Supportability Concepts for Crewed Deep Space Exploration

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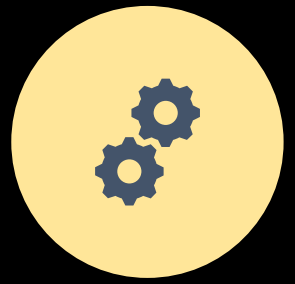
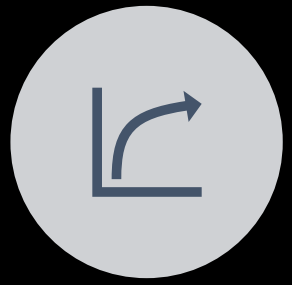


INTRODUCTION & BACKGROUND



KEY CONCEPTS FOR SUPPORTABILITY ANALYSIS

SUPPORTABILITY ANALYSIS INPUTS & OUTPUTS

CASE STUDY

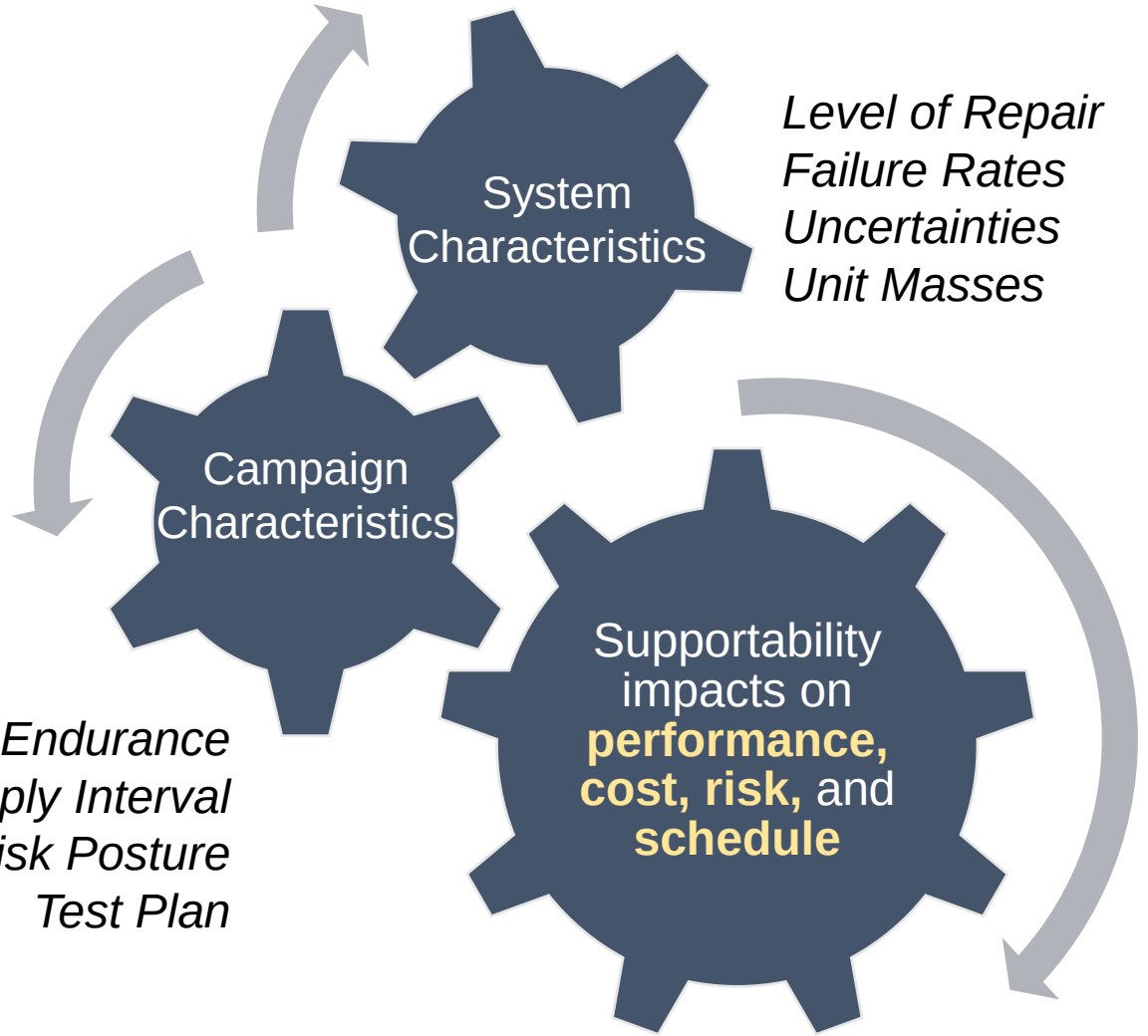
SUMMARY & CONCLUSIONS

Introduction

The **purpose** of this paper is to aggregate and organize key concepts related to supportability that should be considered when evaluating spaceflight systems

Supportability is the set of system characteristics that influence the logistics and support required to enable safe and effective operations of systems[1,2]

Supportability analysis characterizes the relationship between:



Level of Repair
Failure Rates
Uncertainties
Unit Masses

Mission Endurance
Resupply Interval
Risk Posture
Test Plan

[1] Cirillo et al. 2011 [2] Stromgren et al. 2016

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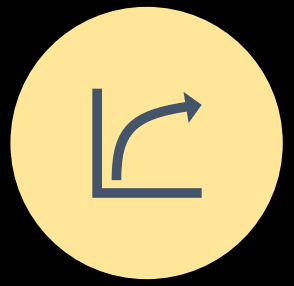

