Value-Driven Analysis of New Paradigms in Space Architectures: An Ilities-Based Approach

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Agenda

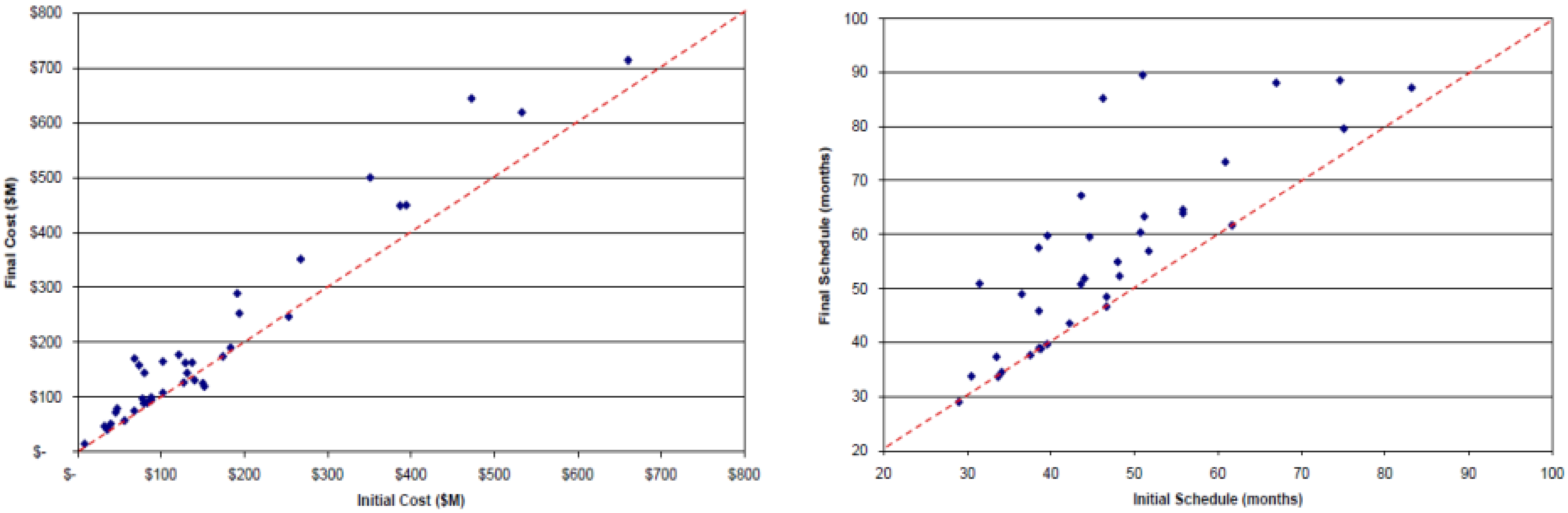
- BLUF
- Introduction and Background
  - Underlying issues with current paradigms
  - Current developments in new trends
- Methods
  - Defining the *ilities*
- Discussion
  - Assessment of ilities offered by each trend
- Conclusions and future work

Bottom Line Up Front

- Current space architectures are NOT taking advantage of available technology improvements and policy alternatives
- Five new ***trends*** can shift paradigms:
  - **Commercialization of space**
  - **Decreased launch costs and reusable launch**
  - **On-orbit servicing and infrastructure**
  - **Aggregation and disaggregation of assets**
  - **Standardized, automated ground systems**

Introduction

- Current space architectures perform exquisitely and reliably
- However, cracks are beginning to show:

