A Complex Systems Perspective of Risk Mitigation and Modeling in Development and Acquisition Programs

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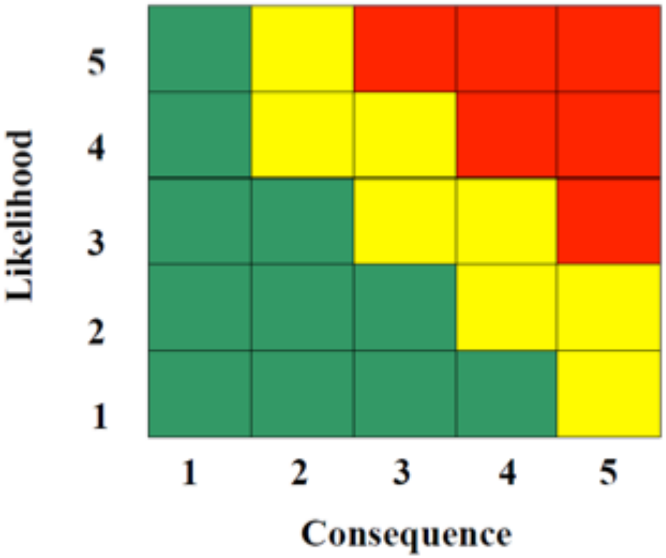
Some Problems with the Current Guidance



"Risk is a measure of future uncertainties in achieving program performance goals and objectives within defined cost, schedule and performance constraints."
- Office of the Undersecretary of Defense

- The current risk identification method does not inform the decision makers well on the underlying causes of risk and consequences.
- No variation (error bars) around three colors. Abrupt shift from one color to other is possible and is seen in practice. Interactions and ordering among risks cannot be shown. Consequences are not presented in tangible forms of potential cost and schedule overruns as well as underperformance
- No typology of risks associated with causes (internal, external), phases of life cycle (certain risks are more common in particular phases), and interconnections among choices.
- Consequences are not presented in tangible forms of potential cost to remedy (a NASA practice) and extent of schedule overruns. PMs cannot use risk matrix to make trades.

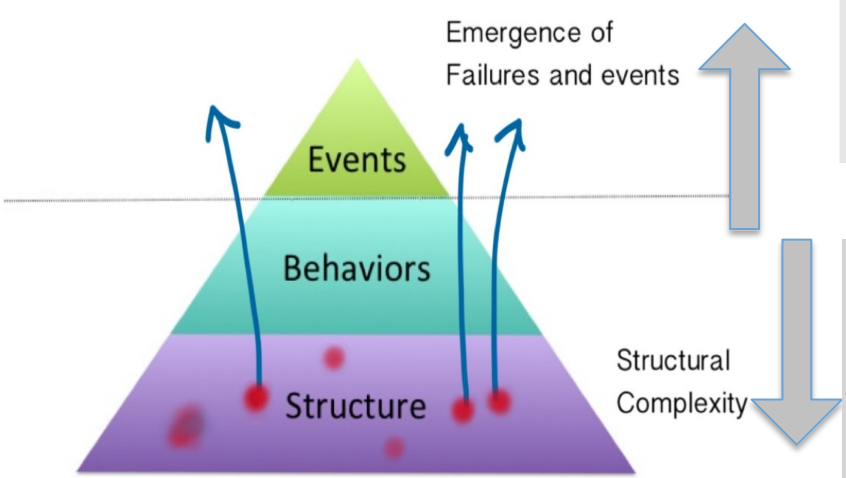
Different Approaches

Two major different Approaches:

1. Incrementally improve the existing probability based assessment methods & tools, including adaptation of risk assessment methods from other disciplines.

2. Investigate and examine program artifacts for roots of technical risk. These in many instances originate from the structure and architecture of the system or from the organization creating the system. Feedback loops and existence of delays are a few of the examples of issues that are often the deep sources of technical risks. Create quantitative measures of the structure of the system and correlate them to current risk measures of the acquisition program.

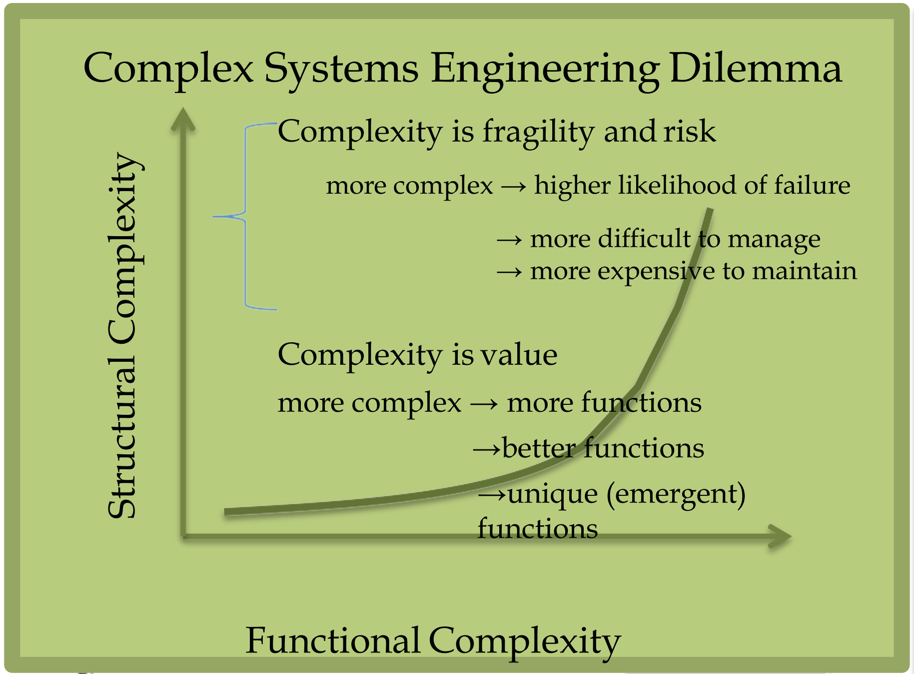
Problem Statement

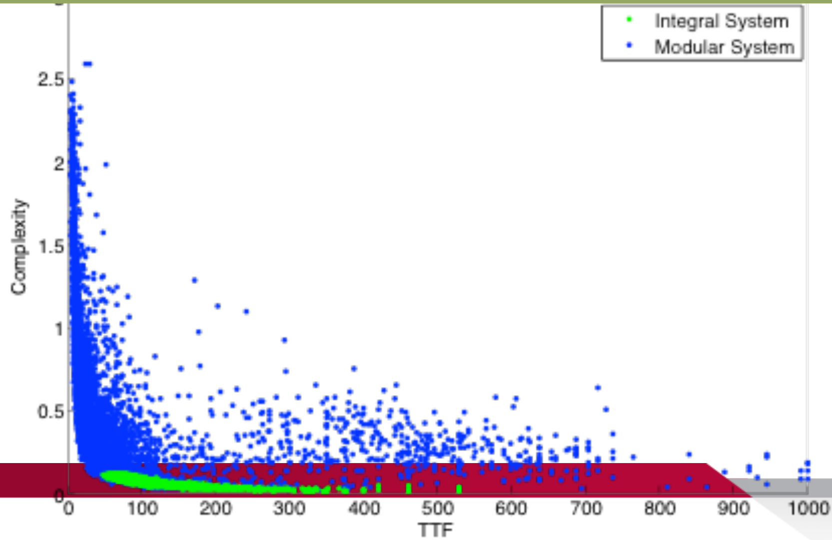


Domain of Risk identification and analysis: A large portion of risks and consequences internal to the system, are observable as symptoms of deeper underlying structure of the system

Domain of Hidden Structural Complexity and Dynamics, vulnerability and fragility: Certain signatures and behavior rooted in structure of the technical system and/or the organization cause the increased risk at the surface level.

Research Approach





Complex systems exhibit:

- Potential for unexpected behavior
- Non-linear interactions
- circular causality and feedback loops
- May harbor logical paradoxes and strange loops
- Small changes in a part of a complex system may lead to emergence and unpredictable behavior in the system (Erdi, 2008)
- Different from complicated systems

The increased complexity is often associated with increased fragility and vulnerability of the system.

By harboring an increased potential for unknown unknowns and emergent behavior, the probability of known interactions that lead to performance and behavior in a complex system decreases, which in turn leads to a more fragile and vulnerable system.

Research Approach

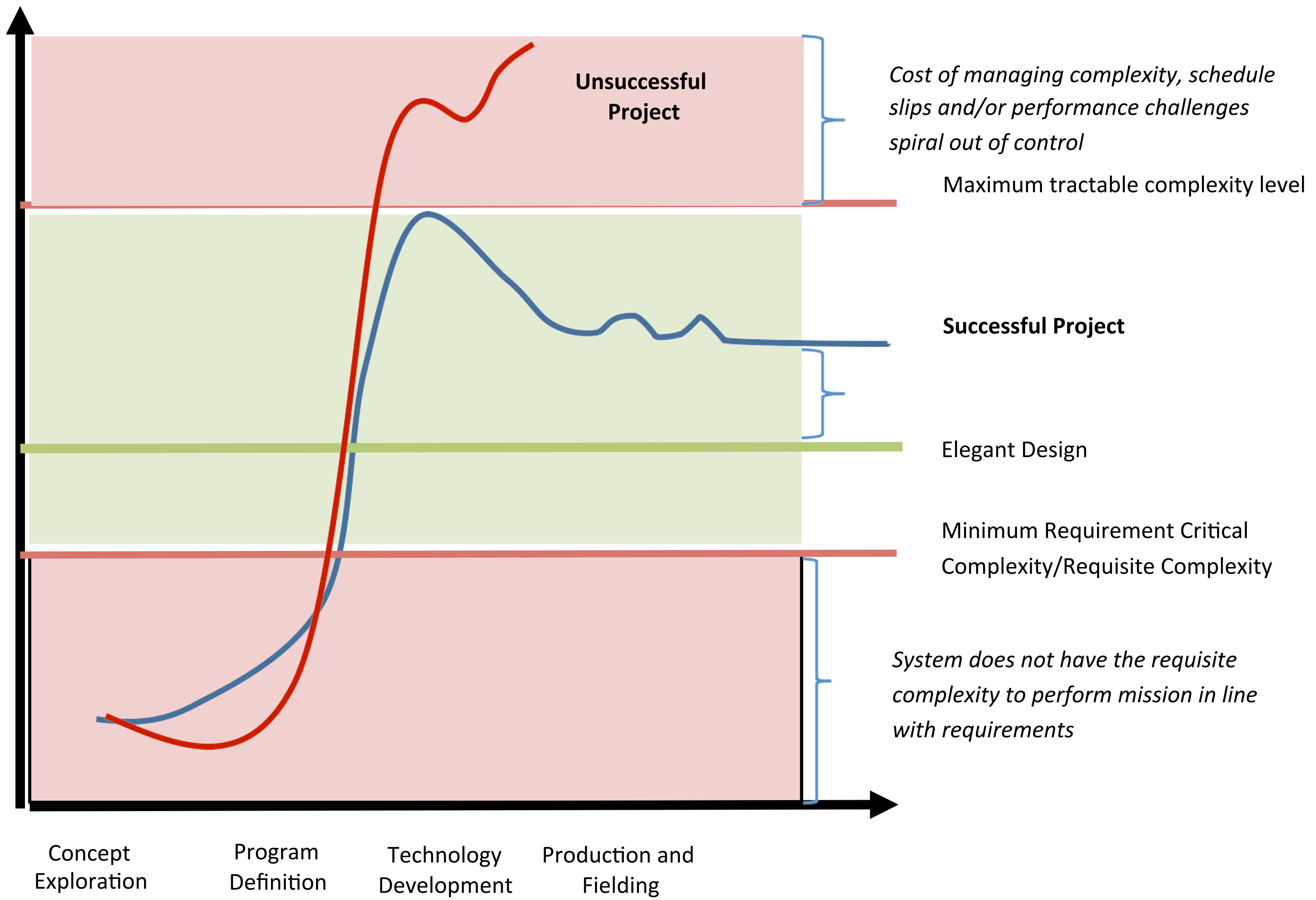
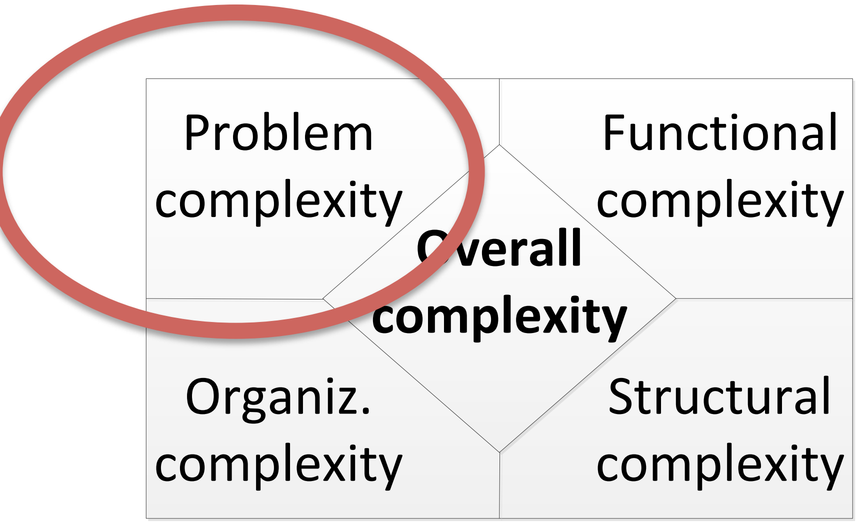


Figure 11. Complexity evolution throughout the systems acquisition lifecycle

Problem Complexity and Requirements



C	=	complexity index
C_f	=	functional complexity index
C_o	=	organizational complexity index
C_p	=	problem complexity index
C_s	=	structural complexity index

Functional requirements (*Do*)

What the system does in essence, which includes what it accepts and what it delivers

Performance requirements (*Being*):

How well the system does it, which includes performance related to functions the system performs or characteristics of the system on its own, such as –ilities

Resource requirements (*Have*):

What the system uses to transform what it accepts in what it delivers

Interaction requirements (*Interact*):

Where the system does it, which includes any type of operation during its life-cycle.

$$H = -K \cdot \sum_{i=1}^{n} p_i \cdot log_j(p_i)$$

$$C(C_p, C_f, C_s, C_o) = -\sum_{c_p}\sum_{c_f}\sum_{c_s}\sum_{c_o} P(c_p, c_f, c_s, c_o) \cdot log_j[P(c_p, c_f, c_s, c_o)]$$

A conflict may exist when…

…two or more requirements ***compete for the same resource***.