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Spares Mass & Crew Time for Maintenance Are Probabilistically Driven

Understanding what demands are probabilistic compared to deterministic enables better modeling of the associated systems

System demands

The likelihood of events can be described via two probability functions

Probabilistic

Spares Mass
Crew Time for Maintenance

Probabilistic demands related to spare parts required to repair random failures, are stochastic.[8]

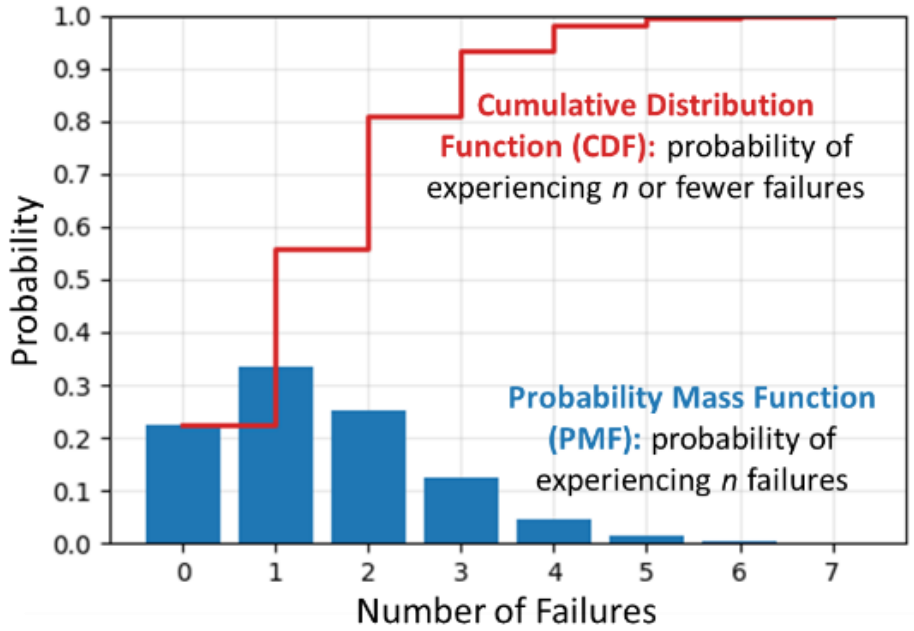
Deterministic

Life limited maintenance items
Crew Time for Sleep

Probability Mass Function (PMF) → Likelihood of a specific number of events occurring

When mission planning and evaluating overall mission risk, analysts may need to be aware of:

Cumulative Distribution Function (CDF) → Likelihood of experiencing a specific number of events or fewer



[8] Owens et al. 2017

Systems Can Be Modeled – Even if Their Characteristics are Not Fully Known

Modeling

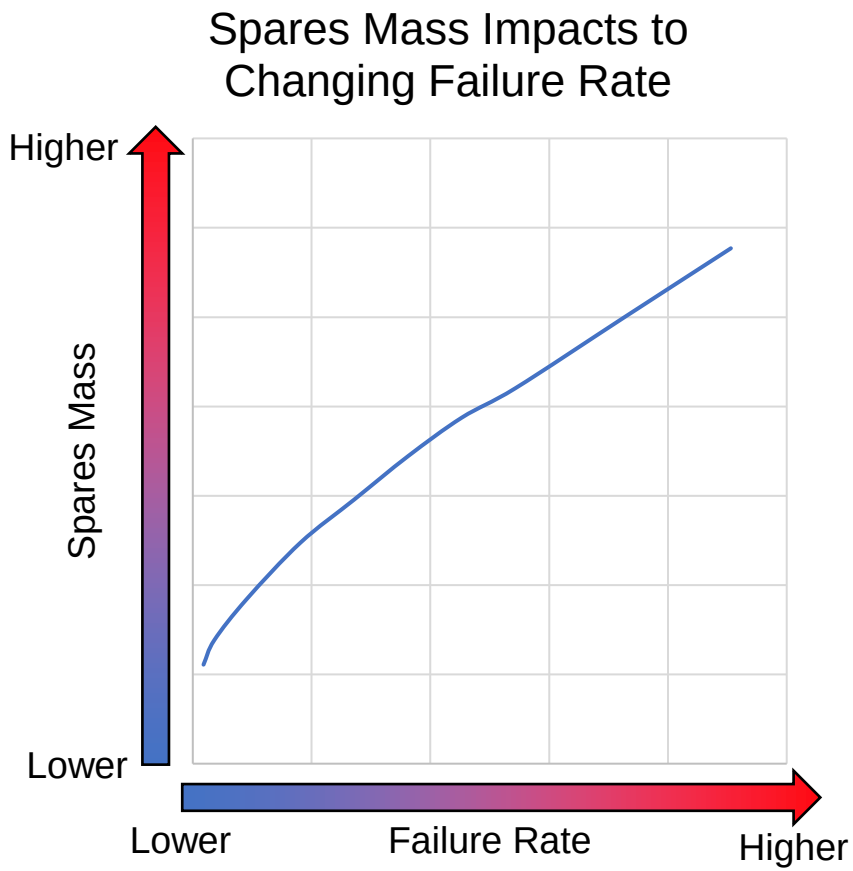
- A model is a relationship between parameters
- Systems can be modeled even if their characteristics, or the input data, are not fully known
  - Failure rates cannot be measured, but a model can be used to explore how failure rates affect other characteristics

Sensitivity Analysis

- Sensitivity analysis determines how different values of an independent variable affect a particular dependent variable under a given set of assumptions[11]
- Sensitivity analysis can help better understand systems when dealing with uncertainty

