

A Methodology for Reliability Assessments of Arbitrary Satellite Constellations

2022.10.24

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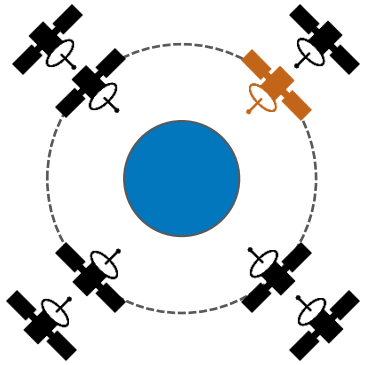
Primer on the Need

- The proliferation of satellite constellation missions is a paradigm shift with the potential to enable more capable and cost-effective space science missions.
  - Collections of small satellites may offer cost savings
  - Distributed and disaggregated systems may be more resilient
- Designing and evaluating constellation missions brings new questions and complexities.
  - How does constellation size affect overall reliability?
  - How does a constellation of Class C satellites compare to a single Class D satellite?
  - How often must elements in a constellation be replaced to ensure constant coverage?
- New methods and standards are required for evaluating the aggregate reliability of constellations as a function of their individual constituents.
- The methodology presented here enables flexible analysis of arbitrary constellations.

Overview of Constellation Concepts and Terminology

Constellation

Mission composed of two or more spacecraft placed into specific orbit(s) for the purpose of serving a common objective