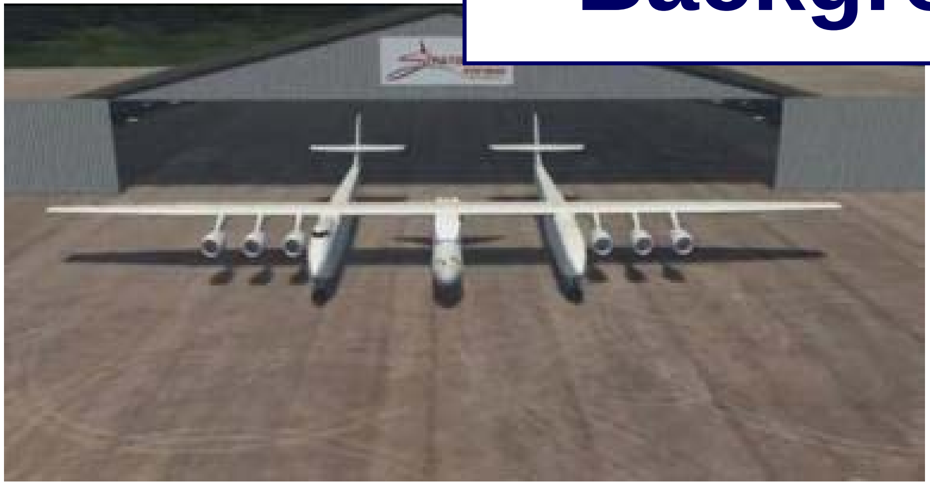


Figures: Cost and schedule overruns of 40 recent NASA space missions, largely due to internal cost/schedule growth (Emmons, Bitten, and Freaner 2007).

New Trends

- New **trends** are emerging which could address these issues and cause significant paradigm shifts in space architectures:
  - **Commercialization of space**
  - **Launch cost reductions and reusable launch**
  - **On-orbit infrastructure and servicing**
  - **Aggregation and disaggregation of assets**
  - **Standardized, automated ground systems**

Background



[Photo credits (CW from top left): NASA Image Archives; DARPA System F6; Scaled Composites Stratolaunch; NASA GSFC.]

Commercialization of Space

- This trend seeks to leverage the strengths of industry in order to decrease costs while maintaining quality
- Shift in *policy*, not technology
  - Pushes greater amount of risk to profit-seeking firms
  - Utilizes well-established processes like industrial learning and scale effects to decrease costs and development cycles

*Pictured are the mission logos of commercial ISS resupply missions conducted by SpaceX and Orbital Sciences.

Developments in Launch

- Cost of launch has stubbornly remained one of the greatest barriers to space utilization
  - Launch costs regularly exceed $10,000/kg
- Proposed solutions include:
  - Reusable and hybrid launch vehicles
  - Commercialization and competition in launch sector

*Pictured: 2014 test of SpaceX reusable first stage technology (Space.com, 2014)

On-Orbit Infrastructure and Servicing

- The ability to repair, refuel, and upgrade spacecraft in orbit has long been envisioned as a means of adding significant value to space architectures
- Orbital infrastructure can also take the form of constellations of resource-sharing payloads
  - The Federated Satellite Systems (FSS) framework shows how a constellation could provide in-orbit data processing and relay (Golkar 2013)

Aggregation/Disaggregation

- Aggregation of missions on to fewer platforms has been an initial response to increased launch and development costs
- Disaggregated space architectures have also been touted as a means of adding value to space architectures
  - While aggregation may lead to cost savings, disaggregation promises to add even greater value to architectures, beyond decreased cost

Automated Ground Systems

- Current Air Force ground control systems rely largely on manpower-intensive human computation of satellite passes
  - Also requires approximately *two years* to add a new mission to the network
- As constellations grow, the current system may be overwhelmed and unable to keep up with the number of computations required
- The solution lies in standardized, automated ground systems, demonstrated by Navy's CGA