Application

- Engineering estimates can be used as placeholders when data are not yet available
- Sensitivity analysis can help engineers better understand the impacts of changing a particular parameter

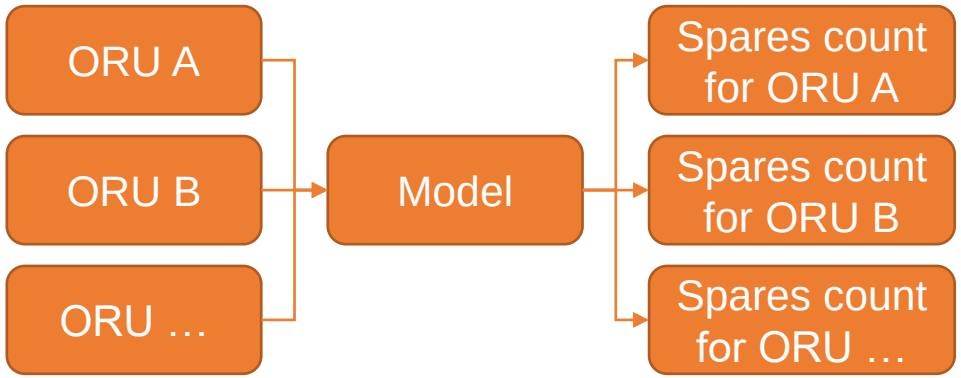


[11] Kenton 2023

Integrated Analysis is Needed to Understand the System

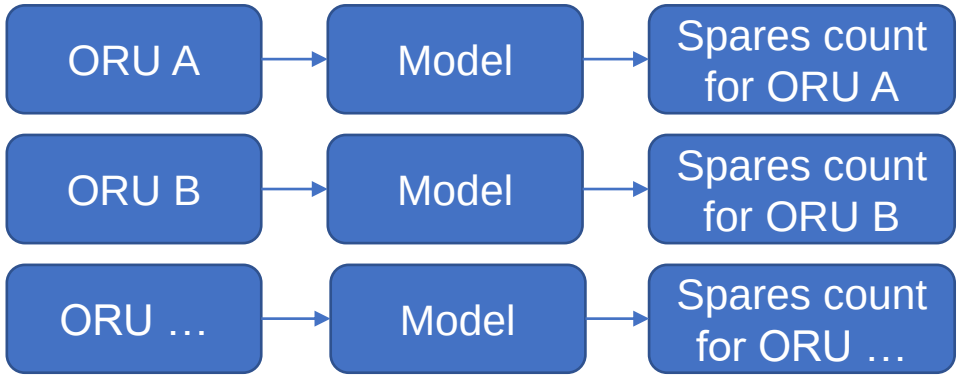
Integrated Evaluation

To evaluate the risk of an integrated system, the individual component probabilities are multiplied together.

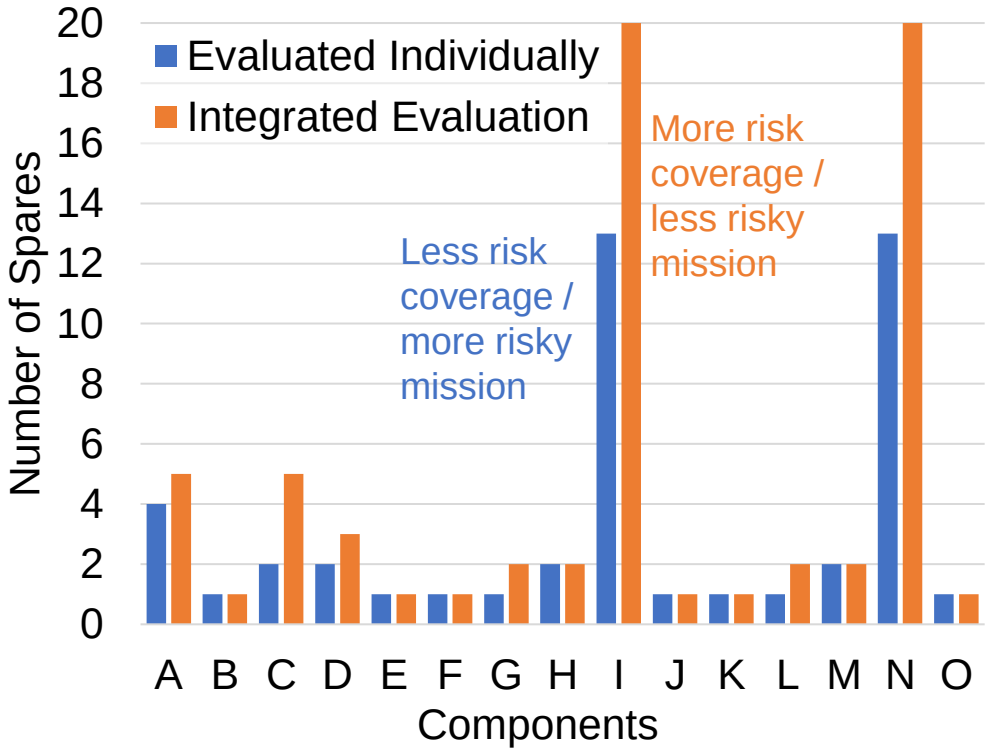


Individual Evaluation

Considering components individually can lead to under-estimating mission risk.