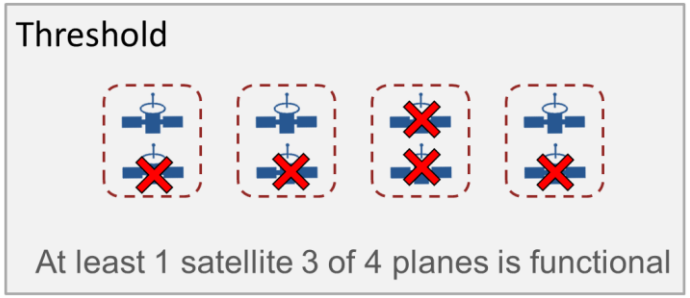


Monolith

Mission composed of single spacecraft capable of meeting objectives

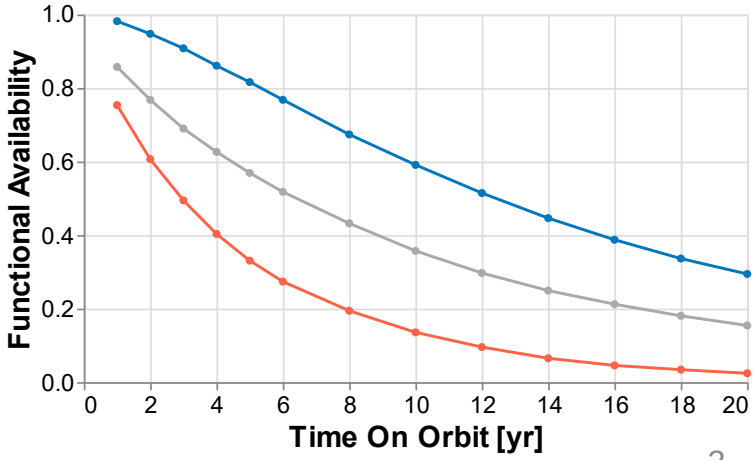
Success Criteria

Set of factors or parameters used to evaluate mission success



Functional Availability

Probability that a constellation meets its success criteria



Homogeneous Constellation

All elements are the same type and provide redundant functions

Heterogeneous Constellation

Elements can either be different type or provide different functions

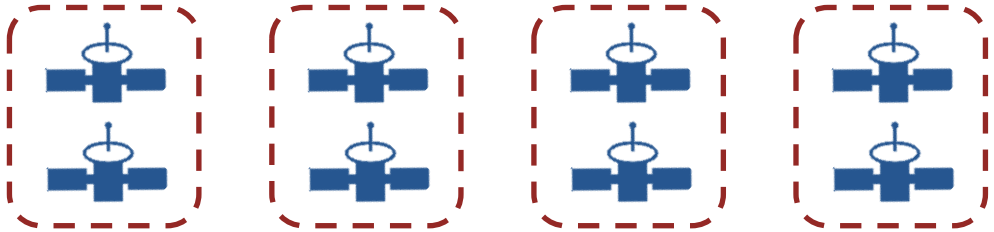
Basic Constellation Architectures

Homogeneous



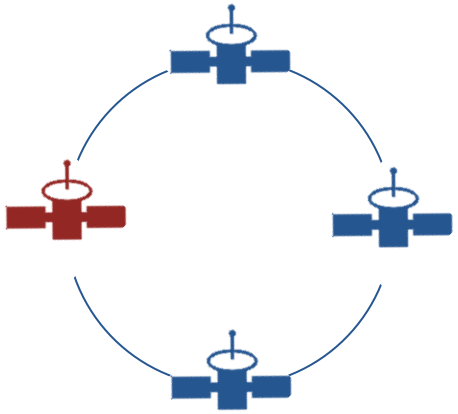
Replace any one satellite with any other

M x N Array



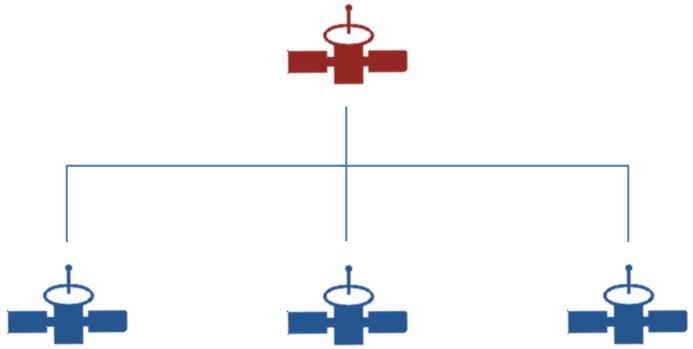
M satellites in N orbit planes

Team of Individuals



Loose hierarchy

Mothership and Swarm

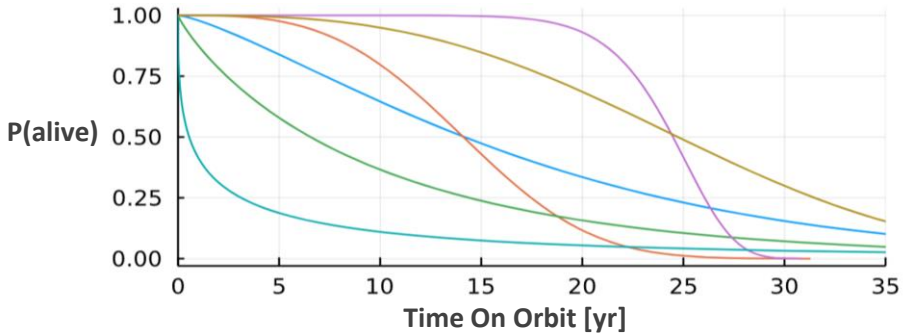


Strict hierarchy

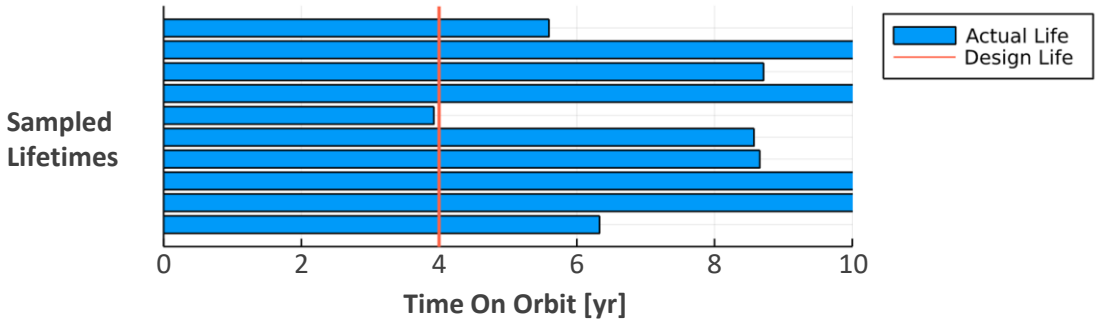
Statistical Sampling Methodology Overview