…two or more requirements oblige the system to ***operate in two or more phases of matter***.

...two or more requirements inject ***opposing directions in laws of society***.

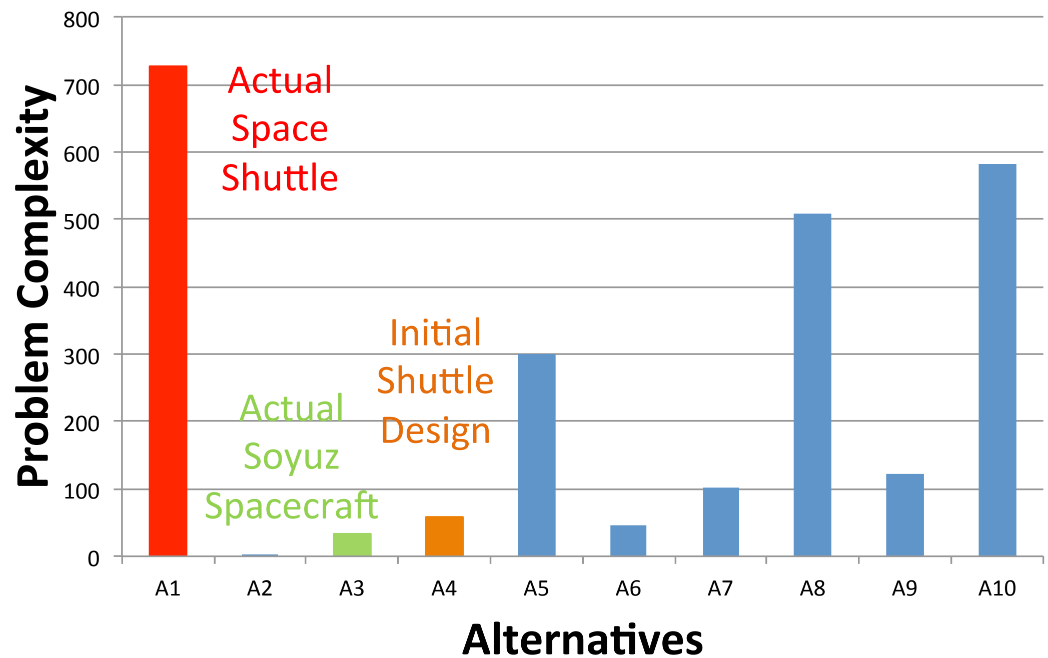
…two or more requirements inject ***opposing directions in laws of physics***.

$$C_p = K \cdot \left(\sum_{i=1}^{n} a_i \cdot r_{f_i} \right)^E \cdot \prod_{j=1}^{m} H_j^{\,b_j}$$

where K is a calibration factor that allows problem complexity to be adjusted to accurately reflect an organization's business performance. The first term represents the size of the requirement set, i.e., how many functional requirements rf the system has to fulfill. These are weighted (*a*) to reflect inherent difficulty of requirements and adjusted for diseconomies of scale (*E*). The last term represents complexity modifiers derived from amount and types of conflicts (*H*). They are adjusted to reflect influence and diseconomies of scale (*b*).

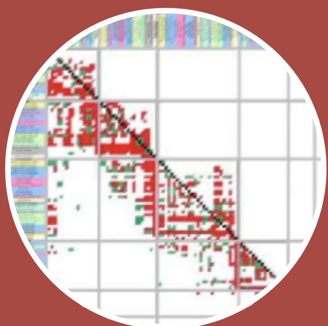
The spacecraft was a partially **reusable** human spaceflight vehicle for Low Earth Orbit, which resulted from joint **NASA and US Air Force** efforts after Apollo. “The vehicle consisted of a **spaceplane** for orbit and re-entry, fueled by an expendable liquid hydrogen/liquid oxygen tank, with reusable strap-on solid booster rockets. […] A total of five operational orbiters were built, and of these, **two** were destroyed in **accidents**.”

“Soyuz is a series of spacecraft initially designed for the **Soviet space programme** and **still in service today**. […] The Soyuz was originally built as part of the Soviet Manned Lunar programme. […] The Soyuz spacecraft is launched by the Soyuz rocket, the most frequently used and **most reliable** Russian launch vehicle to date.”



Problem Complexity: Shuttle vs. Soyuz

Hybrid Structural-Behavioral Complexity Framework



Structural Complexity Metrics

- DSM Based
- Evaluate the complexity of the architecture
- Many examples in existing literature

Interface Characterization Model

- Way of comparing incommensurable interfaces
- Looks at the effect of the interface
- Ranks interfaces based on the level of enablement

Behavioral Complexity Metrics

- Based on the behavior of the system
- Evaluate the complexity of the output
- Many examples in existing literature

Hybrid Structural-Behavioral Complexity Framework

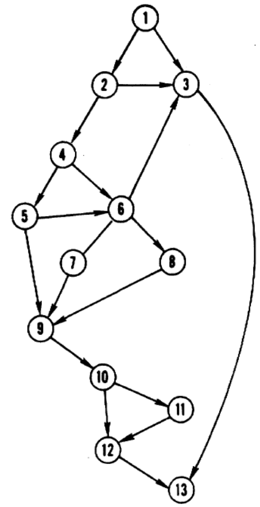
1. Define the architecture of the engineered system
2. Characterize the boundaries and interfaces of each component
3. Use behavioral complexity metrics to assess the complexity of each component
4. Use structural complexity metrics to evaluate the complexity of each subsystem
5. Repeat the previous steps to evaluate the complexity of higher level subsystems

Structural Complexity Metrics McCabe (1976)

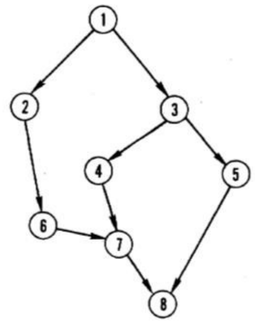
Complexity metric $v(G)$:

$$v(G) = e - n + 2p$$

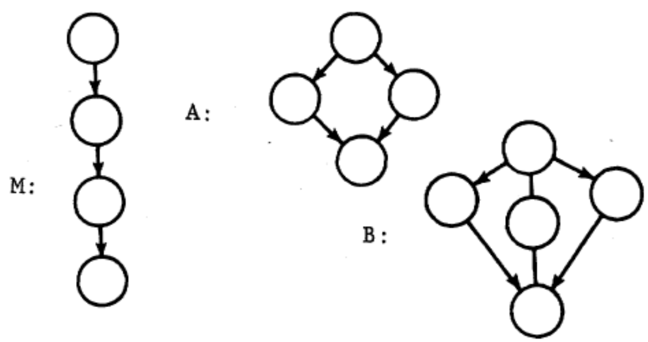
- e is the number of edges
- n is the number of vertices
- p is the number of connected components



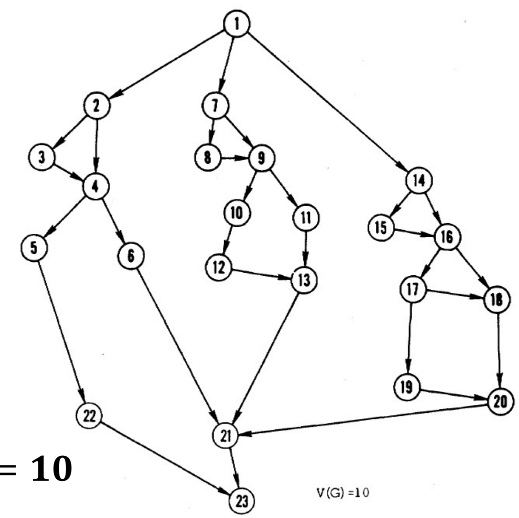
$v(G) = 19 - 13 + 2 * 1 = 8$



$v(G) = 9 - 8 + 2 * 1 = 3$



$v(MAB) = 13 - 13 + 2 * 3 = 6$



$v(G) = 31 - 23 + 2 * 1 = 10$

Structural Complexity Metrics Cotsaftis (2009)

Complexity metric C_S:

$$C_S = n/N$$

- N is the total number of nodes in the system
- n is the number of components that satisfy the inequality

$$\inf p_{i\,j} \gg p_{i\,i}, p_{i\,e}$$

- $p_{i\,j}$ is the flux of resource from node i to node j
- $p_{i\,i}$ is the generation or usage of resource for node i
- $p_{i\,e}$ is the resource flux from node i to the environment

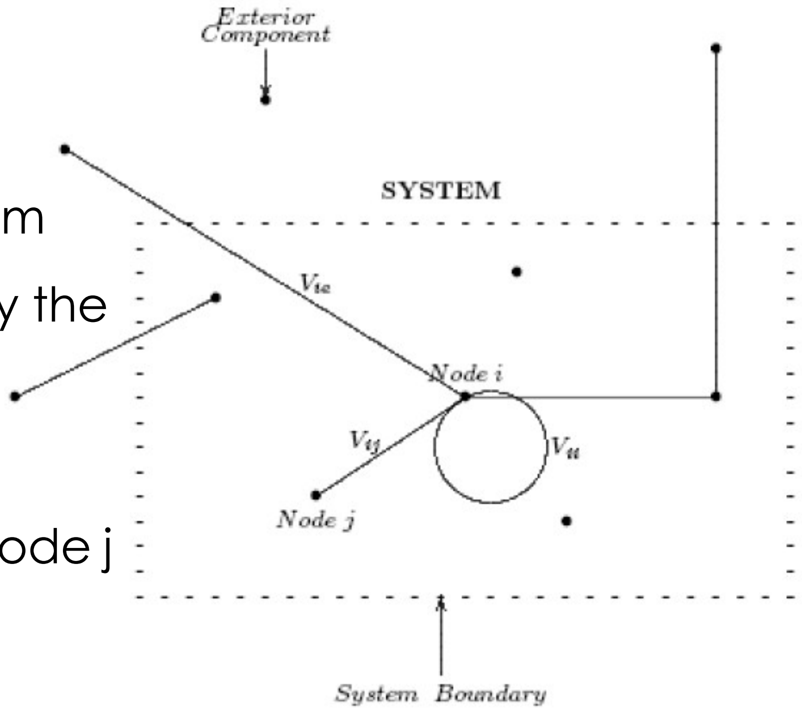


Fig. 2 : Graph Representation of System with its Three Exclusive Types of Vertices V_{ii}, V_{ie} and V_{ij}

Structural Complexity Metrics Sinha & deWeck (2012)

Complexity metric $C(n, m, A)$:

$$C(n,m,A) = \sum_{i=1}^{n} \alpha_i + \left(\sum_{i=1}^{n} \sum_{j=1}^{n} \beta_{ij} A_{ij} \right) \gamma E(A)$$

- n is the number of components
- α_i is the complexity of each component i
- β_{ij} is the complexity of the interface between components i and j
- A is the adjacency matrix of the system
- $\gamma = 1/n$
- $E(A)$ is the energy of the adjacency matrix which is the sum of the singular values of A, evaluated through singular value decomposition

Interface Characterization Model Enablement and Constraint

Components in engineered systems are connected to other components so they can either do thinghs they can't do alone (enablement), or so that they cannot do things they would otherwise do (constraint).

