Calculations of Flexibility in Space Systems

Roshanak Nilchiani
Carole Joppin
Prof. Daniel Hastings

Flexibility

“as the ability of a system to adapt and respond to changes in its initial objectives, requirements and environment occurring after the system is in operation in a timely and cost-effective manner”

- (Saleh et. al, 2002)

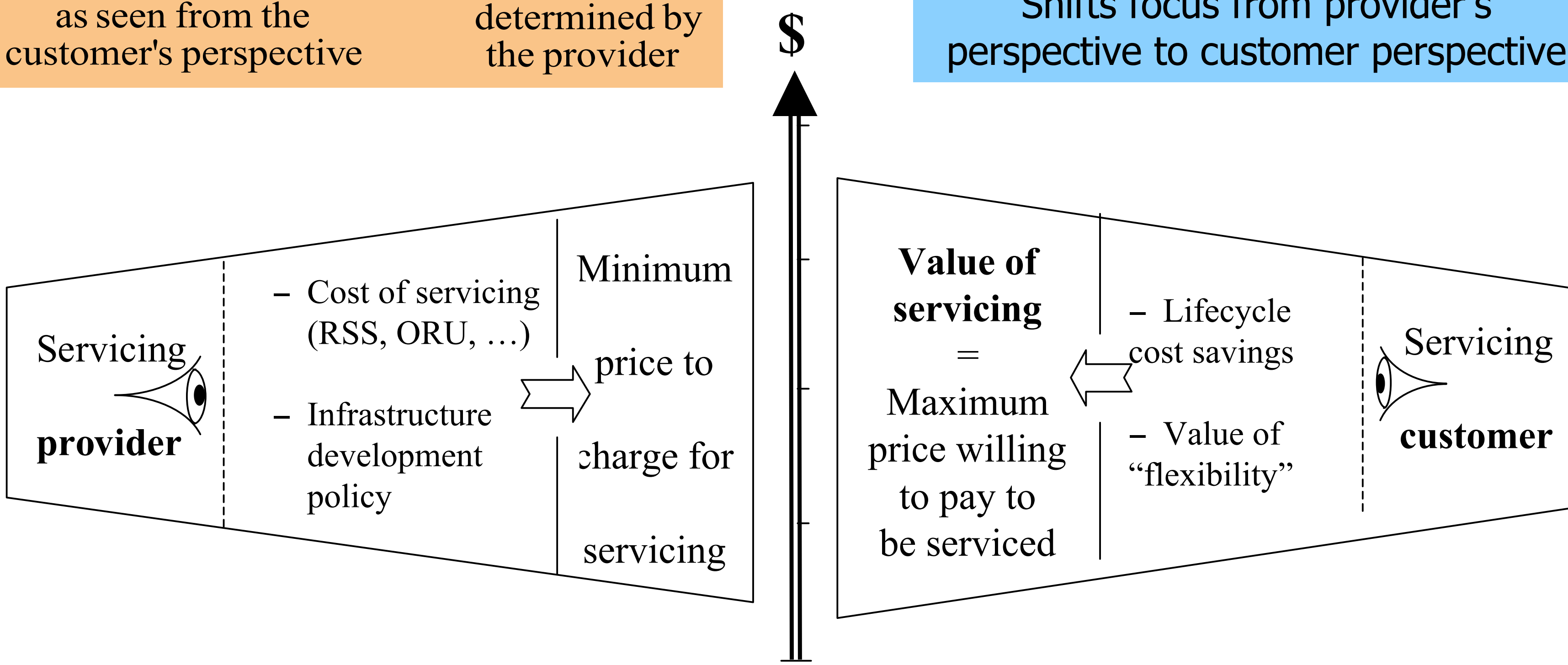
- **can partially protect the operator against risk**
- **and transform uncertainty into new opportunities.**

Flexibility

$$\underbrace{V_{serv} \equiv P_{max\_serv}}_{\text{as seen from the customer's perspective}} > \underbrace{P_{min\_serv}}_{\text{determined by the provider}}$$

Highlighting **value** of servicing:

Shifts focus from provider's perspective to customer perspective



Reference: Saleh et al. "Space Systems Flexibility Provided By On-Orbit Servicing: Part II," *Journal of Spacecraft and Rockets*, Vol. 39, Number 4, July-August 2002, pp. 561-570.

Provider-side Flexibility

–Mix flexibility (long-term change): the strategic ability to offer a variety of services with the given system architecture.