Lifetime Sampling for Satellites

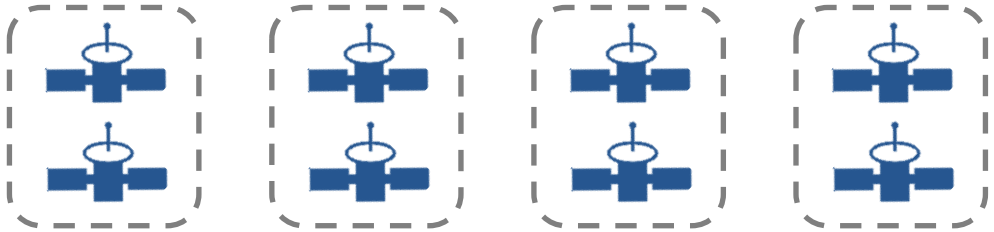
- Satellites are designed for a specific mission duration, but actual on-orbit time varies and can be represented by probability distributions.



- Sampling from appropriately binned satellite populations enables statistical analysis.



Aggregate Analysis of Constellations



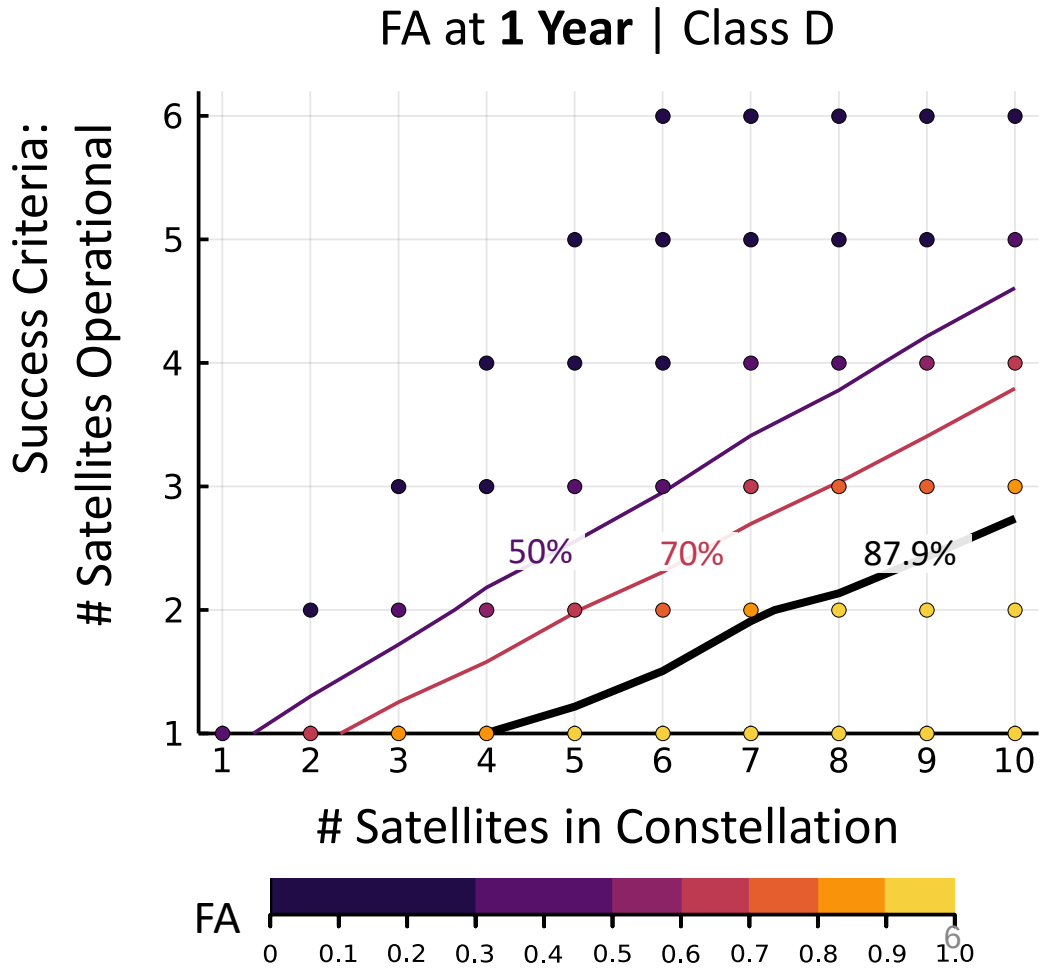
- New data structures enable users to:
  - Configure arbitrary constellations
  - Establish rule-based success criteria
- Combining satellite-level lifetime sampling with constellation-level success criteria, we can study functional availability over time.
- Monte Carlo analysis enables statistical analysis of constellation functional availability.

