimize the number (and costs) of replenishment launches. For this example, 15 replenishment launches are needed to ensure the FA metric is achieved for 20 years. Once a constellation has been established, FA curves typically follow a sawtooth curve shape since the assets' reliability is a nonincreasing function, but new assets are added to the constellation via replenishment launches to replace the failed assets. One item of note is that the sawtooth curve for launches 9 through 12 takes a more compressed form (as a result of asset reliability shown in Figure 3) due to the need to replenish the initial vehicles that have reached wear out (e.g., end of life). This example requires 20 total assets (and 20 launches) to achieve an FA of ≥0.90 for 20 years and has a mean launch cadence of 11.4 months, so about once a year, a new asset is added to the single plane constellation and the failed asset transitions to disposal operations.

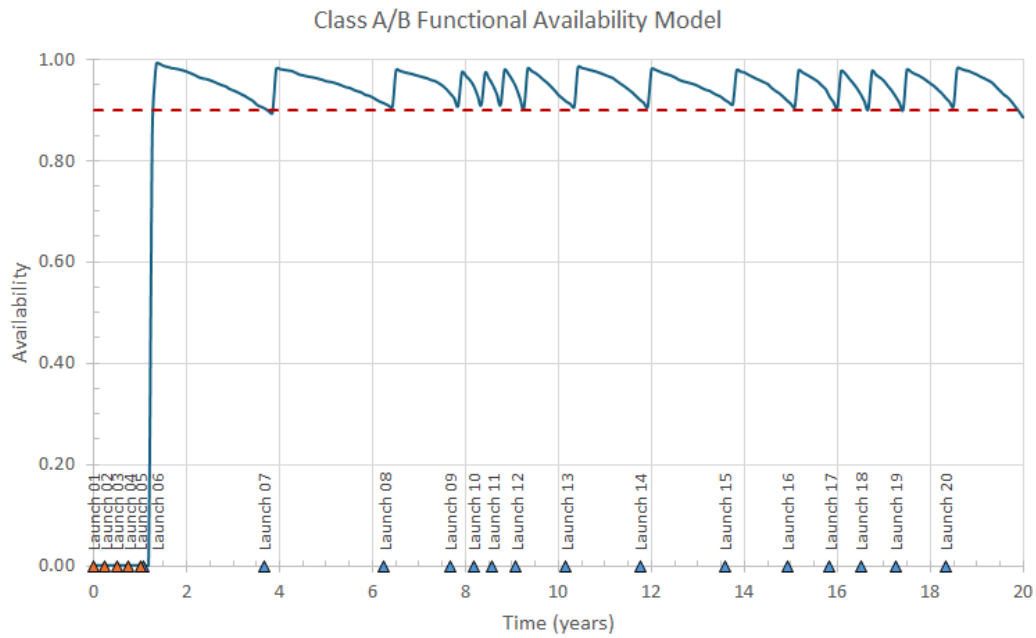


Figure 9. Class A/B asset initial functional availability.

Unlike the CR example that initially failed to meet the requirement before various design changes were employed, the FA analysis has the launch replenishment variable to adjust to ensure the requirement is achieved. However, if it is determined that 15 additional assets (and launches) are too costly or that logistically the mean launch cadence is too frequent, then redesigns of the assets should be considered (like those posed in the CR examples).

3.2.2 Notional Program Class C/D Example

This example is similar to the one described in Section 0 of 30 small LEO assets distributed amongst 3 planes, each plane an 8-out-of-10 redundant configuration (again, likely the Class C/D program risk spectrum). This example has the desired design attributes delineated in Table 5 and has a single functional success criterion that all pertinent mission functions must be viable for 20 years. The assets, launched 10 at a time to populate a single plane, are assumed to be identical and a critical input to the FA analysis will be the asset reliability, which again is illustrated as Figure 3.

Table 5. Class C/D FA Initial Design Attributes

Attribute	Criteria
FA requirement	≥0.90
Desired mission length	20 years
# of planes	3
Assets per plane	10
Total # of initial assets	30
# of launches to initialize	3
# of replenishment launches	To be determined
# of assets needed	8 per plane
Asset checkout time	3 months

Again, a Monte Carlo simulation was developed and executed for a sufficient number of trials and the result are shown in Figure 10. A complicating aspect of this FA analysis is that a replenishment launch of 10 assets (represented as blue triangles in Figure 10) are distributed across all 3 planes as needed (with more assets assigned to planes established earlier as those assets are more likely to have failed).