Assumption: for each interface between two components the level of enablement/constraint that a component exercises on the other can be measured.

The model will quantitatively rank interfaces based on the level of enablement/constraint, independently from their nature (e.g. mechanical, thermal, chemical, electromagnetic).

http://www.zerohedge.com/sites/default/files/images/user5/imageroot/2014/08/herd%20direction.jpg

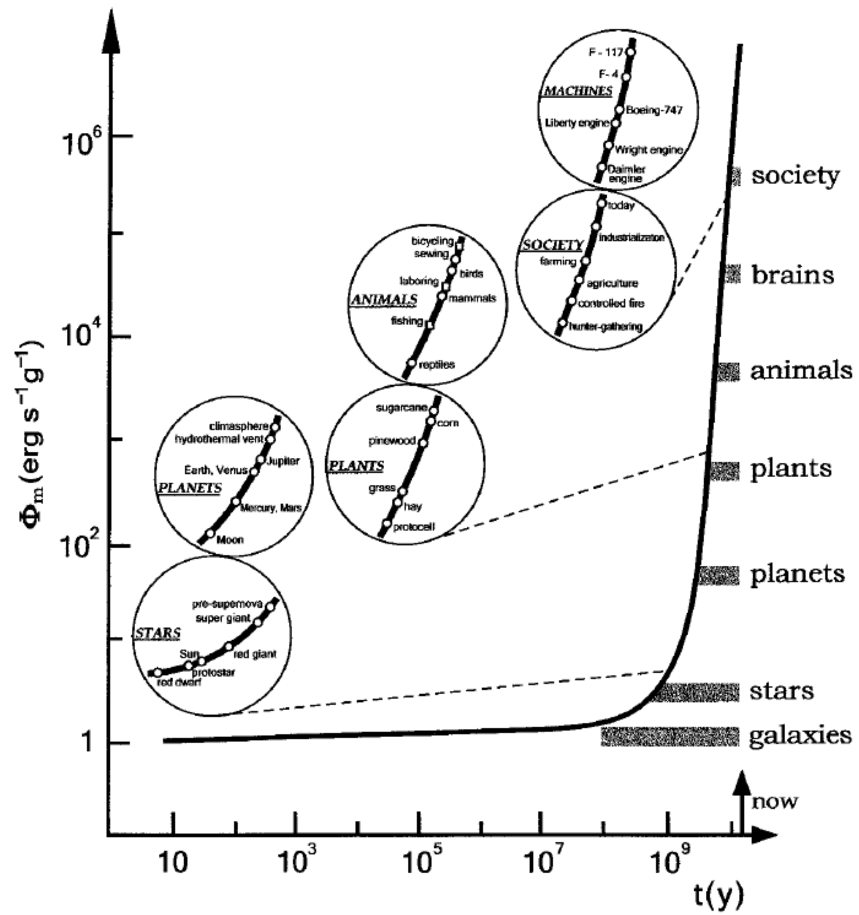
http://thatscienceguy.tumblr.com/post/48996081962

Behavioral Complexity Metrics Chaisson (2004)

Chaisson just provides a definition for this metric as, free energy rate density, which is *energy entering the system per unit of time per unit of mass*.

He did although evaluate its value for many entities in the universe.

The accurate trend leads to think that a metric based on this concept could be useful in the measurement of complexity for engineered systems.



Behavioral Complexity Metrics Willcox (2011)

Complexity metric $C(Q)$:

$$C(Q) = \exp(h(X))$$

$$h(X) = -\int_{\Omega_X} f_x(x) \log f_x(x)\, dx$$

- X is the joint distribution of the quantities of interest
- $h(X)$ is the differential entropy of X
- Ω_X is the support of X
- f_x is the pdf of a specific distribution

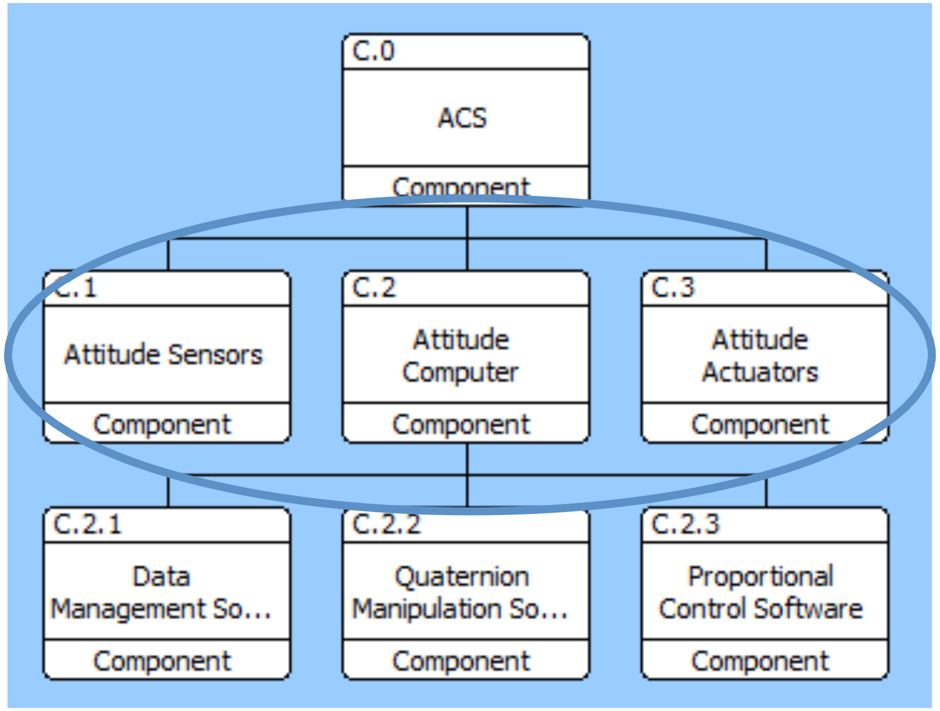
This metric shows how the framework would be able do accommodate uncertainty at the component level.

Use Case: Satellite Attitude Control System

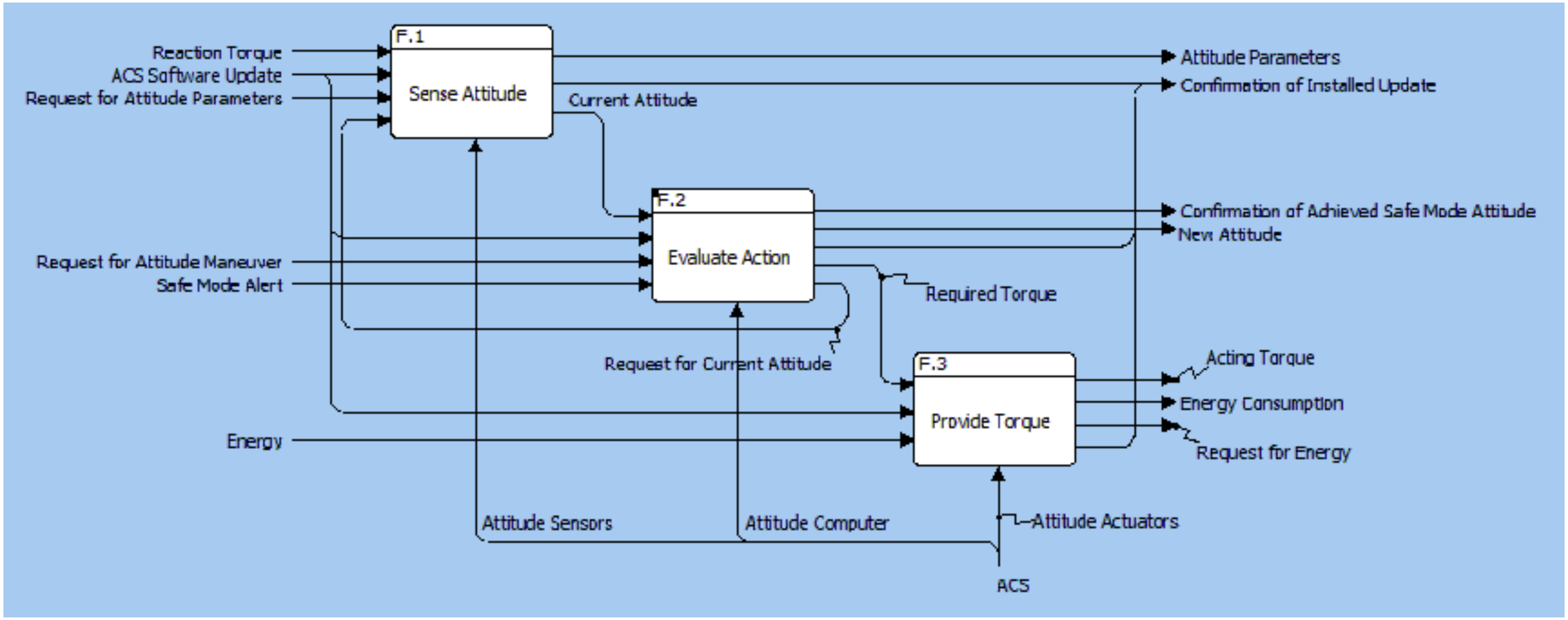
We are going to show the application of the framework using the structural complexity metric proposed by Sinha & deWeck (2012).

The evaluation of the complexity of the component C.0 is performed using the components at the 1st level C.1, C.2, and C.3.

$$C(n,m,A) = \sum_{i=1}^{n} \alpha_i + \left(\sum_{i=1}^{n} \sum_{j=1}^{n} \beta_{ij} A_{ij} \right) \gamma E(A)$$



Use Case:
Satellite Attitude Control System



$$A_{C.0} = \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}$$

$$C_{C.0} = C_{C.1} + C_{C.2} + C_{C.3} + \frac{1+\sqrt{2}}{3}(\beta_{12} + \beta_{21} + \beta_{23})$$

Use Case: Satellite Attitude Control System

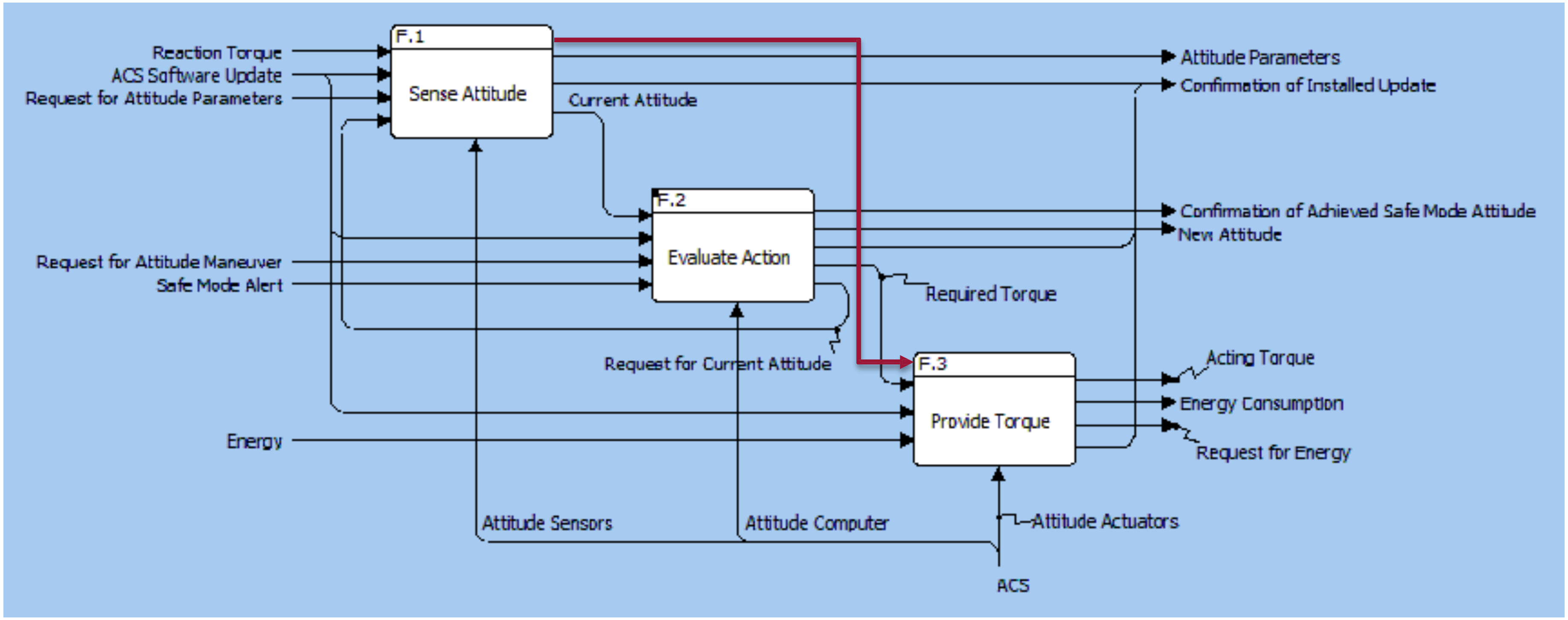
$$C_{C.0} = C_{C.1} + C_{C.2} + C_{C.3} + \frac{1+\sqrt{2}}{3}(\beta_{12} + \beta_{21} + \beta_{23})$$

The missing terms in the equation above cannot be evaluated in the current state of the framework.