–Volume flexibility (mid-term change): the ability to respond to drastic changes in demand.

–Emergency service flexibility (short term change): the tactical ability of the system to provide emergency (non-scheduled) services to satellites in duress.

Customer-side Flexibility

	System Performance	***System Mission***
Life Extension	Continue same performance level	Same as initial mission
System Upgrade	Increase initial performance level	Same as initial mission
Mission change	-	Extended mission

Provider-side Flexibility

$$f_m = \frac{S_m - E_m}{S - E}$$

$$f_v = \frac{\int_0^E e^{-rt_m}(S - E)p(S)dS}{I_{Risk-free}}$$

$$f_E = \frac{Cap_{\max}}{Cap_{current}}$$

$$f = \frac{\sum_{i=M,V,E} w_i f_i}{\sum_{i=M,V,E} w_i}$$

The overall flexibility metric

A provider-side Flexibility Case Study: Orbital Transportation Network

Orbital Transportation Network: A mass transportation network for refueling, servicing and tugging of satellites and other on-orbit units.

Components:

- Satellites (Military,Commercial, Scientific)
- Infrastructure (Origin points):
  - Fuel Depot(s)
  - Service/Repair Station(s)
  - Ground station(s)
- Vehicles :
  - Launch vehicles
  - Orbital Maneuvering Vehicles (OMVs)

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Development of Value and Performance Metrics

Value metric:

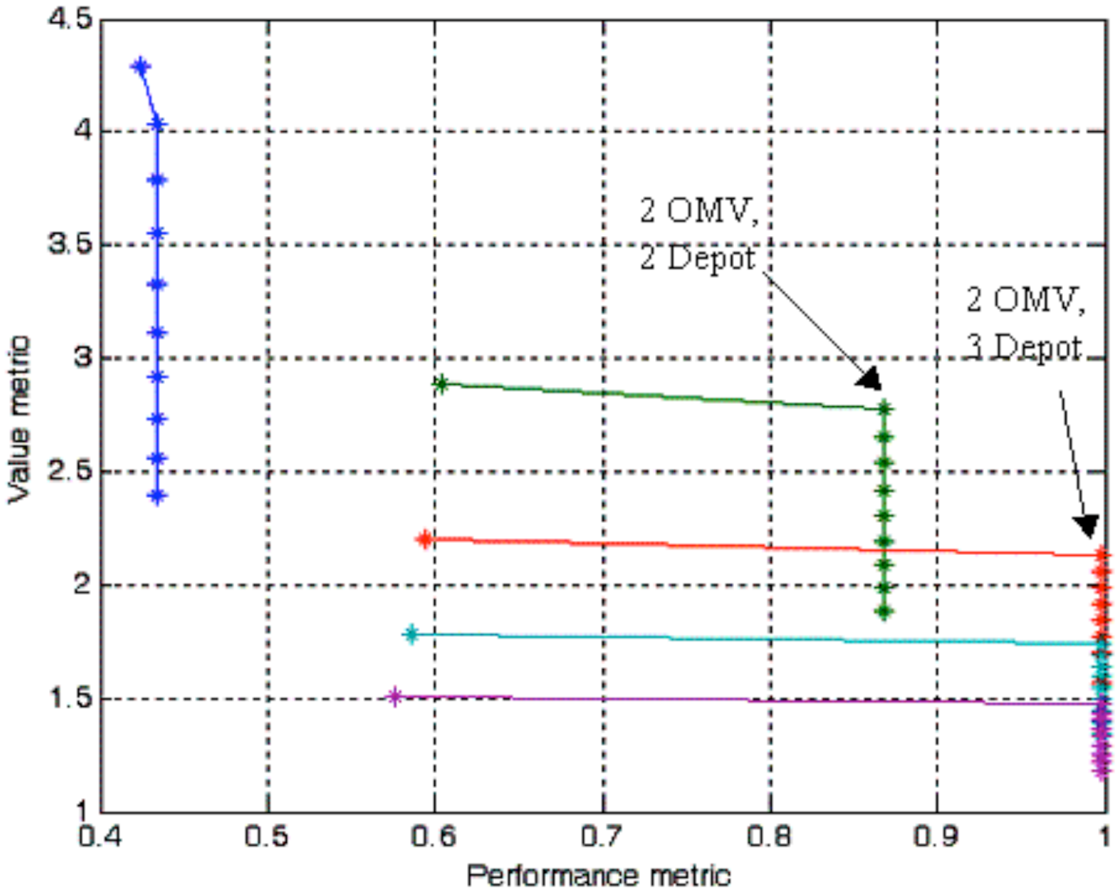
$$V = \frac{\Pr_{customer}}{C_{provider}}$$

The value metric above 1 shows that the architecture is economically viable

The **performance metric**, is the product of availability of service and reliability of service , and measures from 0 to 1.0.