Homogeneous Constellation Analysis

Question: What combinations of Class D elements and success criteria can provide similar functional availability to a Class C monolith?

Answer:

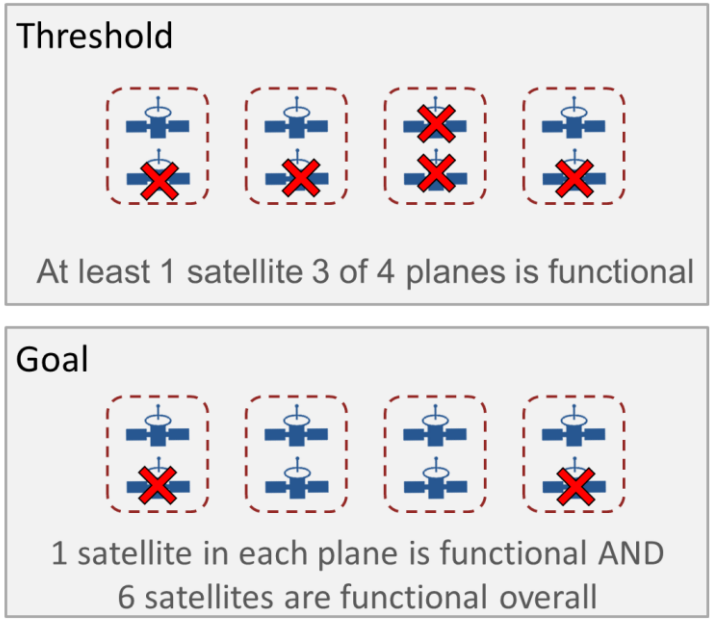
- Observations
  - At one year, the Class C monolith has FA = 87.9%
  - There exist configurations of Class D satellites that can meet or exceed the Class C performance
- Example
  - Assume we can construct a constellation and set >= 2 operational satellites as the baseline.
  - To meet or exceed the Class C monolith performance, we must fly at least 8 Class D satellites