The complexity of the components is going to be evaluated using behavioral metrics, using historical information about input/output of the components. In our opinion this is better than using historical complexity/ reliability/robustness data, since do not depend on the history of the specific components.

The complexity of the interface is going to be evaluated using the interface characterization model.

Modification of Existing Metrics Sinha & deWeck (2012)



$$A_{C.0} = \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}$$

$$A_{C.0'} = \begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}$$

Modification of Existing Metrics Sinha & deWeck (2012)

$$C(n,m,A) = \sum_{i=1}^{n} \alpha_i + \left(\sum_{i=1}^{n} \sum_{j=1}^{n} \beta_{ij} A_{ij} \right) \gamma E(A)$$

$$C_{C.0} = C_{C.1} + C_{C.2} + C_{C.3} + \frac{1+\sqrt{2}}{3} (\beta_{12} + \beta_{21} + \beta_{23})$$

$$C_{C.0'} = C_{C.1} + C_{C.2} + C_{C.3} + \frac{1+\sqrt{3}}{3} (\beta_{12} + \beta_{13} + \beta_{21} + \beta_{23})$$

Following the addition of one connection between C.1 and C.3 the metric has a twofold change. We propose the following modification to this metric:

$$C(n,m,A) = \sum_{i=1}^{n} \alpha_i + \gamma E(B)$$

where B is the matrix whose elements are β_{ij}.

Summary and Future Work

In this work we introduced the Hybrid Structural-Behavioral Complexity Framework.

The framework backbone has been defined, but its modules are yet to be developed.

Some modules are to be developed by modifying existing complexity metrics, while others are to be developed ex novo.

Future work will focus on the development of those modules and the validation of the framework using real data.

Thank you for your attention

Questions?

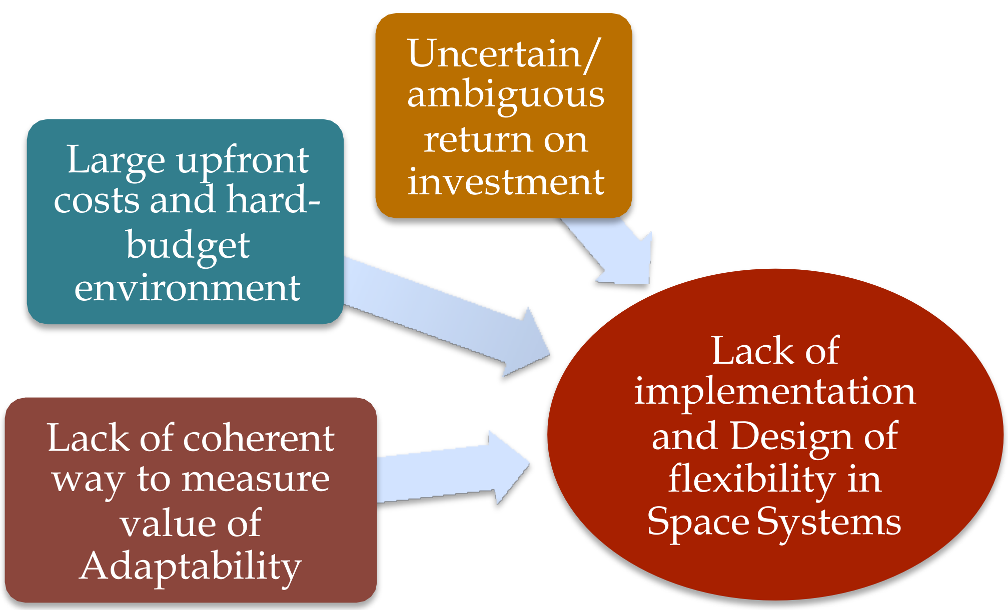
Backup Slides

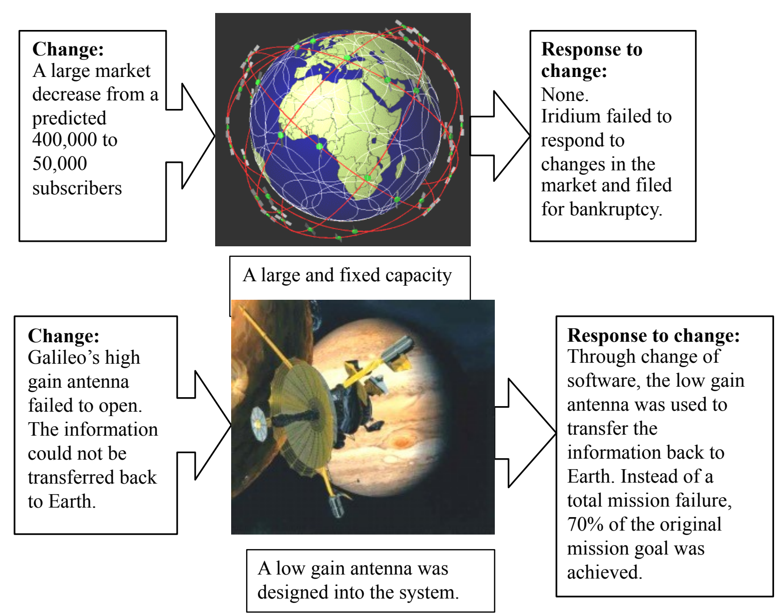
Example: DARPA F6 Program

Context: The Need for Adaptability and Resilience in Space Systems In Uncertain World

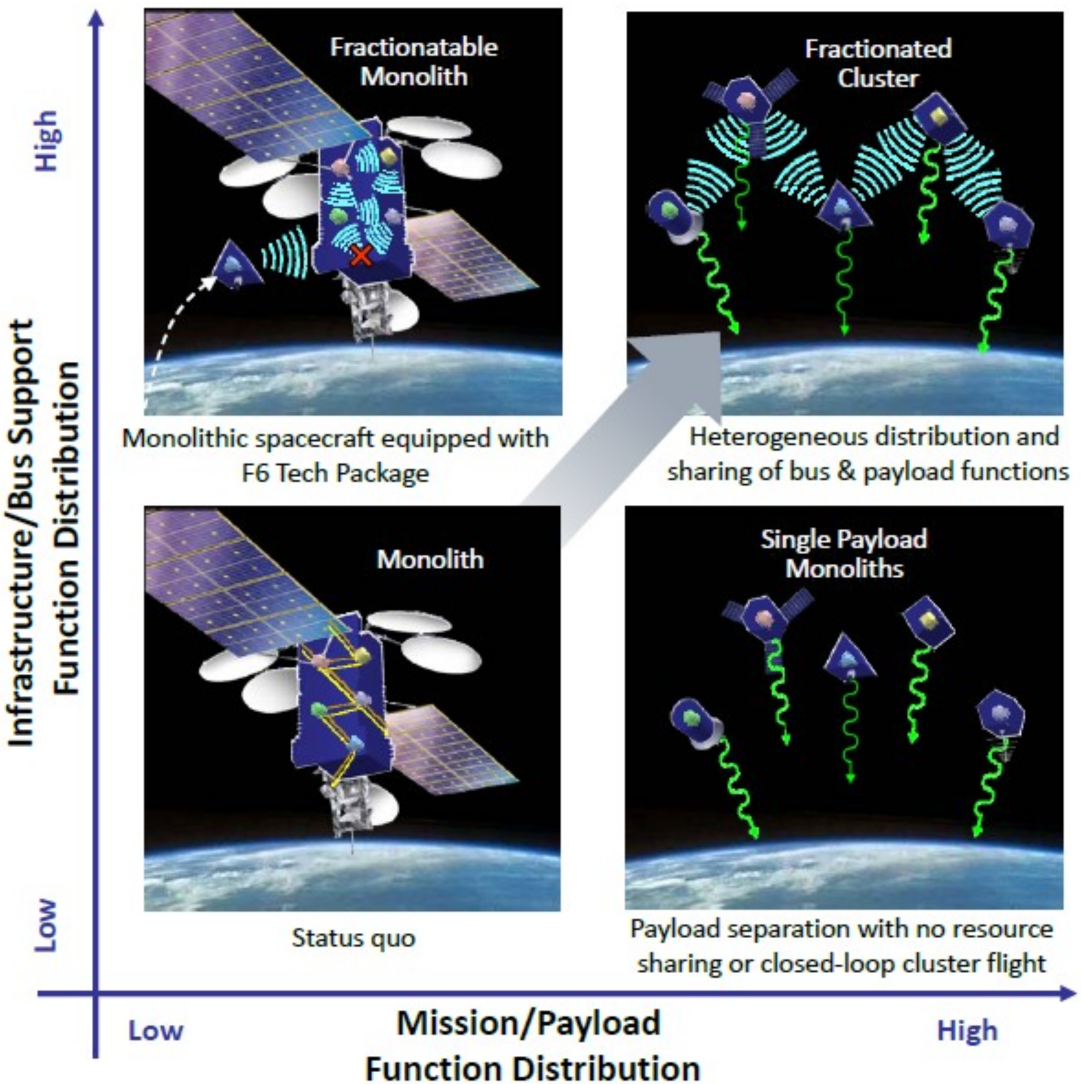
- Space Systems:
  - Lengthy design and manufacturing
  - Long lifetimes
  - Very expensive
  - Limited access after launch
  - Face **extensive uncertainties** during their lifetime

- Space systems often provide a good response to initial requirements but:
  - They fail to meet new market conditions
  - They cannot adapt to new applications
  - Their technology becomes obsolete
  - They cannot cope with changes in context/ environment (markets, policy, technological innovation, changing human needs)





An Overview of a Fractionated Spacecraft Concept



Enablers of Fractionated Space Architectures

- Cluster maintenance
- Rapid cluster maneuvering
- Relative navigation
- Wireless networking
- Real-time resource sharing
- Multi-level security

- 24/7 LEO-ground connectivity

- Open F6 Developer's Kit
- Modular F6 Tech Package

- Adaptability Metrics
- Design-for-Adaptability Tools

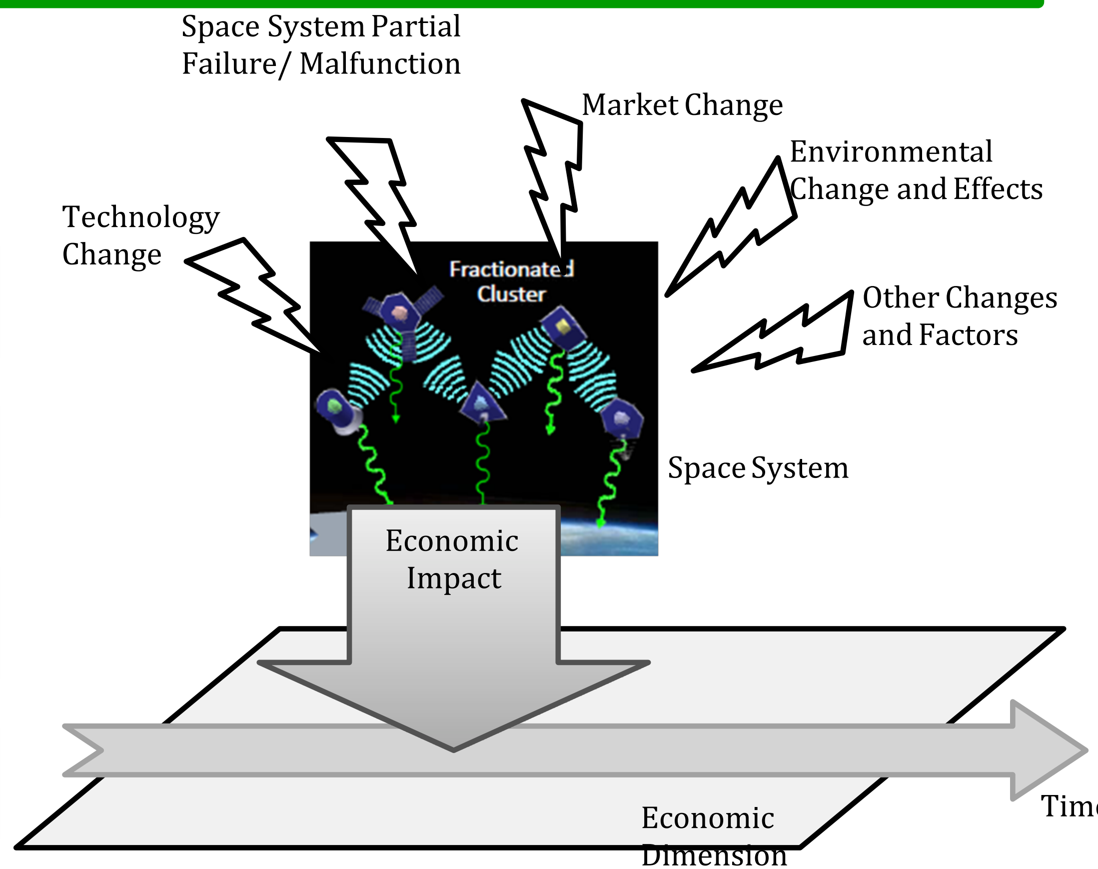
Credit: Mr. Eremenko, DARPA

Value of Adaptability Under Risk and Uncertainty

What is the quantitative value of Adaptability in fractionated spacecrafts?