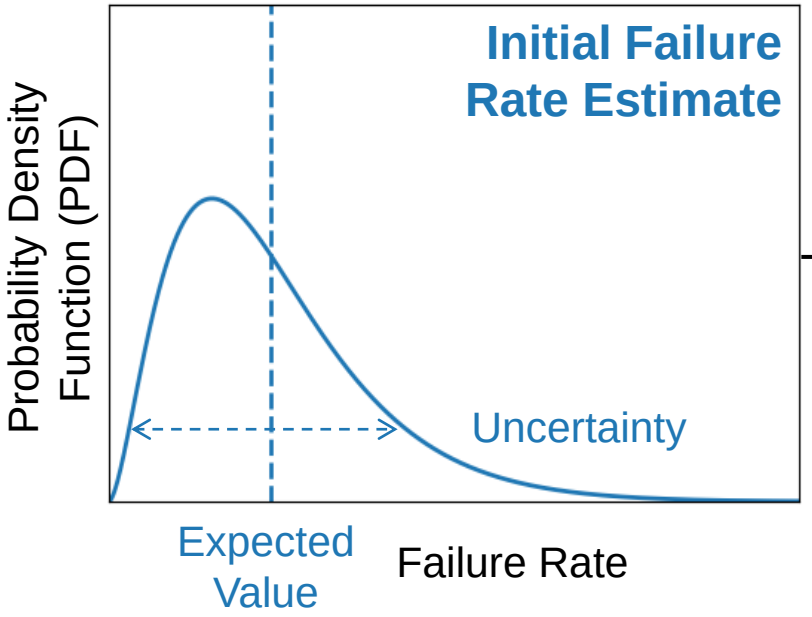


Considering components in an **integrated** manner allows **for more accurate predictions of mission risk**



ORU = Orbital Replacement Unit

Failure Rates Cannot Be Measured Directly, but Can Be Estimated



International Space Station (ISS) experience shows that initial estimates can be inaccurate

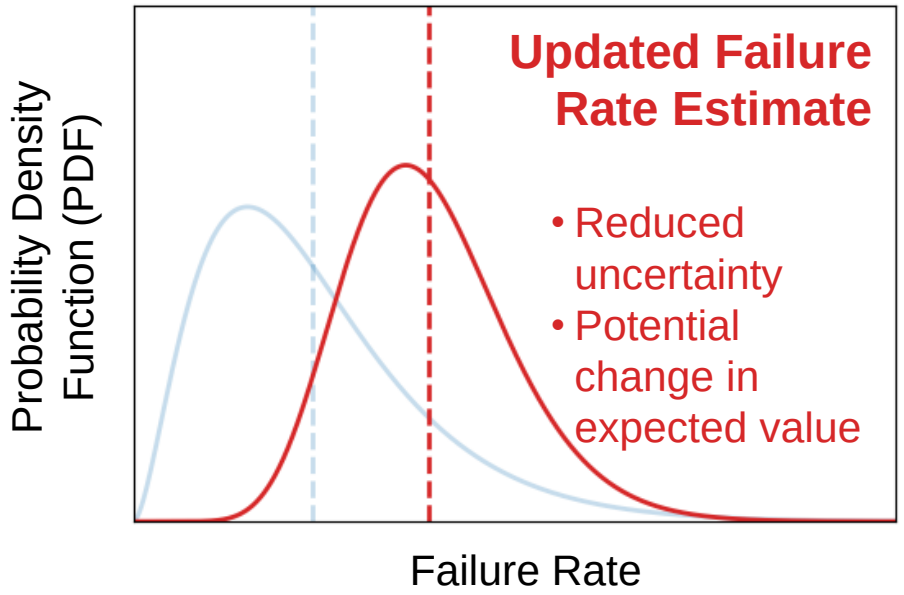
Stromgren et al., 2016

Initial estimates can be refined over time with testing and operating data

Bayesian analysis takes in initial failure rate estimates and updates them using testing and operating data

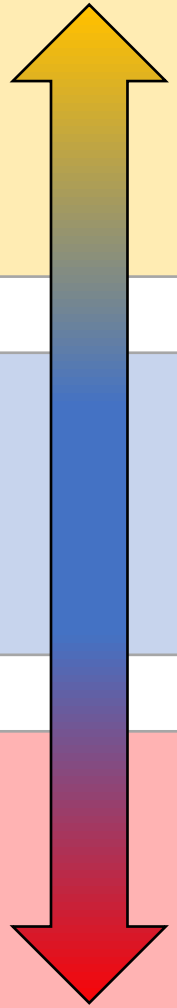
Test/Ops Data:
- Operating time
- Number of random failures

Bayesian Analysis



Testing Is Valuable Regardless of the Outcome

Initial Failure Rate Estimate	Value of Testing
Too High *System is more reliable than anticipated*	• Reveal and help correct overestimate • Reduce spares mass
Accurate *System is as reliable as anticipated*	• Validate estimate • Reduce uncertainty • Reduce spares mass
Too Low *System is less reliable than anticipated*	• Reveal and help correct underestimate, mitigating previously hidden risk of insufficient spares • Enable identification and potential removal of failure modes to improve system reliability



Supportability Concepts for Crewed Deep Space Exploration

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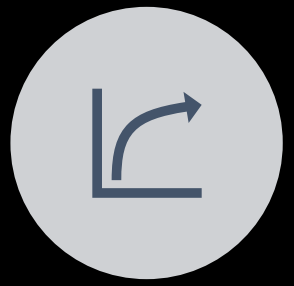
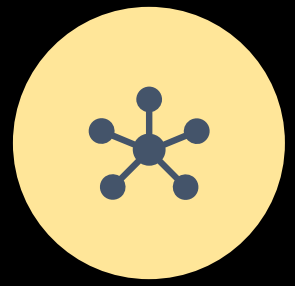