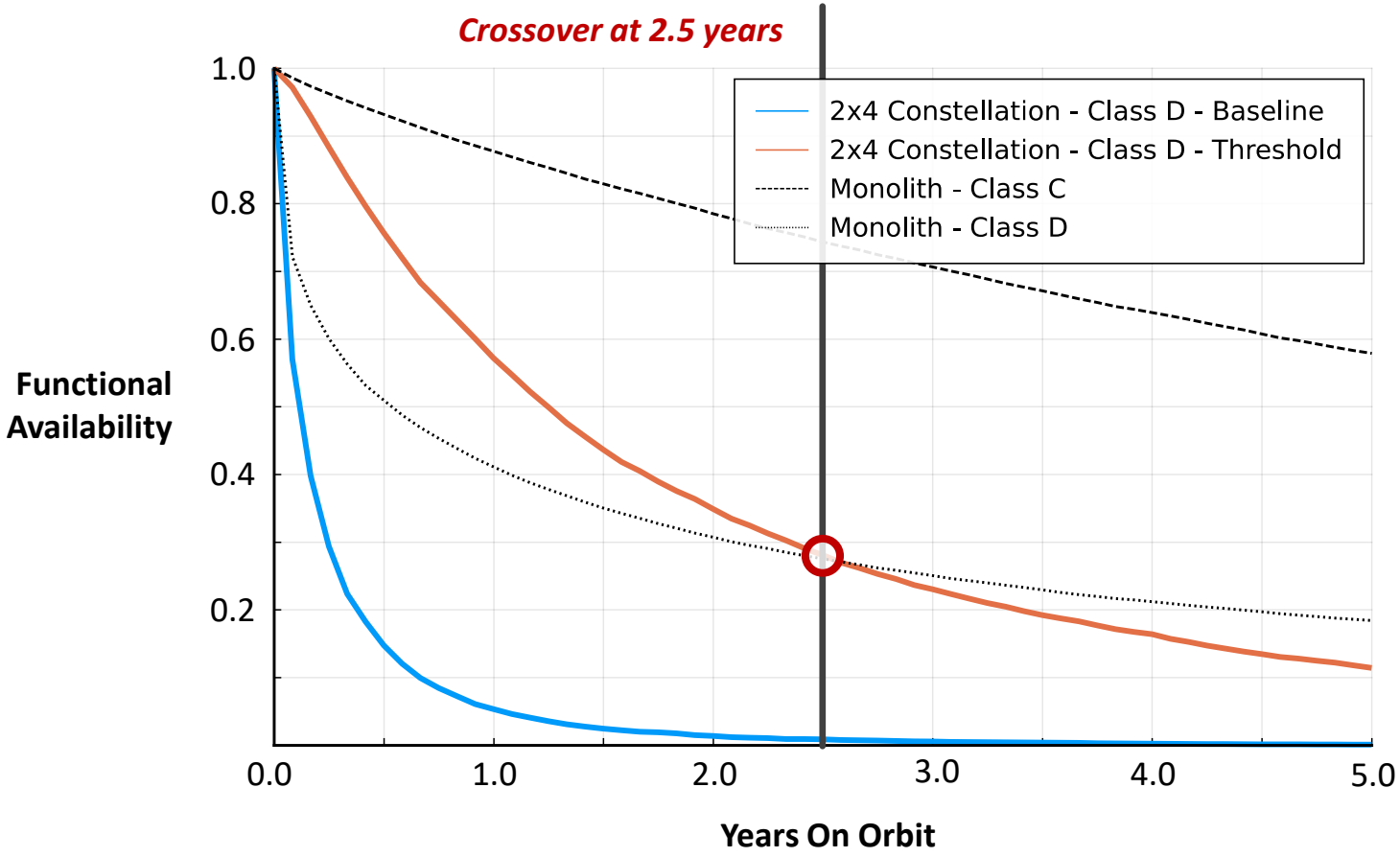


Heterogeneous Constellation Analysis

Question: Does functional availability for a given constellation ever drop below an equivalent monolith?

Case: Consider an M x N constellation





Answer: After 2.5 years, the monolith maintains higher functional availability.

Constellation Replenishment Analysis

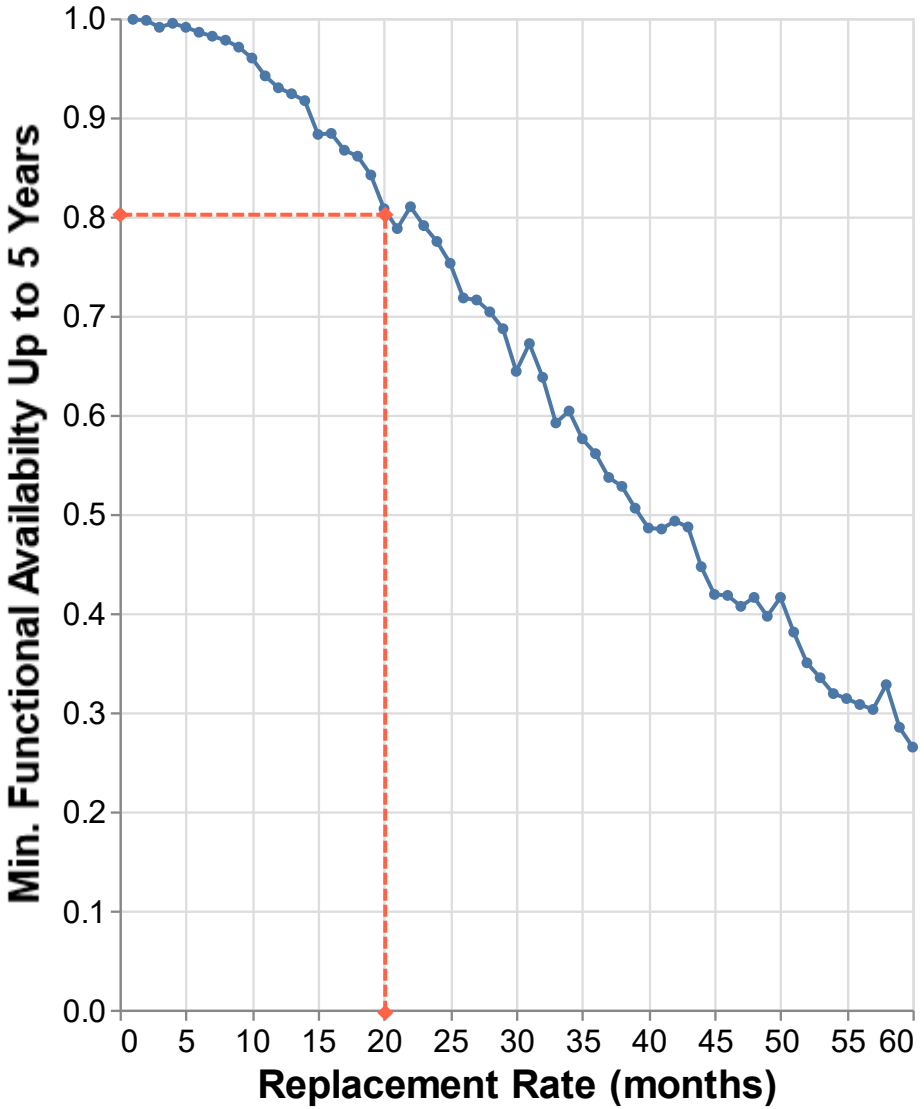
Question: For a given constellation and duration, **how quickly must a failed element be replaced** to maintain functional availability?