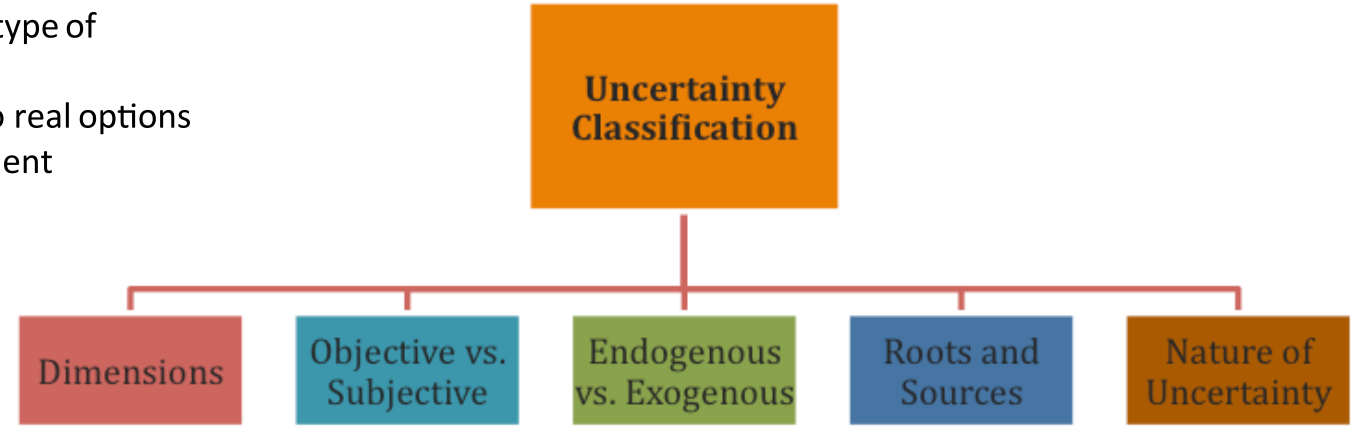
Integrating various systems "ilitis" into a single framework in the presence of multi-dimensional uncertainty using scenarios and Real options

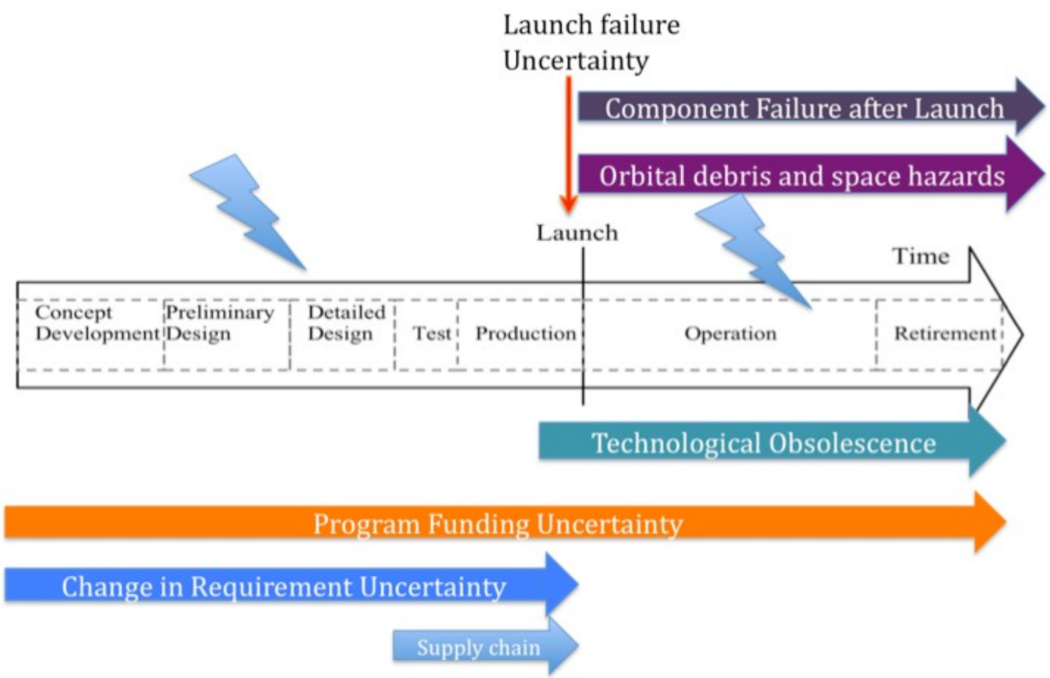
- What is the physical, temporal, and logical Boundaries of the Space Systems Under Study?
- What are the types of Uncertainties (risks and opportunities) a Space System is facing, and how they manifest themselves? (Scenarios)
- What are Stakeholders preferences on Requirements and Utilities of the space mission?
- What are the Real Options in and on space systems and how to model them?

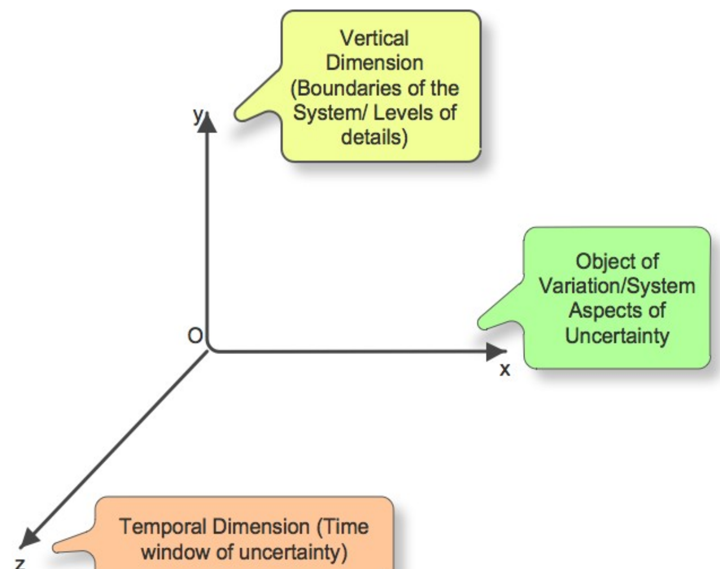


Uncertainty Science, Characterization and Modeling

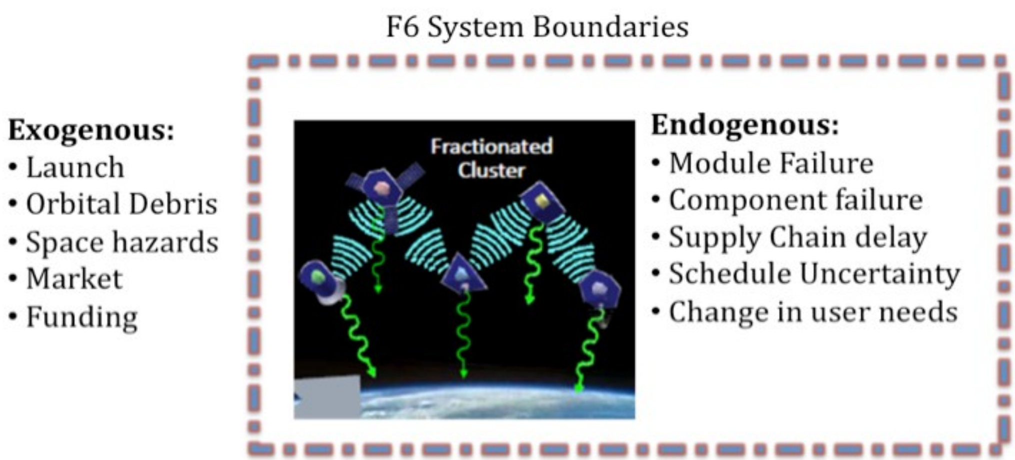
1. Classifies all types of relevant Space Systems Uncertainties
2. Relevant Models for each type of uncertainty
3. Uncertainty is plugged into real options for Adaptability Measurement

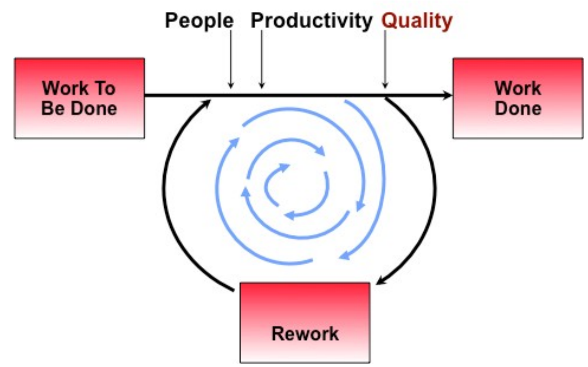


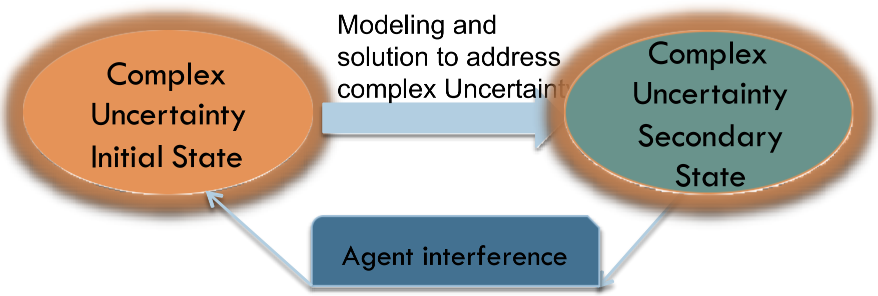


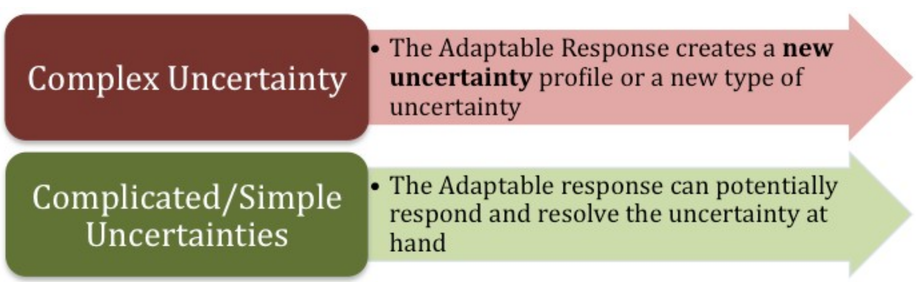


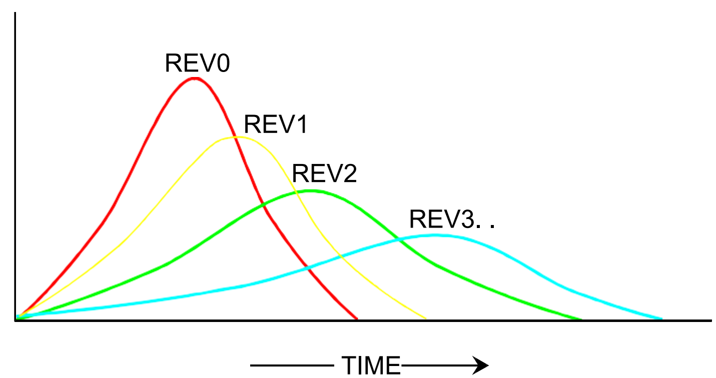
Uncertainty Science, Characterization and Modeling