- **Availability**: the fraction of completed missions to required missions.
- **Reliability**, *is* defined as the fraction of missions that are successful.

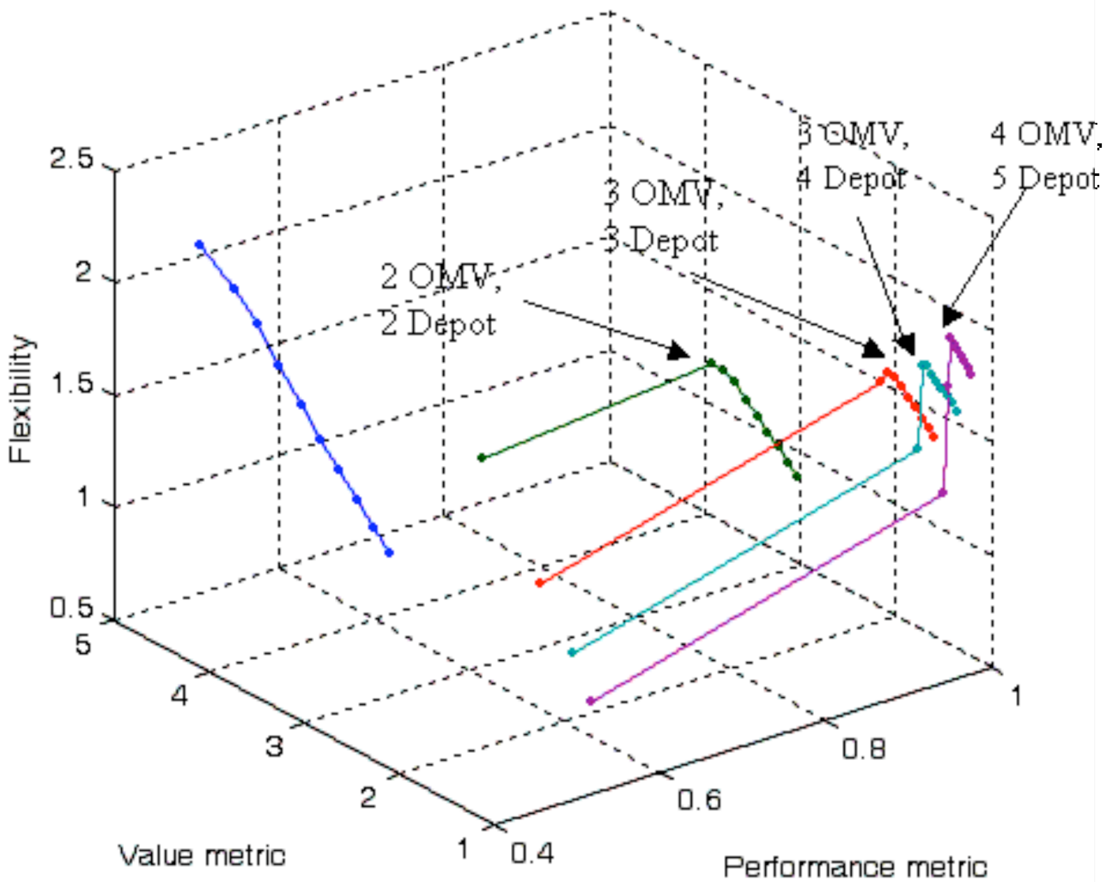
A provider-side Flexibility Case Study: Orbital Transportation Network



Optimal architectures based on value metric and performance metric.

(Based on a refueling price of $8 million per satellite for satellites in GEO, and a client set of 110 satellites).

A provider-side Flexibility Case Study: Orbital Transportation Network



Optimal architectures based on value metric, performance metric and flexibility metric.

(Based on a refueling price of $8 million per satellite for satellites in GEO, and a client set of 110 satellites, we assumed w_v=0.2, w_E=0.7, w_M=0.1).

Consideration of the Flexibility, Changes the optimal architectures.