Case: Constellation of 8 spacecraft with success criteria of 6 operational for a mission duration of 5 years

Answer:

- Process
  1. Select acceptable functional availability
  2. Use chart to determine required replacement rate

- Example
  To achieve minimum functional availability of 0.8, the time to replace a failed satellite should be **no more than 20 months**

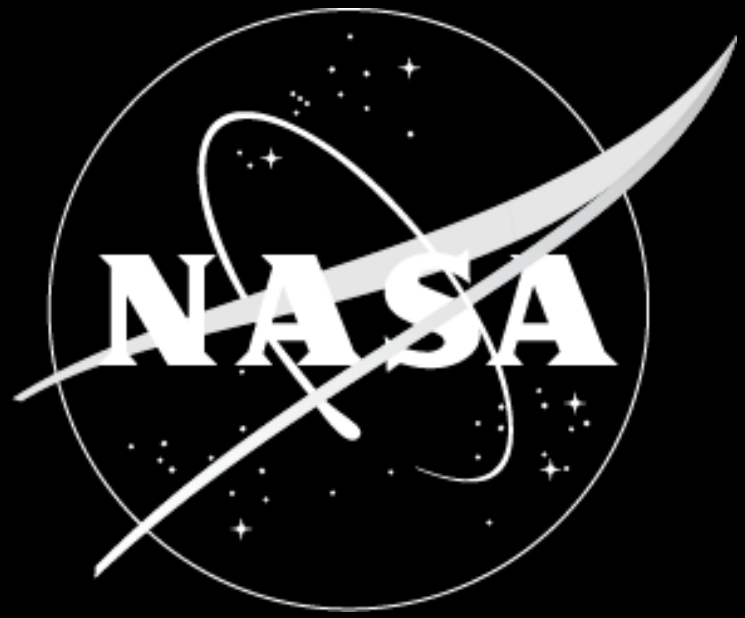


Summary & Study Contributions

- A methodology has been developed to model the functional availability of a constellation
  - Capable of simulating behavior of homogeneous and heterogeneous constellations
  - Evaluates constellation performance against rules-based success criteria
  - Supports constellation replenishment via proactive and reactive launch strategies

- Using the modeling developed by this study, it is possible to develop tables and graphics that describe functional availability for a wide range of homogenous constellations
  - Heterogenous constellations require more case specific definitions and are not as well suited to generalized tables for describing functional availability

- Constellation configurations and success criteria rules were developed to describe the functional availability of representative heterogenous constellations
  - Heterogeneous configurations require case-specific success criteria definition
  - This methodology can be leveraged for specific constellation definitions when identified by either generating new rules for success criteria evaluation or by combining the example rules to represent more complex configurations