KEY CONCEPTS FOR SUPPORTABILITY ANALYSIS

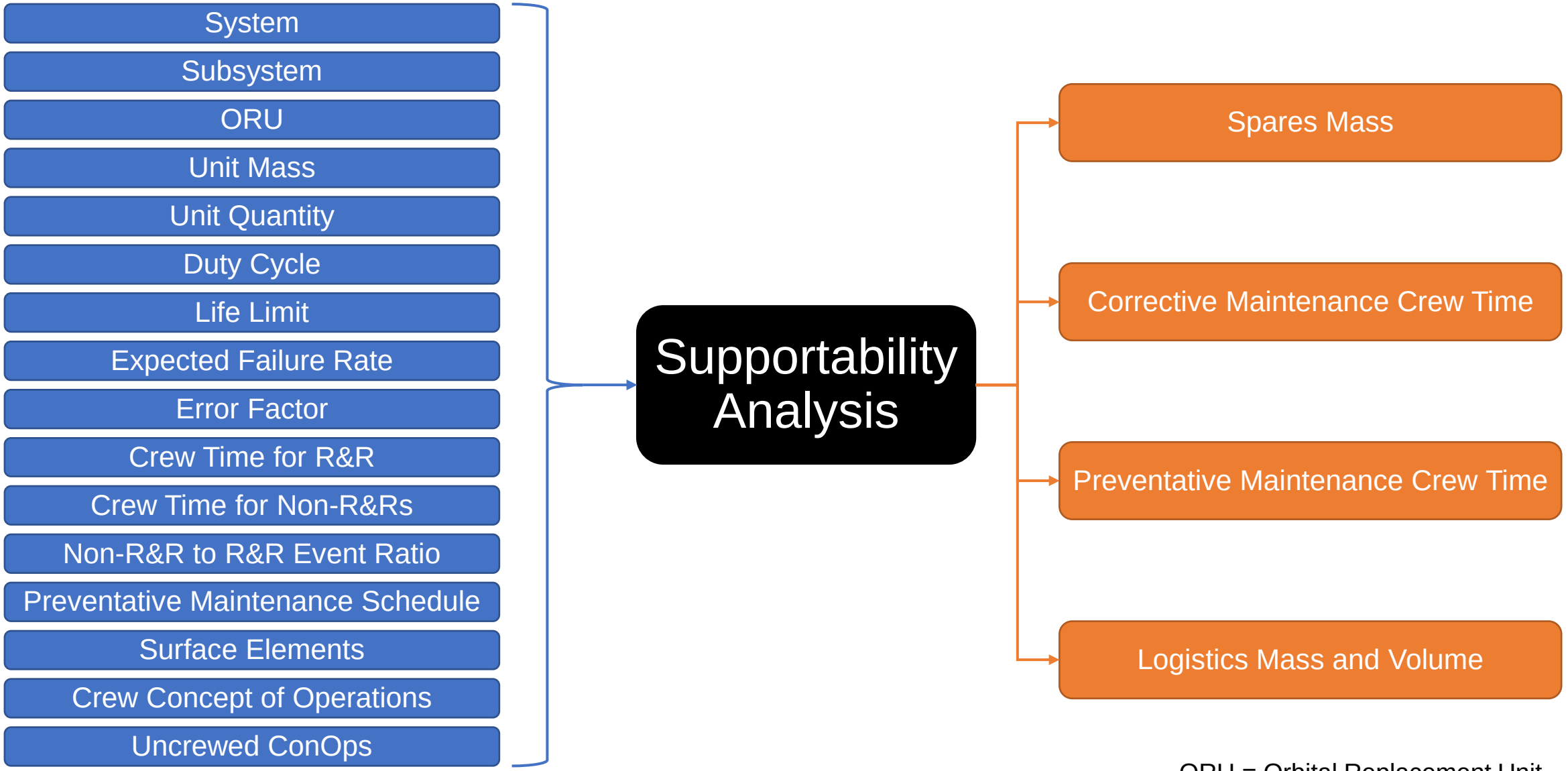


SUPPORTABILITY ANALYSIS INPUTS & OUTPUTS

CASE STUDY

SUMMARY & CONCLUSIONS

Supportability Analysis Inputs and Outputs



ORU = Orbital Replacement Unit
R&R = Remove and Replace

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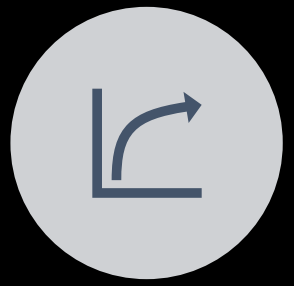