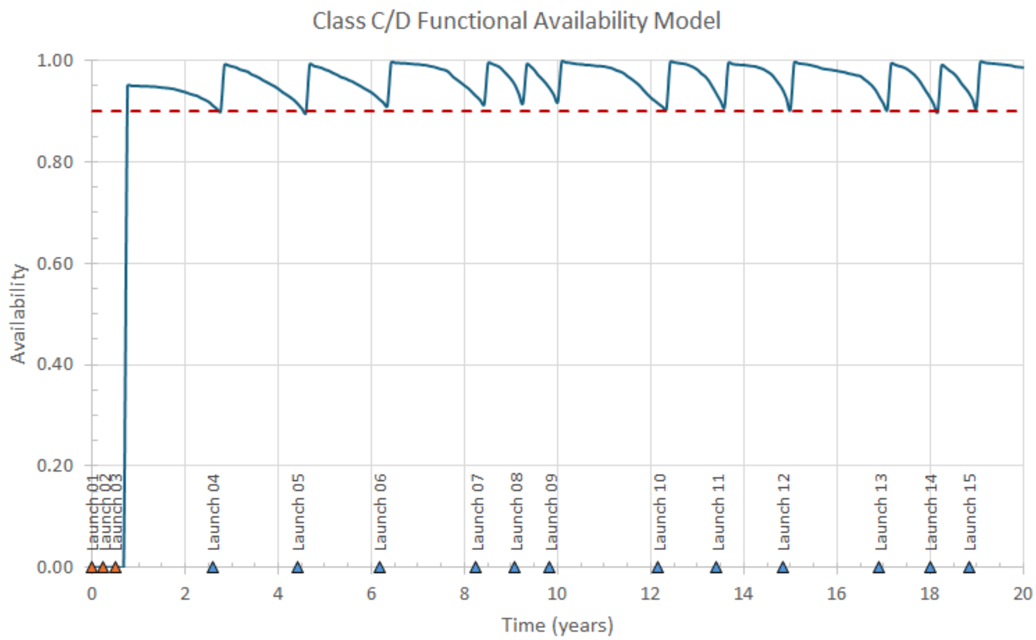


Figure 10. Class C/D asset initial functional availability.

This FA plot clearly shows that the objective of ≥0.90 was achieved for 20 years given a robust replenishment strategy. The FA plot shows the additional replenishment launches (10 assets per launch vehicle) as blue dots advantageously spaced to ensure the FA requirement is achieved while attempting to minimize the number (and costs) of replenishment launches.

For this example, 12 replenishment launches are needed to ensure the FA metric is achieved for 20 years. Again, once a constellation has been established, FA curves typically follow a sawtooth curve shape. This example requires 150 total assets (and 15 launches) to achieve an FA of ≥0.90 for 20 years and has a mean launch cadence of 15.9 months. So, about every 16 months, 10 new assets are added and advantageously distributed across the 3 planes based upon current asset reliabilities. If it is determined that 120 additional assets (and 12 launches) are too costly or that logistically the mean launch cadence is too frequent, then redesigns of the assets should be considered (like those posed in the CR examples).

3.3 Example Summary

A CR analysis focuses on achieving mission objectives usually at one particular time while an FA analysis concentrates on achieving mission objectives across a spectrum of time. An FA analysis considers replenishment launches while a CR analysis typically does not. The additional variables of launch replenishment and launch cadence inherently make the FA analysis more difficult to resolve but allow for the flexibility to meet reliability goals without modifying the individual asset or the mission objectives. A customer typically requires either a CR or FA metric for a constellation of assets, but both could be prescribed if a more holistic perspective of a constellation's risk profile is desired. To reemphasize, while these examples were notionally characterized as conventional Class A/B or Class C/D programs with associated risk profiles, the process execution of a CR or FA analysis is agnostic to the program class designation.

4. Summary and Recommendations

This document describes the utilization of FA and CR as an iterative and well-bounded process to ensure constellations achieve the best cost, schedule, and technical solutions to achieve a mission. These approaches enable mission architectures to be traded and optimized across different configurations and defined success criteria. CR is the probability that a related collection of assets will perform its intended functions adequately for a specified period of time without failure. FA is the probability that a related collection of assets will perform its intended functions adequately (meet its FSC) for a specified period of time when planning for incorporation of on-orbit or launched replacement assets are considered. It highlights the merit of using CR as an optimal vessel to capture the relevant reliability requirements to drive asset-level design to deliver a constellation (homogenous or heterogenous) that will achieve mission success.

We recommend that future constellation acquisitions avoid specifying reliability requirements at the asset-level and below to avoid overconstraining design. This includes specifying asset-level probability of success requirements and redundancy schemes. Additionally, focusing on the constellation-level performance, FA or CR, will enable comparisons and analyses of architectures that better assess the merits of design decisions and trades and avoid a point solution at the asset-level that is suboptimized. Contract language should leverage CR and use it as a basis of requirements to ensure that the resulting design solutions meet the overall success criteria over time to achieve the requisite FA for future missions.

Accurate modeling of constellation reliability and functional availability depends on having high-quality lifetime data to describe the constituent elements and assets. The space industry should align modeling techniques and standardize training for modeling FA and CR so that comparison and trending of results can be readily achieved. Finally, future steps for the discussed simulation methodology need to involve data curation and verification, as well as expanding the scope of relevant, operational asset data sharing. This will require a large, queryable dataset to provide statistical inputs for various spacecraft classifications or configurations, allowing for more accurate modeling of CR and FA.

5. Acronyms

A_O	operational availability
ATR	Aerospace technical report
CONOPS	concept of operations
CR	constellation reliability
EEE	electrical, electromechanical, and electronic
FA	functional availability (aka constellation availability)
FSC	functional success criteria
GEO	geostationary Earth orbit
LEO	low Earth orbit
LV	launch vehicle
MSIW	Mission Success Improvement Workshop
PLF	payload fairing
SME	subject matter expert
SWaP	size, weight and power
USG	United States government

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