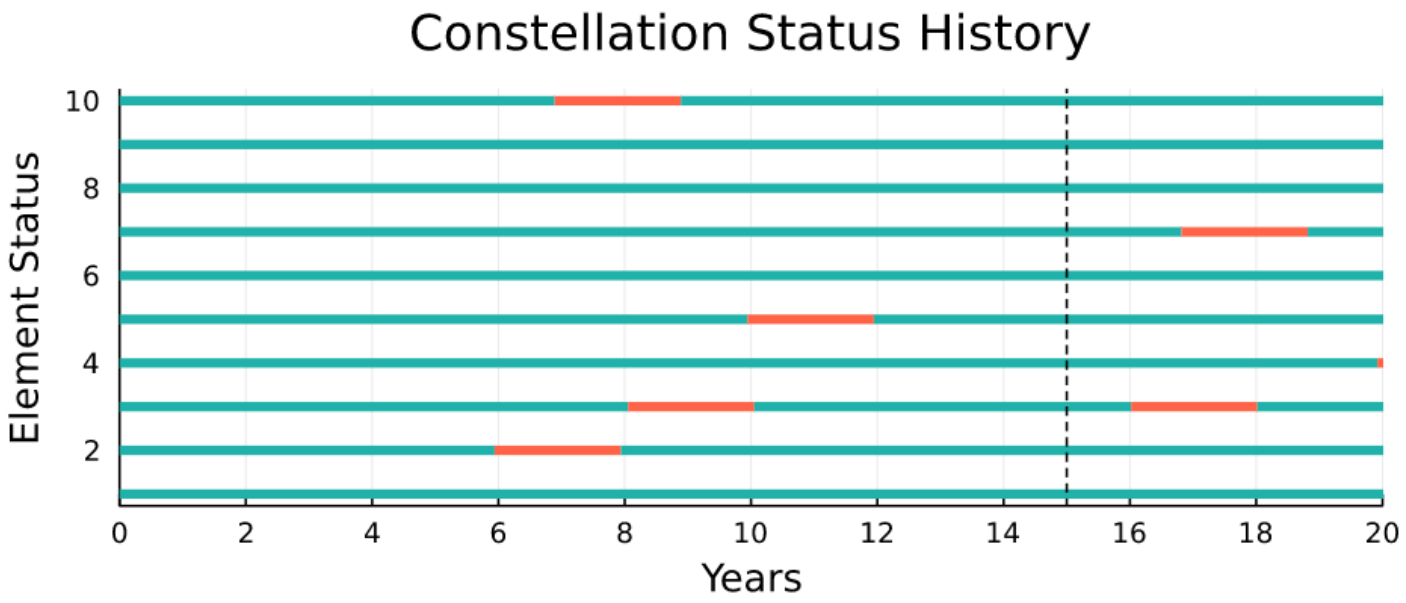

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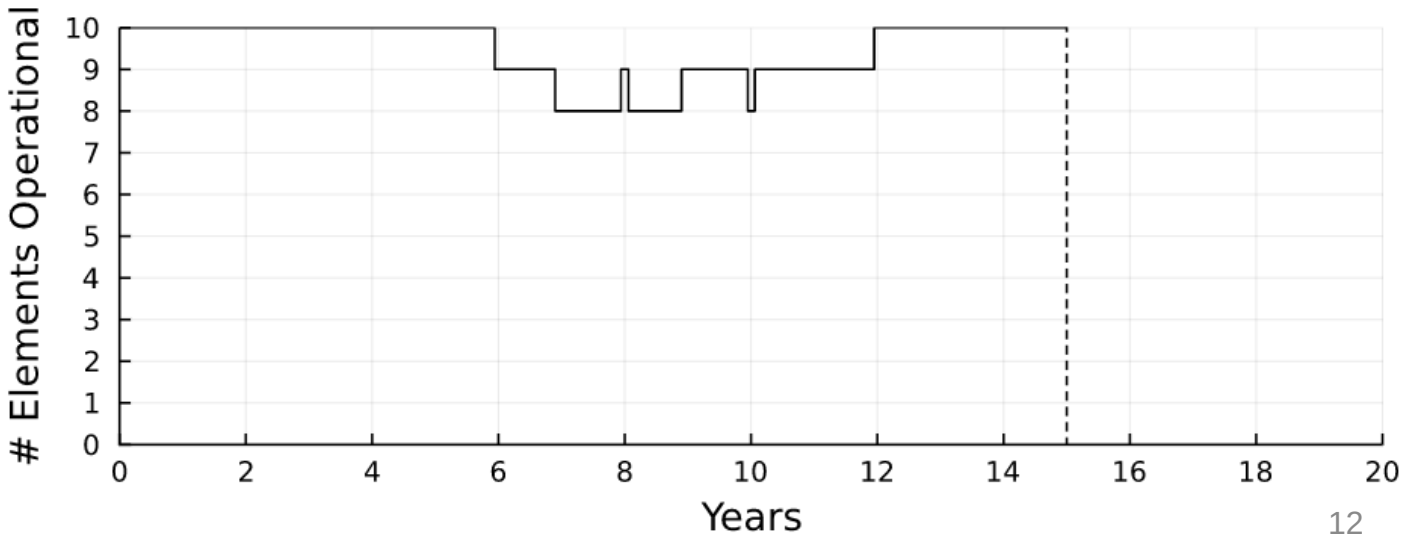
Backup