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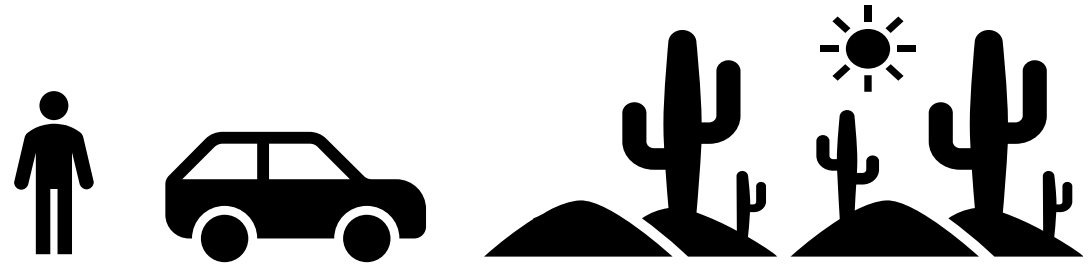
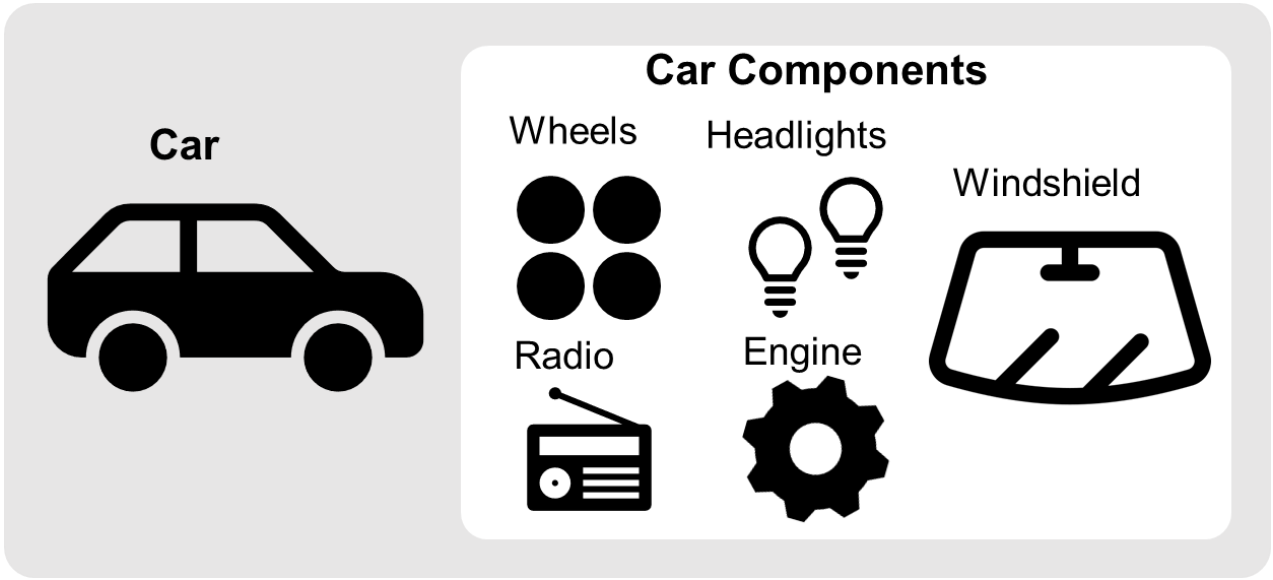
Case Study Overview

This case study is a simple example used to illustrate supportability concepts, but this approach can be applied to any system and any mission



Case study: one crew member on a mission to explore the Sahara

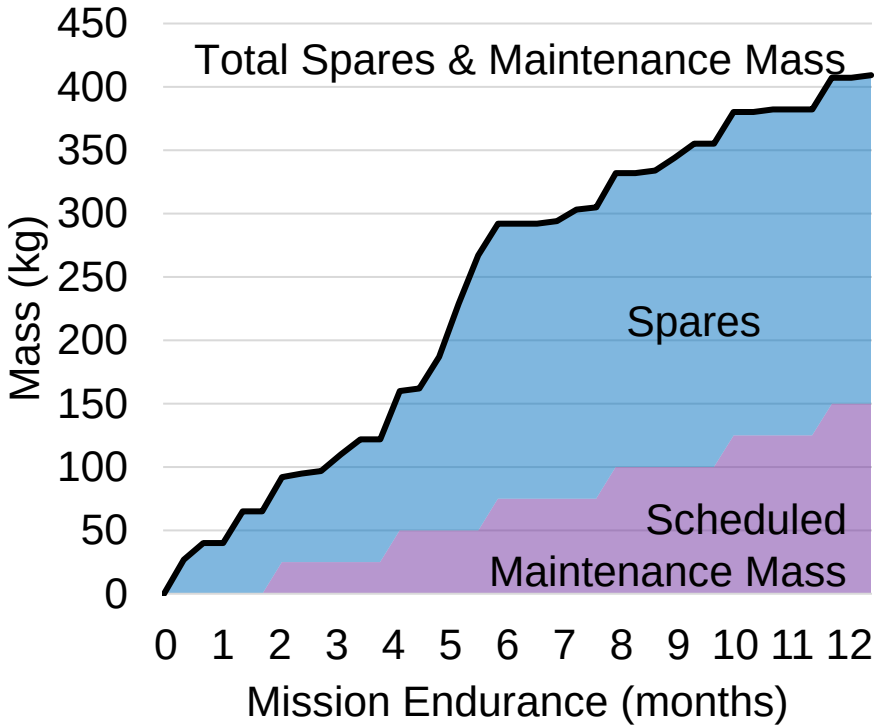


Type of questions supportability analysis can help answer

- How much spares mass should be allocated?
- What is the total spares and maintenance mass as a function of mission duration?
- How much crew time is likely needed for maintenance?