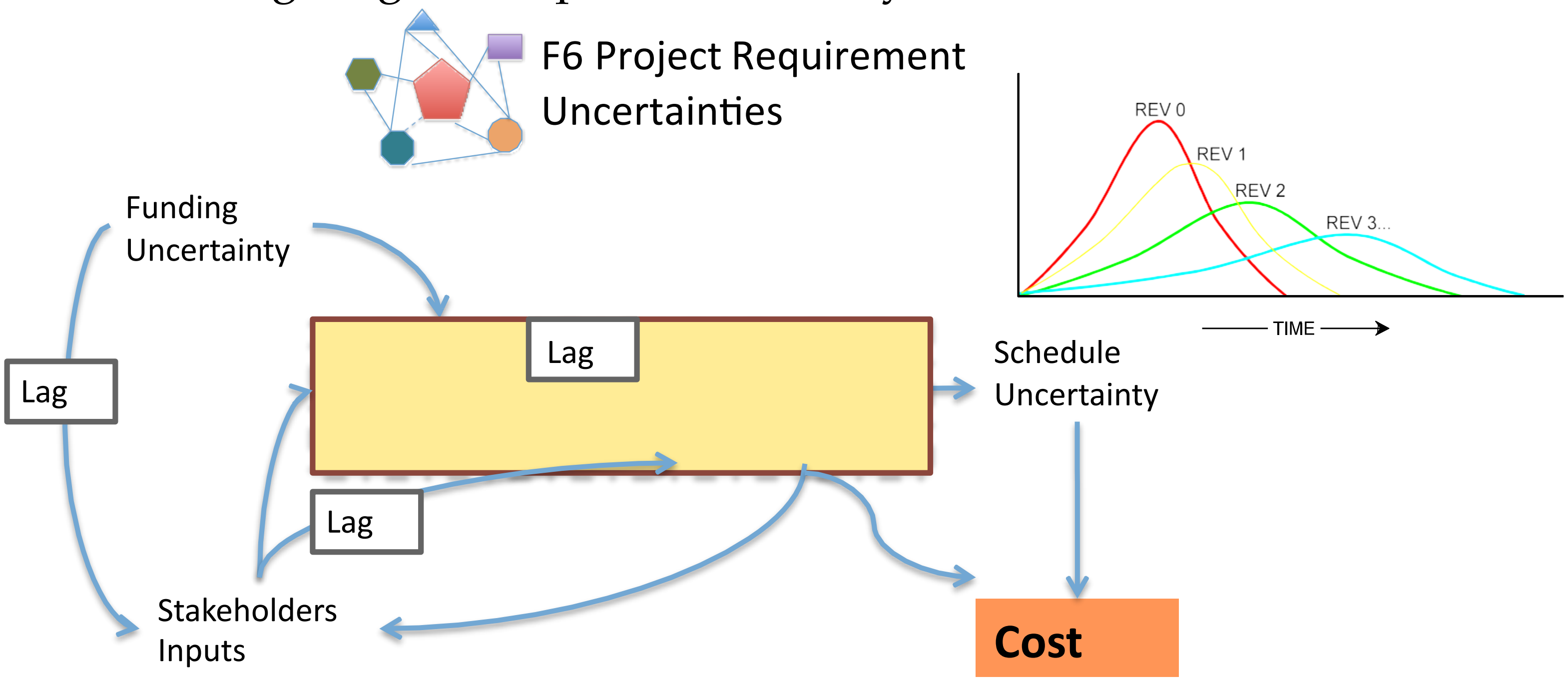






Uncertainties and Complexities in Space Systems

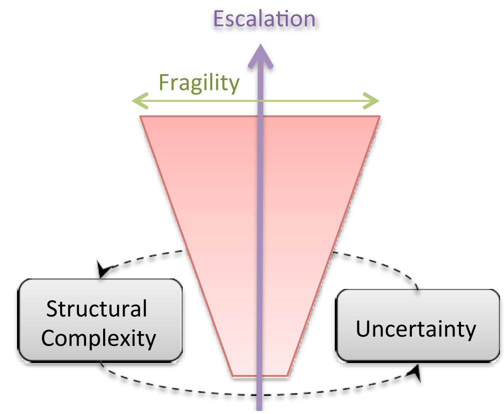
Modeling Single Complex Uncertainty



Requirement Uncertainty is mainly a function of changing user and stakeholders need, funding uncertainty, and incomplete or unclear set of initial requirements. There are delays in requirement gathering and classification and prioritization process and several loops of iterations that affect cost and project schedule dramatically

Uncertainties and Complexities in Space Systems

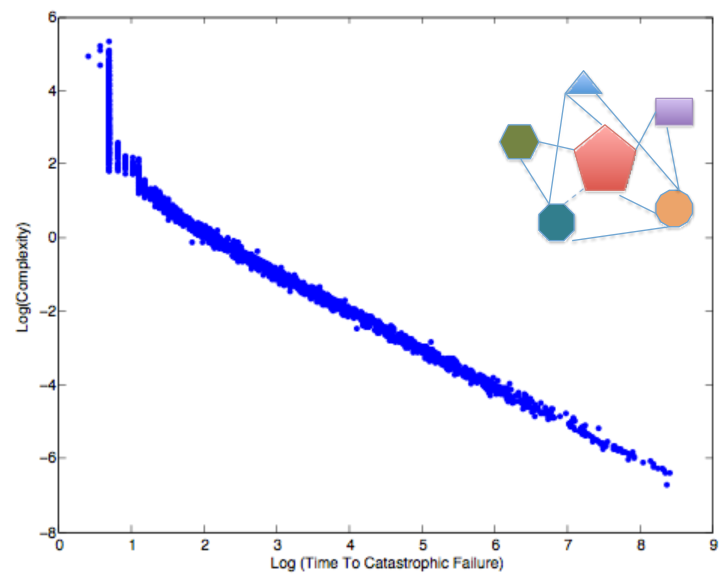
- On-going Research: Multiple Uncertainties, Realistic Scenarios and Catastrophic failures
  - Correlation between various space systems-related uncertainties
  - Realistic Scenarios: manifestation of a uncertainty and chain reaction effect of triggering other uncertainty types, Time lag between Uncertainties (Window of opportunity of options)
  - Correlation of increasing in complexity measure and structural complexity of the F6 and catastrophic chain of Uncertainties (Murphy's Law!)



Group	Uncertainties
Policy	Export, frequency allocation, mission-specific regulations, disposal.
Technology	Obsolescence, technology readiness, system readiness.
Organization	Supply chain, cost, technical capability, key people, V&V, design, requirements, customer involvement.
Service performance	Reliability, availability, space debris, space radiation, weather hazard, lifetime, performance.
Market	Market size, discount rate, competition, market capture, schedule.

Correlation Matrix of Space Systems Related Uncertainties

The Less Complexity in Design Structure and Architecture of F6, The slower the propagation of specific types of uncertainty in the F6 architecture, the more time to interfere and respond and/or exercise Real Options, Therefore More Adaptability



Propagation of Failure in F6 Network and correlation with Complexity measure of the Network

Complexity and Uncertainty in F6: Uncertainty Correlations

- Why Uncertainty Correlation matters?
  - Realistic Scenarios, Realistic Options, Time to Exercise and Option
  - Trigger possibility, Chain reaction effect

		Techn.			Service performance							Market					Organization								Legal			
	Columns are triggered by rows	Obsolescence	Technology readiness	System readiness	Reliability	Availability	Debris	Radiation	Weather hazard	Lifetime	Performance	Market size	Discount rate	Competitor	Market capture	Schedule	Supply chain	Cost	Technical capability	Key people	V&V	Design	Requirements	Customer involvement	Export	Frequency allocation	Mission-specific regulations	Disposal
Technology	Obsolescence		11	12		21				41							100	110							79			
	Technology readiness	1		13												72	101	111							80			
	System readiness	2														73	102	112							81			
Service performance	Reliability					22				42																		
	Availability													63	68			113										
	Debris					23				43																		99
	Radiation					24				44																		
	Weather hazard					25				45																		
	Lifetime	3			18	26	31	34	38			?		?	?													
	Performance									?		60		64	69													
Market	Market size					27				46	52			65									135		82	92		
	Discount rate																											
	Competitor											61			70		103			123			136		83	93		
	Market capture					28				47	53			66											84	94		
	Schedule	4	6	14			32	35				62		67	71		104	114		124			137	146	85			
Organization	Supply chain															74		115	150		127			147				
	Cost																						139	148				
	Technical capability		7	15							54					75					128	132	140	149				
	Key people																		119									
	V&V				19	29				48	56																	
	Design				20	30				49	57																	
	Requirements																											
	Customer involv																											
Policy	Export																											
	Frequency alloc																											
	Mission-specific																											
	Disposal						33			?											?	?	145					

Rare catastrophic events in complex systems are poorly probable yet highly possible!! The collective effect of insignificant uncertainties have grave consequences. In the end it is hard to figure out what went wrong!

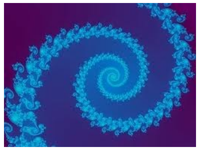
Uncertainties and Complexities in Space Systems

Category	Description
Policy	Uncertainties related to law and regulation that impact the system. Most common examples include ITAR, EO laws, or ITU frequency allocation. It is important to mention that uncertainties falling under this category have not really been explored in the available literature. When discussing Policy uncertainty, it is normally related to government funding, which we allocate to market.
Technology	Uncertainties that are related to the availability of technology or technical solutions. Most common examples are obsolescence, state-of-the-art, achievability, TRL, SRL, etc.
Organization	Uncertainties that are related to the organization of the system (project) and may impact the development or the operation of the system. Most common examples include supply chain, complexity of operations, directives to use specific suppliers, loss of key personnel, inadequate personnel, etc. It is important to mention that uncertainties falling under this category have never been looked into in the available literature.
Service performance	Uncertainties that are related to the impacts of bringing the system into real-life operation. They could be defined also as uncertainties included in the design by definition (performance based on probabilities). Most common examples may include reliabilities, availabilities, TX power, degradation, lifetime, orbit accuracy, fuel usage, radiation, atmospheric effects, network load, integration to other systems, etc.).
Market	Uncertainties related to "funding and revenues", which may be impacted by business case success or effects of internal and external competitors: *Commercial project:* market capture, effect of other company putting the system in place earlier or at lower cost, impact of competitors with same service in other industry (e.g. terrestrial networks). *Government project:* actual scientific return, competitors making funding fluctuate (e.g. budget moved from Human spaceflight to Earth observation), etc.

Structural vs. Functional Complexity

The Simple

Single cause and single effect
A small change in the cause implies a small change in the effect
Predictability and Modelability

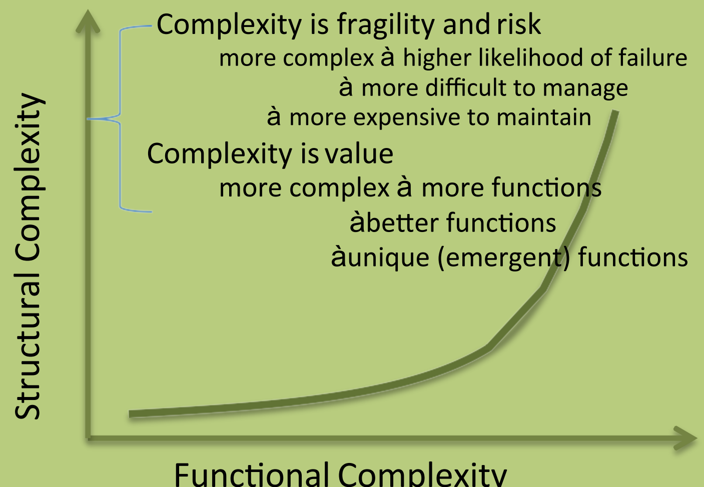


The Complex

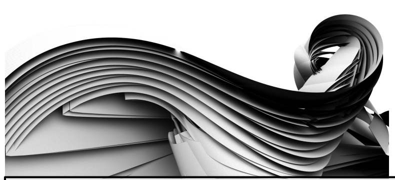
Circular causality, feedback loops, logical paradoxes, and strange loops
Chaos: small change in the cause implies dramatic effects
Emergence, unpredictability and entropy

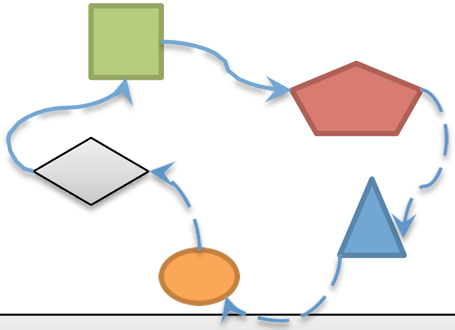
Complex Systems Engineering Dilemma

Complexity is fragility and risk
more complex à higher likelihood of failure
à more difficult to manage
à more expensive to maintain
Complexity is value
more complex à more functions
àbetter functions
àunique (emergent) functions