A Customer-side Flexibility Case Study: Hubble Space Telescope

- Designed in the 1970s
- Launched on April 25th 1990
- Only space platform ever designed to be regularly serviced by the Space Shuttle
  - 4 servicing missions
  - Reproduce in space the equivalent of an observatory on Earth

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Achievements of the servicing missions

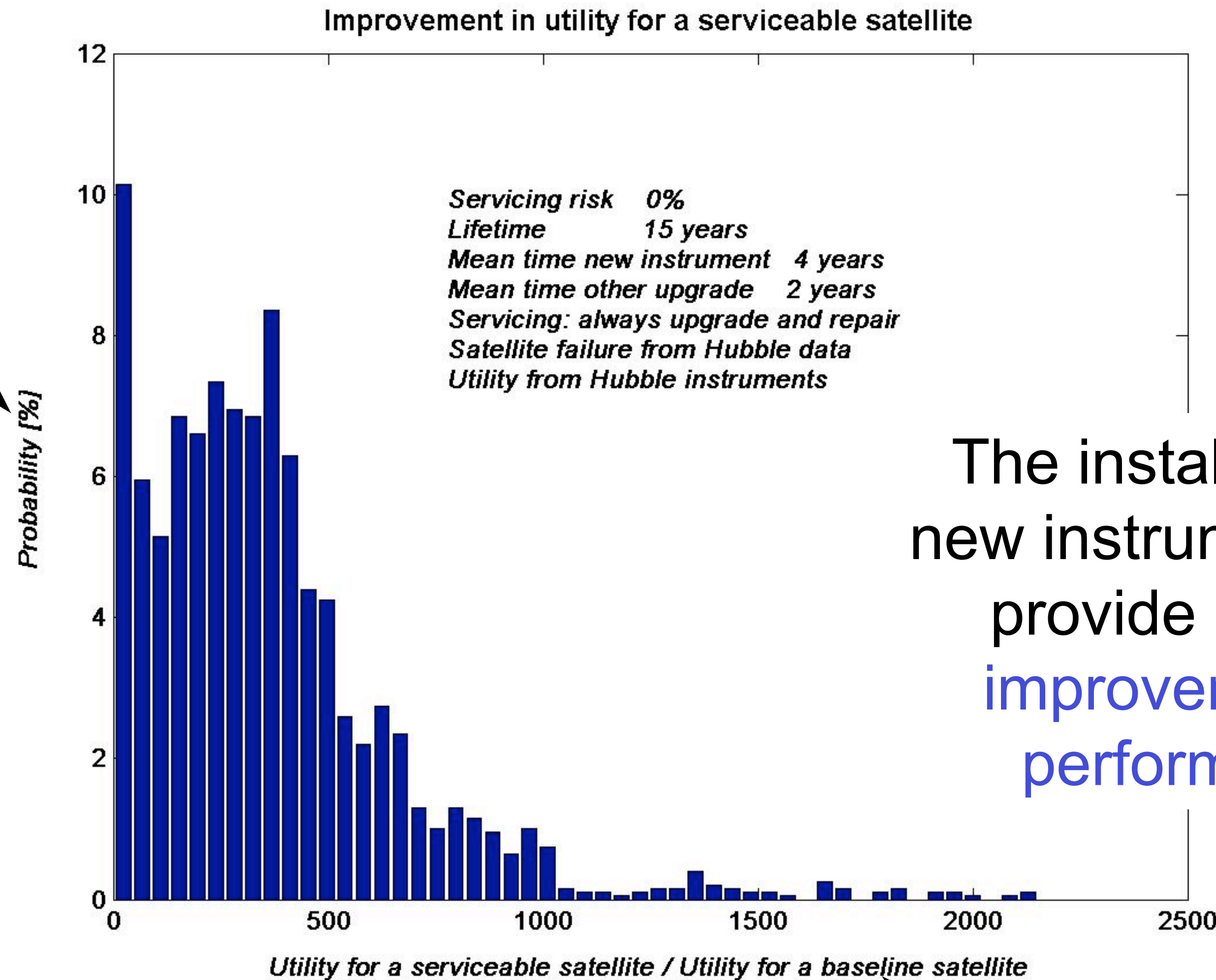
- Mission salvage
- Repair and maintenance
- Instrument upgrade
- Other bus upgrades

On-orbit servicing missions have made the Hubble Space Telescope a state of the art observatory along the 13 years it has been operated

Model of a Scientific Space observatory
Based on the Hubble Space Telescope Mission

- *Evaluation Method:* Monte Carlo simulation
- *Utility metric:* Discovery efficiency
- *Mission utility* depends on:
  - Platform instrument generation
  - Platform instrument compatibility with the other on-board bus subsystems
- *Servicing operations* considered:
  - Spacecraft repair
  - New instrument installation
  - Upgrade of other bus subsystems
- *Decision model:* The operation is carried out if the utility per cost metric exceeds a predefined threshold.