Additional visualizations

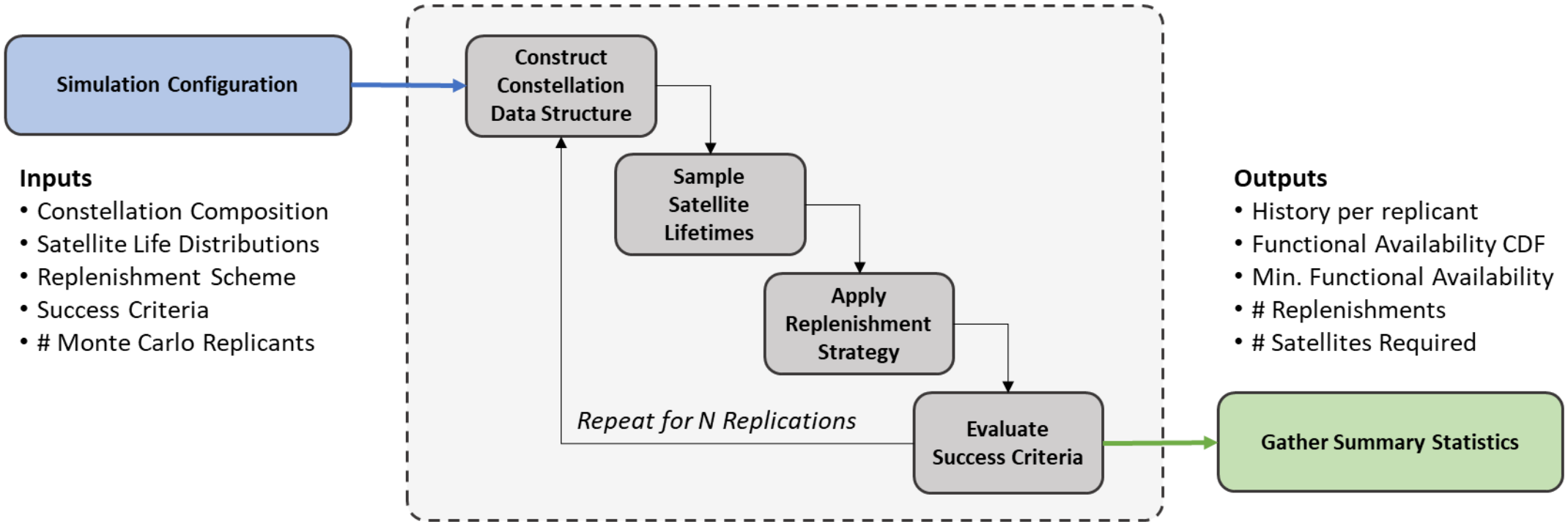
Aggregate Diagnostics for a Satellite Constellation

- As satellites fail (red) and are replaced, we can track the aggregate number of operational satellites to evaluate the entire constellation
- Minimum number of operational elements is an example of a simple success criteria.
- Repeat similar analysis in a Monte Carlo loop to generate summary statistics.





Simulation Flow Block Diagram



Inputs
- Constellation Composition
- Satellite Life Distributions
- Replenishment Scheme
- Success Criteria
- # Monte Carlo Replicants

Outputs
- History per replicant
- Functional Availability CDF
- Min. Functional Availability
- # Replenishments
- # Satellites Required