Complexification driving force

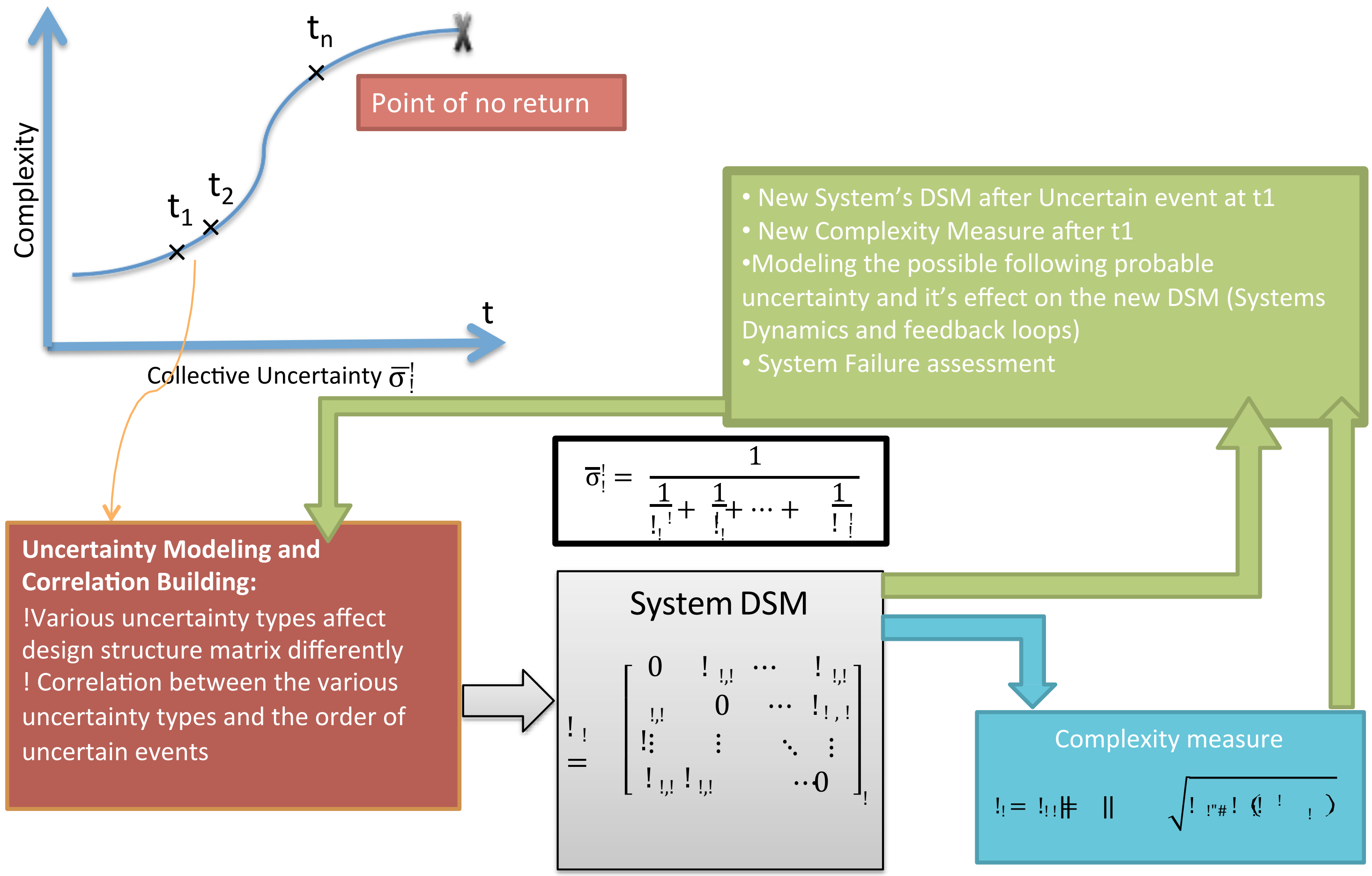




Emergence

Exist in the whole not in the parts
Cannot be modelled
In complex systems failure can be emergent
Structural Complexity is the potential for and intensity of emergence
It is important to measure complexity

Research Approach

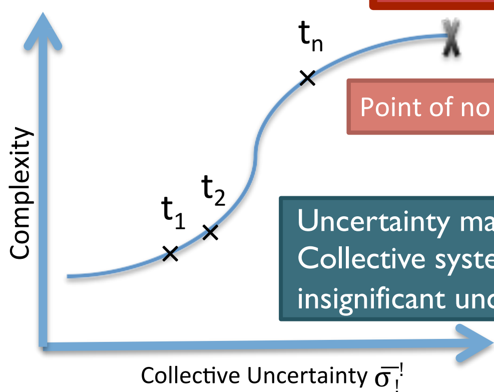


Our previous research has shown a direct correlation between an increase in structural complexity and how fast a failure or risk propagates in a complex satellite SoS (Example: a security attack on one of the satellites in the network).

Uncertainty and Complexity in F6: Catastrophic Failure

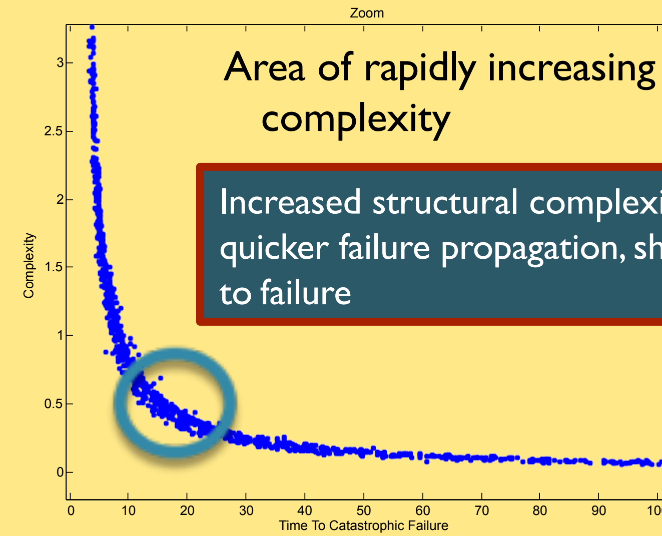
Low rate of complexity increase provides a response time window

Response time window → 0



Point of no return

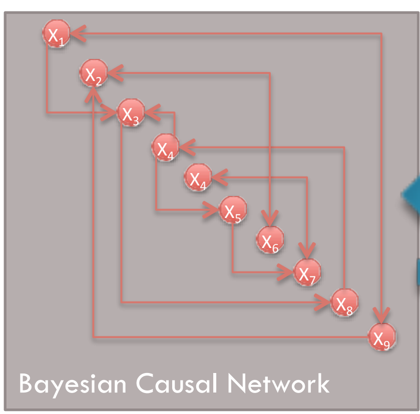
Uncertainty magnification:
Collective system tolerance of most insignificant uncertainties →0



Area of rapidly increasing complexity

Increased structural complexity means quicker failure propagation, shorter time to failure

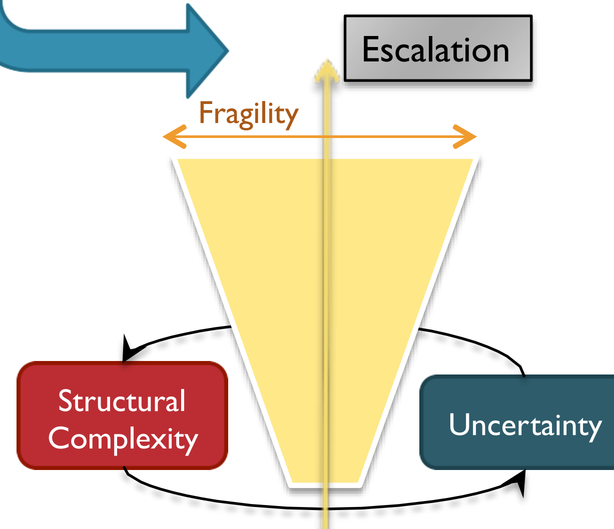
$$\bar{\sigma}_!^! = \frac{1}{\frac{1}{!_!^{\,!}} + \frac{1}{!_!^{\,!}} + \cdots + \frac{1}{!_{\,!}}}$$



Engineered system modeled by a Discrete non-linear Markov process:

! ! ! ! = !(!!, !) + !!

!"# !(= Σ! = […]



Failure Propagation Overview: Time To Failure Concept

- §Failure propagation as precursor model
- §Affects Complexity, vulnerability and Adaptability of F6
- §Used in calculation options values in face of various failures
- §Will be used in Security enhancement options

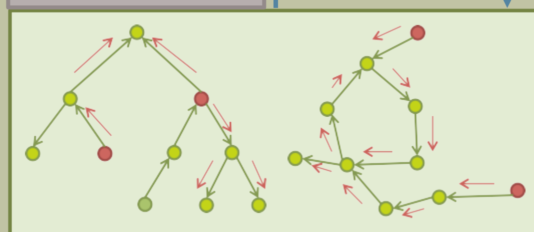
Uncertainty

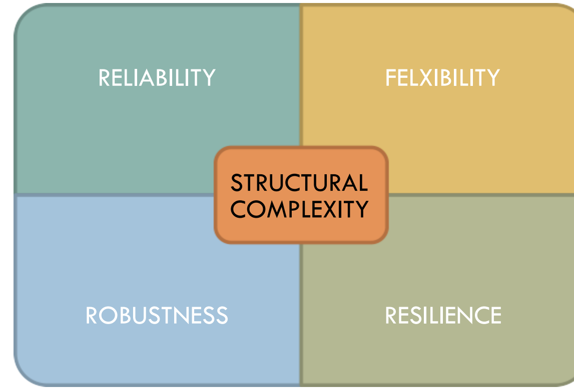
Partial Failure

Bayesian Network failure propagation
Monte Carlo Simulation

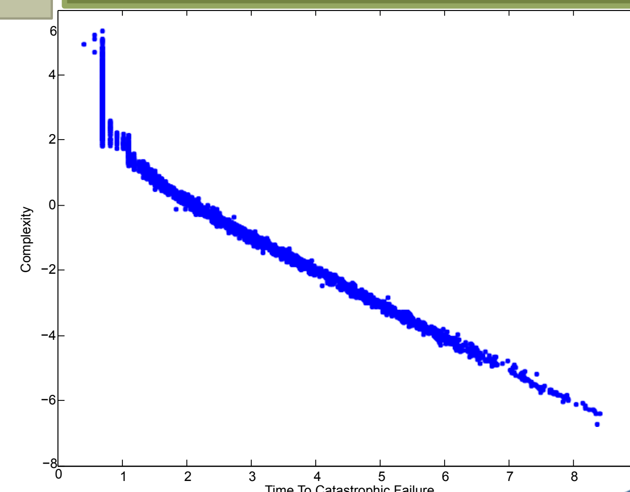
$$F_i^{t+1} = F_i^t + \sum_{j \neq i} d_{i,j}^t F_j^t$$

System Abstraction

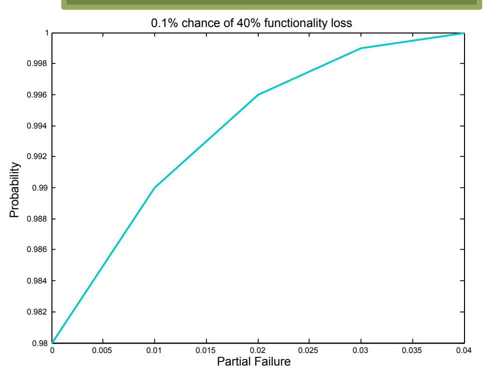




Correlation of Time to Failure with Structural Complexity



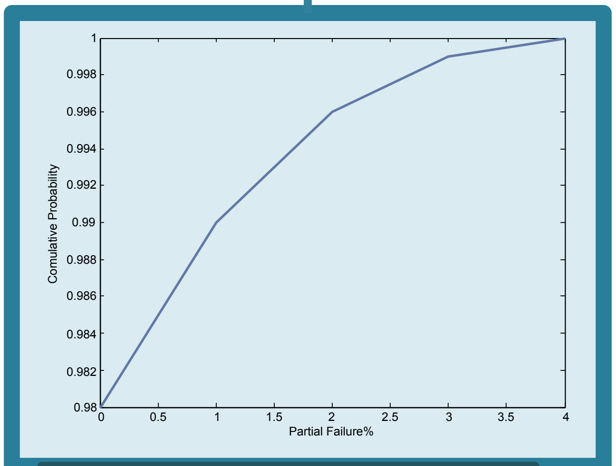
Partial failure probabilities



Monte Carlo Simulation

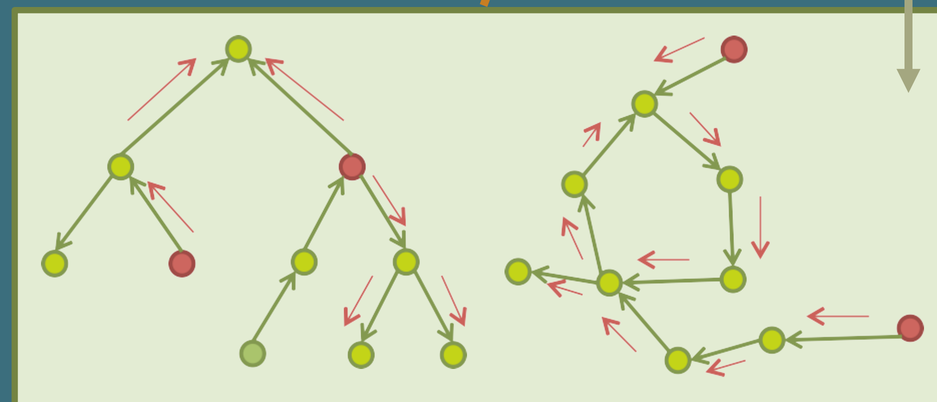
Generate a Random System:
1. Number of nodes
2. Link density

Uncertainty and Complexity in F6: Failure Propagation



Sensitivity to low probability low impact partial failures

$$F_i^{t+1} = F_i^t + \sum_{j \neq i} d_{i,j}^t F_j^t$$



Bayesian Network failure propagation
Monte Carlo Simulation

Choose Number of subsystems

Choose Links density

Form

! ! = 0 ! !,! ⋯ ! !,!
! !,! 0 ⋯ ! !,!
⋮ ⋮ ⋱ ⋮
! !,! ! !,! ⋯ 0 !