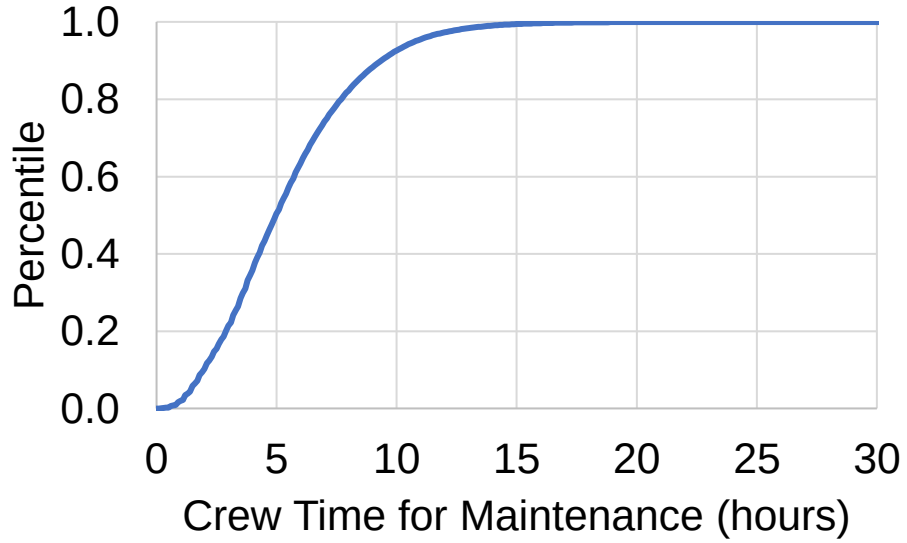
Case Study Results Summary

Spares mass for a car as a function of mission endurance for a 0.99 Probability of Sufficiency (POS)



Likelihood →	Consequence → Negligible	Minor	Moderate	Significant	Severe
Very likely				Wheel fails	
Likely		Headlight fails			
Unlikely	Radio fails		Windshield fails		
Very unlikely					Engine fails

Example CDF of maintenance crew time required for a 1-year mission.



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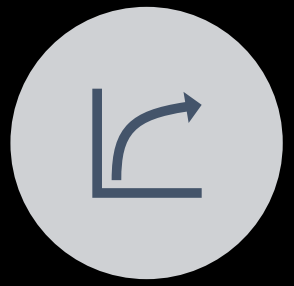

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Summary

Spares mass and crew time for maintenance are **probabilistically driven** and therefore should be modeled and evaluated in a probabilistic manner.

Systems can be modeled even if their characteristics are not fully known. Sensitivity analysis can help.

Space systems are complex with coupled interactions and limited resources, and therefore **integrated analysis** is needed to understand the system.

Failure rates cannot be measured directly but they can be estimated.

Testing is valuable regardless of the outcome.

Key Concepts for Supportability Analysis

Conclusions

Supportability analysis concepts can be **applied to any system** or subsystem at any level of available data

Supportability analysis has been used to examine **Environmental Control and Life Support Systems (ECLSS),**[12] future Mars exploration missions,[12] and sustained lunar surface missions.[7,18,19]

Supportability will be a **much larger driver of mass, risk, and crew time** for future human exploration missions due to the more challenging mission context

The real-world processes that drive maintenance requirements and other **supportability-related characteristics are probabilistic**, and therefore **require different mental models and conceptual approaches** than are used for more deterministic aspects of space systems.

[7] Owens et al. 2022 [12] Owens et al. 2020 [18] Lynch et al. 2022 [19] Stromgren et al. 2022

Questions?

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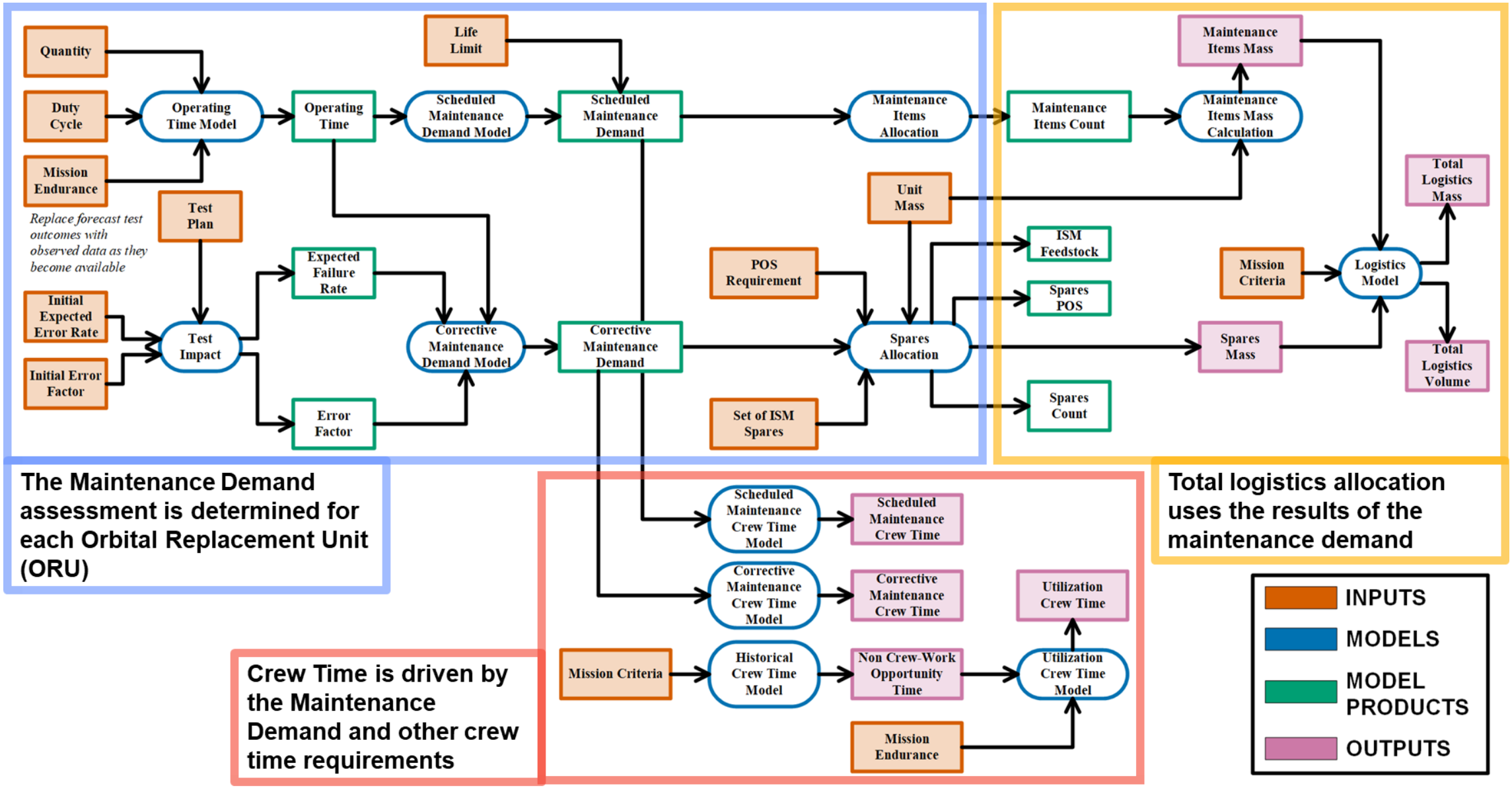
Supportability Modeling