Mission Utility for a Serviceable Architecture (1)

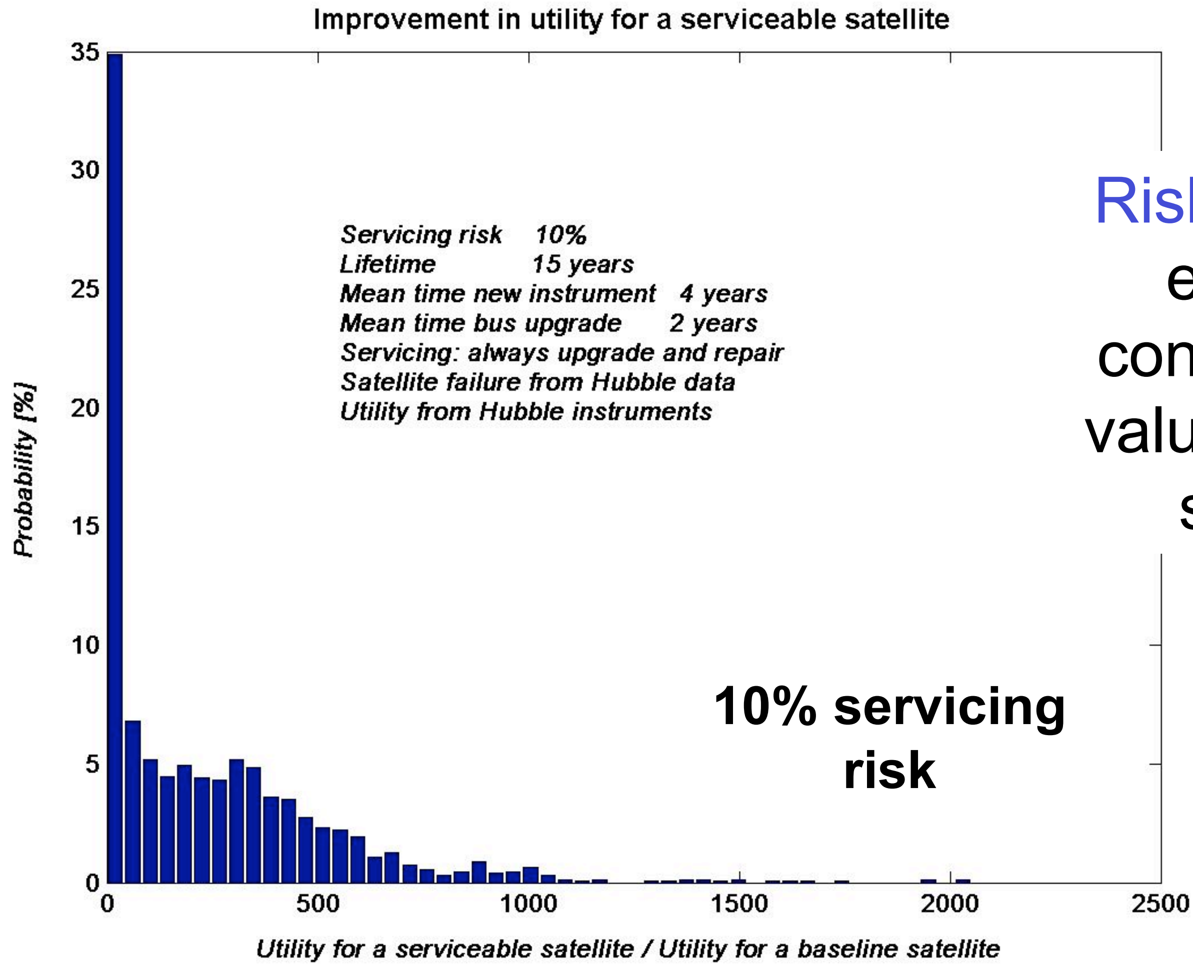


Probability

Utility improvement

The installation of new instruments can provide a huge improvement in performance

Mission Utility for a Serviceable Architecture (2)