Methods

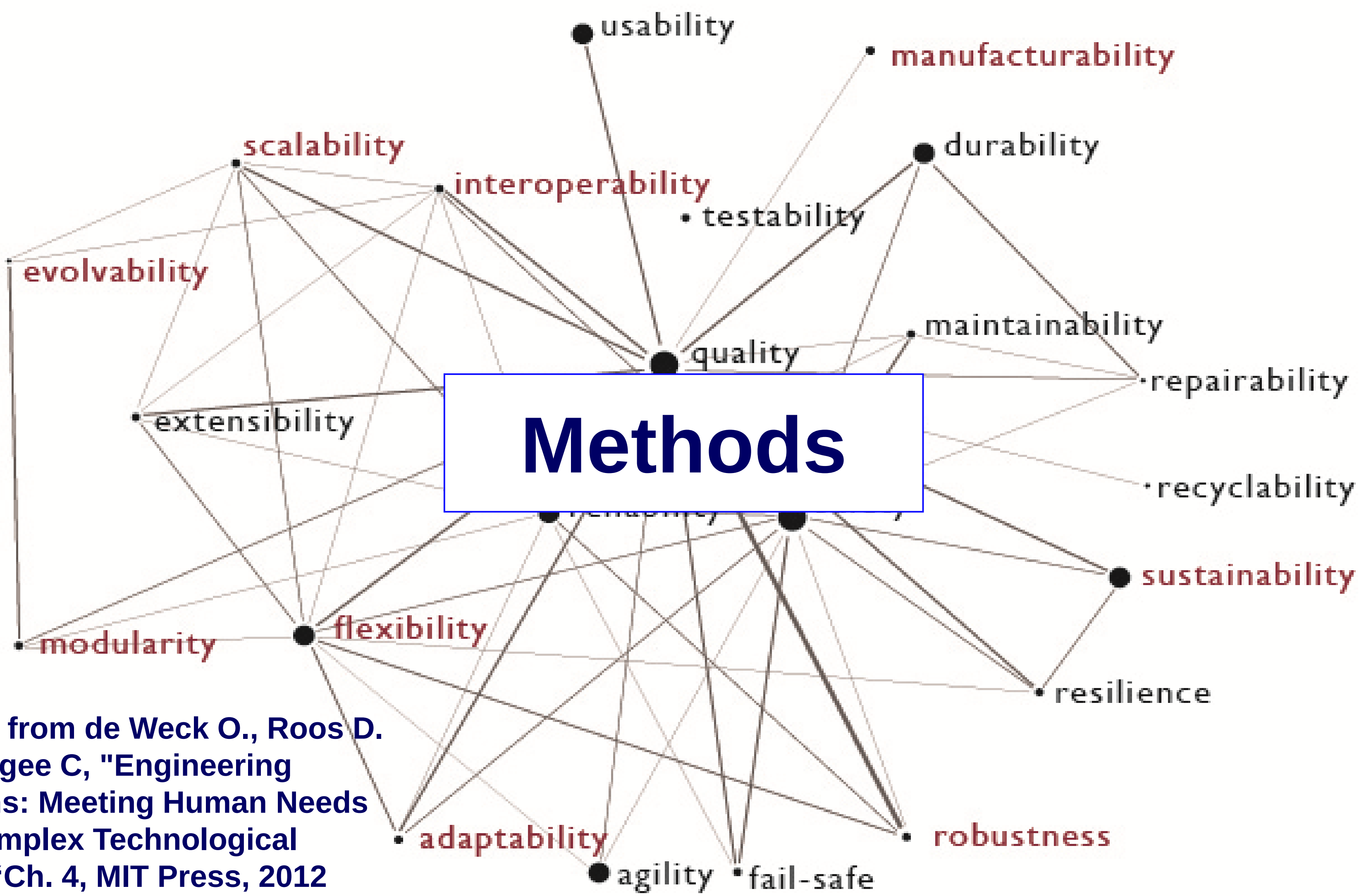


***Figure from de Weck O., Roos D. and Magee C, "Engineering Systems: Meeting Human Needs in a Complex Technological World,"Ch. 4, MIT Press, 2012**

Ilities

The ***ilities*** are desired properties of systems, such as flexibility or maintainability (usually but not always ending in "ility"), that often manifest themselves after a system has been put to its initial use.

These properties are not the primary functional requirements of a system's performance, but typically concern wider system impacts with respect to time and stakeholders than are embodied in those primary functional requirements.

The ilities do not include factors that are always present, including size and weight (even if these are described using a word that ends in "ility").

-de Weck, Roos and Magee 2011

Ilities

- *Ilities* are relatively intangible attributes, often left unquantified, which characterize a system's response to changes in ***context***
- Our analysis focused on the following ilities:

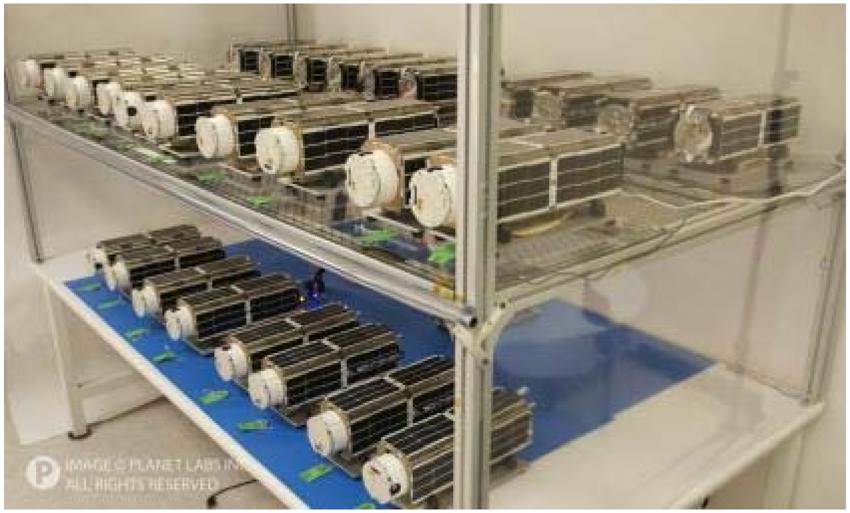
Quality	**Scalability**
Reliability	**Extensibility**
Affordability	**Testability**
Survivability	**Flexibility**
Robustness	**Resiliency**