Flow chart from Vega et al., Modeling Logistics and Supportability for Crewed Missions Beyond Low Earth Orbit

Change in Estimated ISS MTBF Values

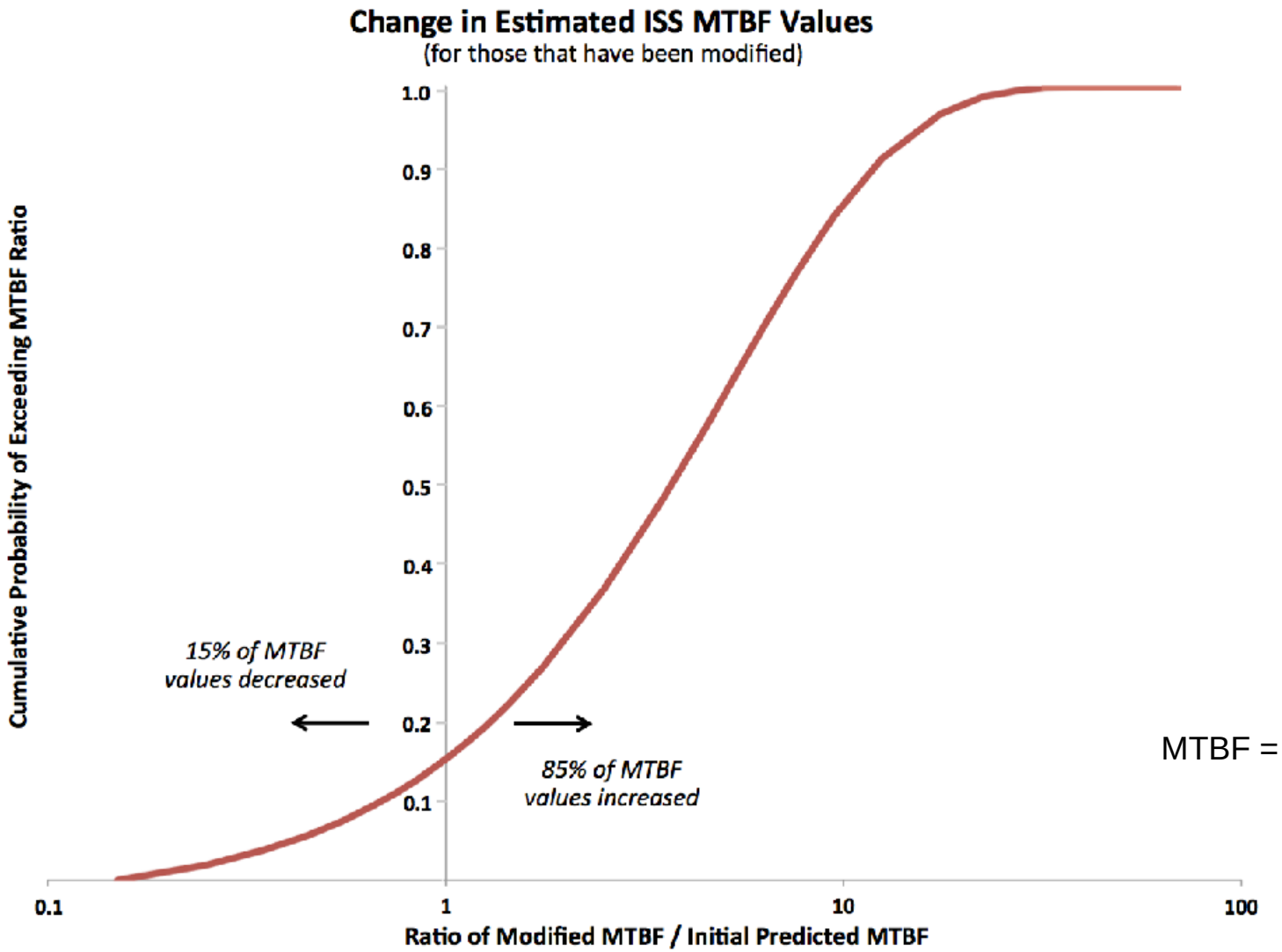


Figure 3 – Change in Estimated MTBF Values (for those that have been modified)

MTBF = Mean Time Between Failures

Figure from Stromgren et al., The Threat of Uncertainty - Why Using Traditional Approaches for Evaluating Spacecraft Reliability Are Insufficient for Future Human Mars