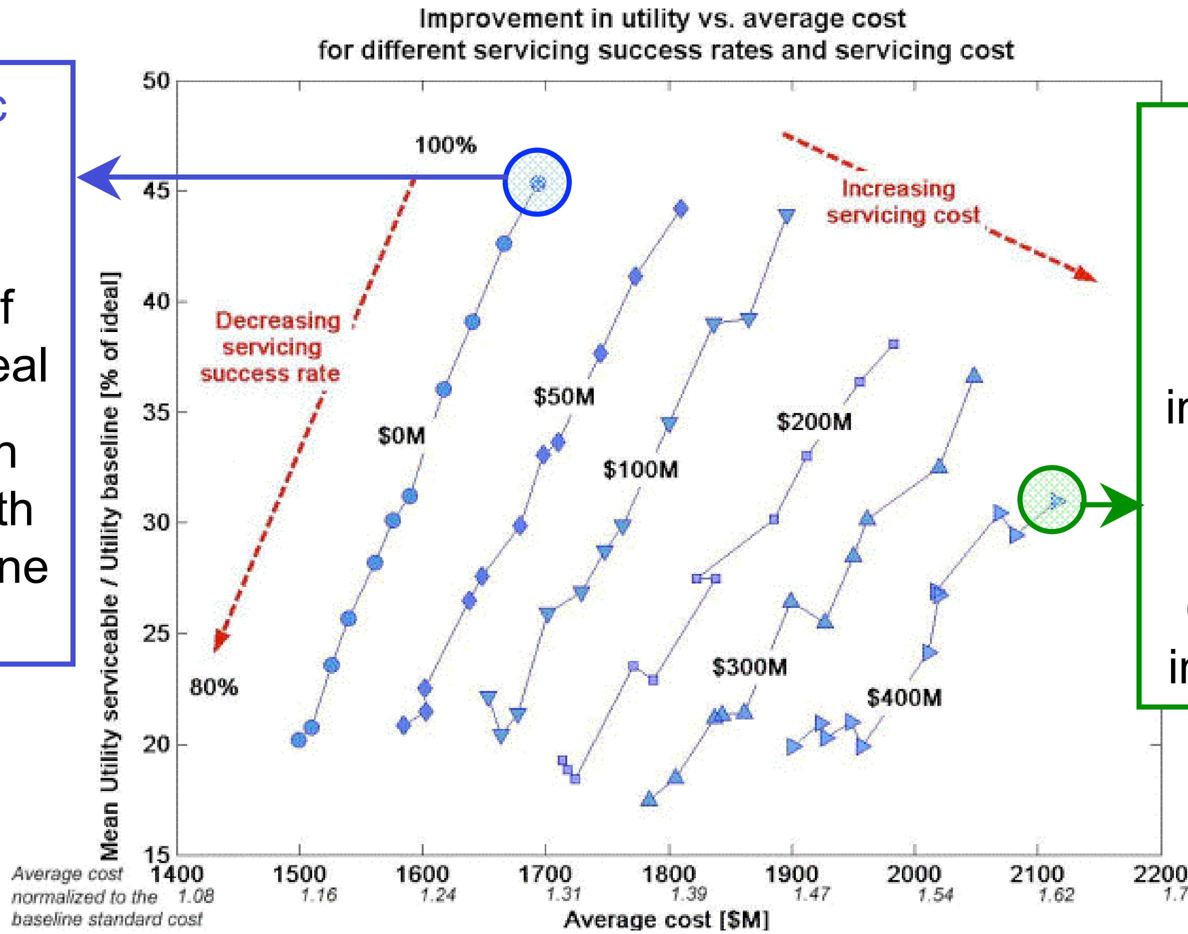
Risk is a critical element in considering the value of on-orbit servicing.

System Design Choices: Reliability, System replacement, Flexibility

Most optimistic case:

Mean improvement of utility: 45% of ideal

30% increase in average cost with respect to baseline architecture



Shuttle servicing mission cost

Mean improvement of utility: 30% of ideal

62% increase in average cost

The flexibility associated with servicing comes at substantially smaller cost than replacing the system.

The change in utility associated with servicing is so large that it is hard to achieve similar changes for less cost.

Conclusion

- Consideration of flexibility in the design of space systems architecture changes the optimal architecture.
- The feasibility of designing flexibility into a space system depends heavily on the value of the service that the system is providing.
- Consideration of flexibility is a crucial element of architecture design and provides a fundamental ability for space systems to respond to external changes and results in considerable cost savings.