*Photo credit: European Space Operations Centre, European Space Agency (ESA), http://www.esa.int/About_Us/ESOC/Fifth_European_Conference_on_Space_Debris_to_address_key_issues

Commercialization

- This trend contributes the following ilities:

Robustness **Testability**
Scalability **Quality**
Extensibility **Affordability**



Pictured: Planet Labs Flock 1 (forbes.com); Cubesats launched from the ISS (amsat-uk.org)

Developments in Launch

- This trend contributes the following ilities:

Robustness | **Flexibility**

Resiliency | **Quality**

Testability | **Affordability**

Pictured: Virgin Galactic White Knight 2 (newscientist.com); SpaceX Grasshopper (spacex.com)

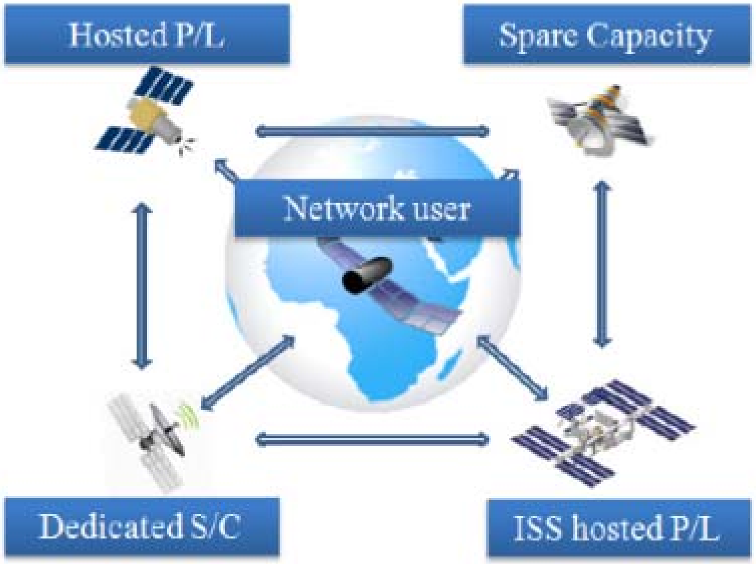
On-Orbit Infrastructure and Servicing

- This trend contributes the following ilities:

Robustness **Extensibility**

Resiliency **Flexibility**

Scalability



Pictured: DARPA Orbital Express (darpa.mil); Federated Satellite Services (Golkar 2013)

Aggregation/Disaggregation

- This trend contributes the following ilities:

Survivability

Resiliency

Robustness

Scalability

Extensibility

Testability

Flexibility

Photo credit: DARPA System F6 Disaggregated Architecture Study (darpa.mil)

Automated Ground Systems

- This trend contributes the following ilities:

Survivability	**Testability**
Scalability	**Flexibility**
Extensibility	**Affordability**

- Common ground architectures primarily reduce the risk that a system's utility will be degraded due to overwhelming complexity within the ground segment

Photo credit: GPS ground station at Schriever AFB (http://www.af.mil/shared/media/photodb/photos/040205-F-0000C-001.jpg)

Conclusions and Future Work

Photo credit: James Vernacotola, Feb. 2010

Conclusions

- The five trends presented offer significant value to space architectures, in the form of *ilities*, and would shift architectures to new and more sustainable paradigms
- Whether or not these trends lead to paradigm shifts is yet to be seen
  - Risk management practices must also be changed in order to shift to new paradigms

Future Work

- System dynamics and tradespace exploration would be useful in assessing the overall utility of new architectural trends
  - Both under normal operating contexts as well as significant context shifts during a system's lifecycle
- Modeling must be focused on understanding the break points in shifting space architectures to new paradigms

Final Thoughts

- With these trends, we envision space architectures that are:
  - **Increasingly funded and developed by commercial firms**
  - **Launched much less expensively and more frequently**
  - **Composed primarily of smaller, simpler, shorter-lived space vehicles**
  - **Linked to servicing infrastructures that provide valuable resources**
  - **Seamlessly integrated to ground systems**

Systems Engineering Advancement Research Initiative

Questions?