Bayesian Recursive Error Propagation

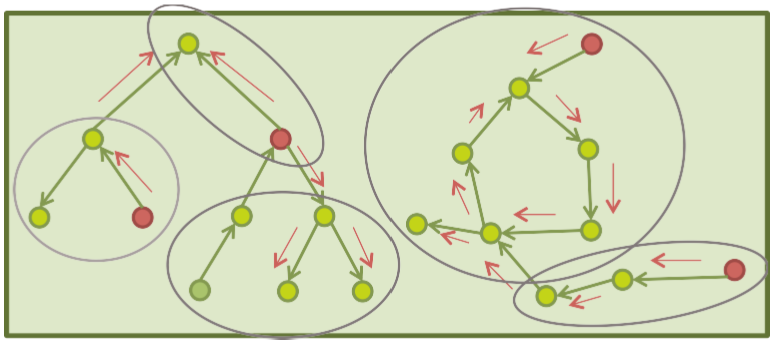
! (! ! |! !) = ! ! !!! + ! (! ! ∩ ! !) ! (! !)

! (! ! ∩ ! !) ~ ! !,!

Static: ! !,! = ! !,! = ⋯ = ! !,!

Rare catastrophic events in complex systems are poorly probable yet highly possible!! The collective effect of insignificant uncertainties have grave consequences. In the end it is hard to figure out what went wrong!

Uncertainty and Complexity in F6: Failure Propagation vs. Various Number of Fractions



Propagate failure inside of each subsystem once

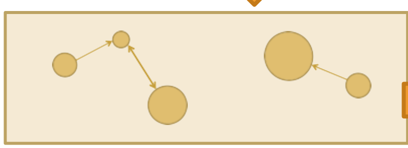
Propagate between modules based on collective effects based on average rates

Stop when a component in any module is 100% failed

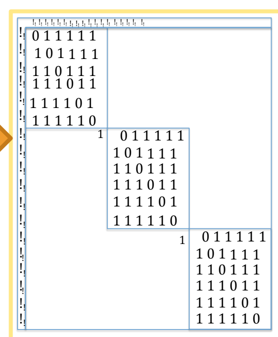
Fractionation 10%

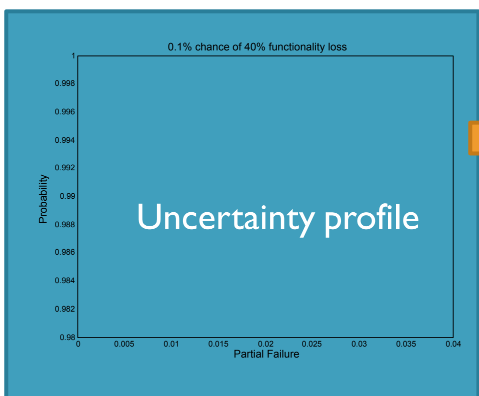
Connectivity

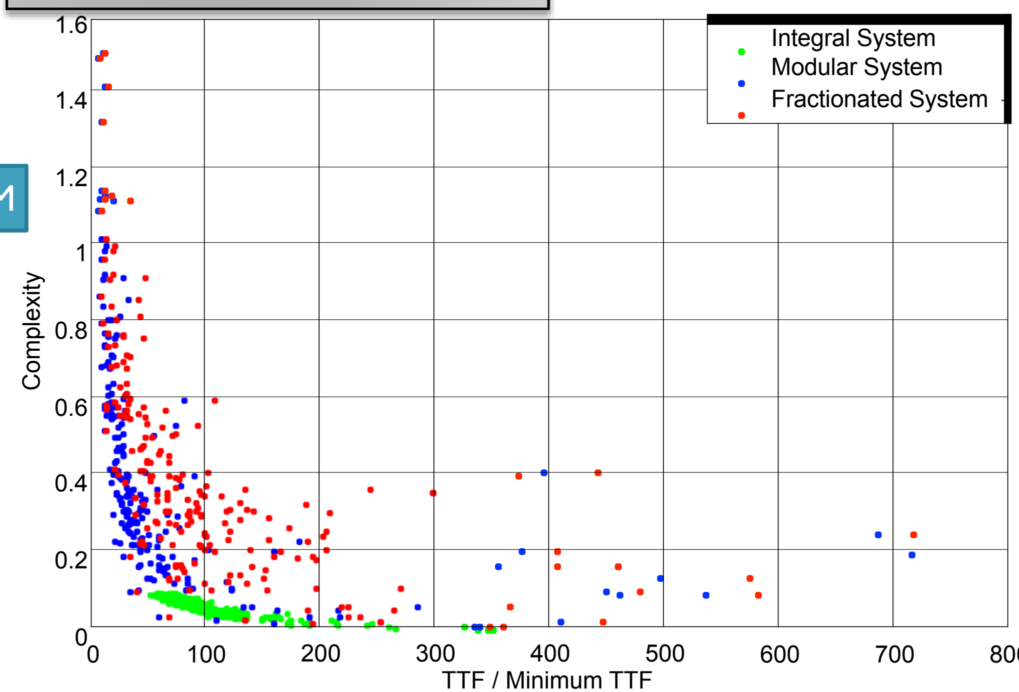
Information
Material
Energy
Adjacency



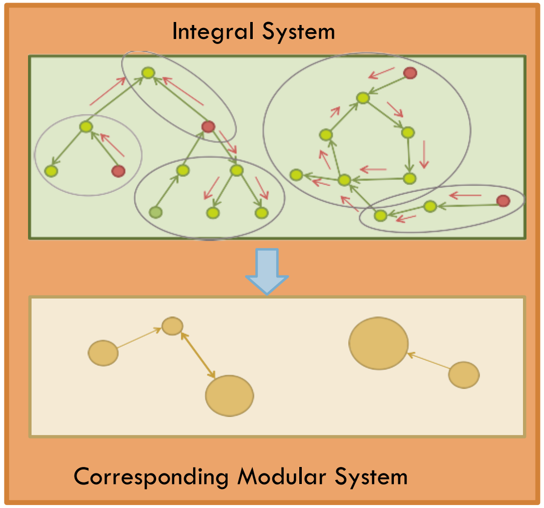
Form the block DSM







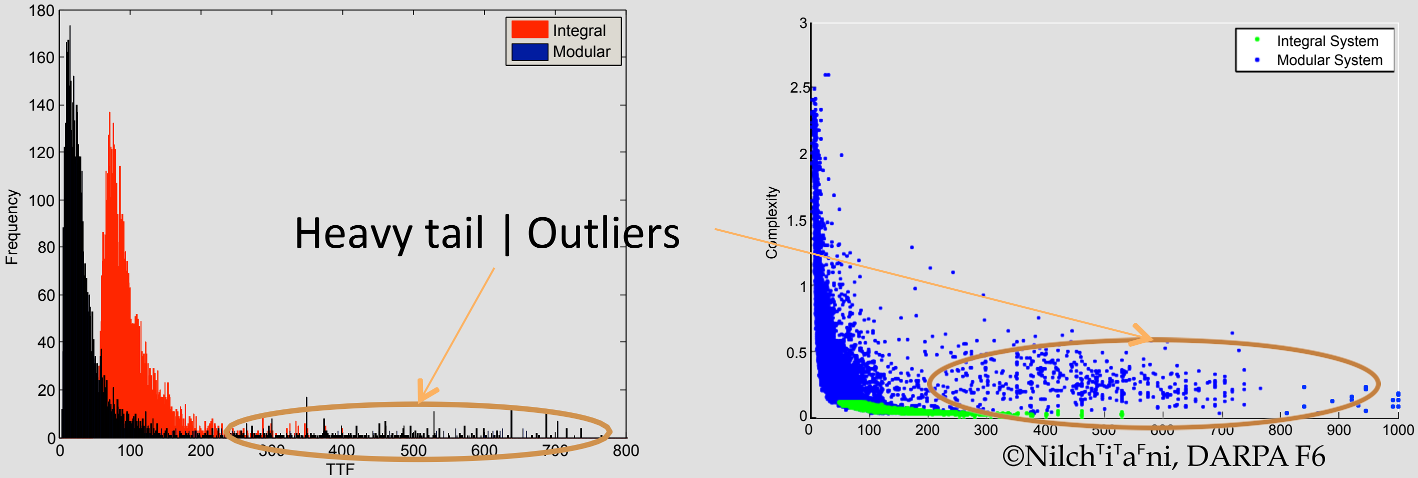
Failure Propagation: Results and Insights



Insights:
Our goal in to increase TTF, since it gives us more time to detect and remedy failures before they become detrimental to the whole F6 architecture

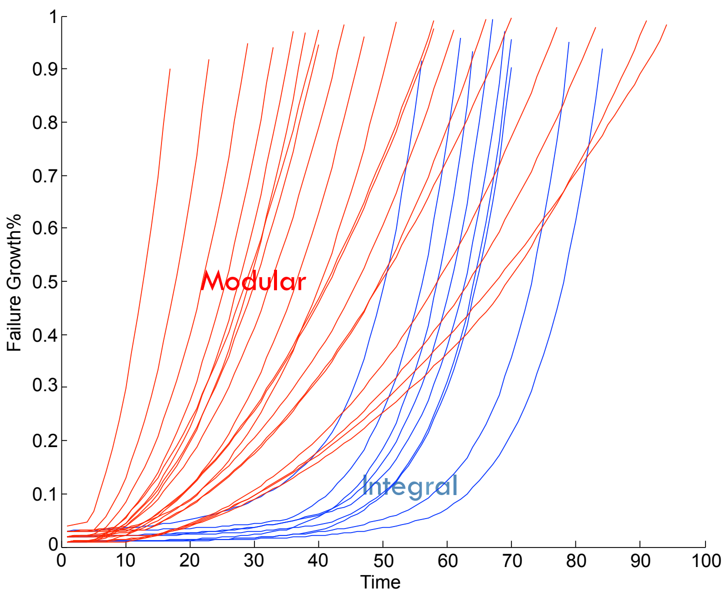
- •Correlation of number of modules and Complexity measure of the system: Monoliths often have the least structural complexity
- •Mean Time to Failure decreases with number of fractions and modules for majority of module architectures
- •F6 architectures with higher complexity measures are more vulnerable and prone to catastrophic failures
- •The art of module making: maximum cuts creates high degree of coupling between fractions and therefore higher complexity

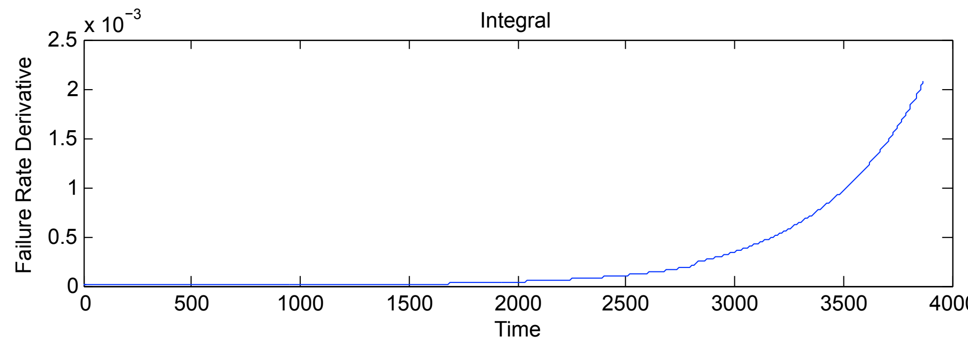
Sensitive to initial partial failure locations, modular systems can be extremely res

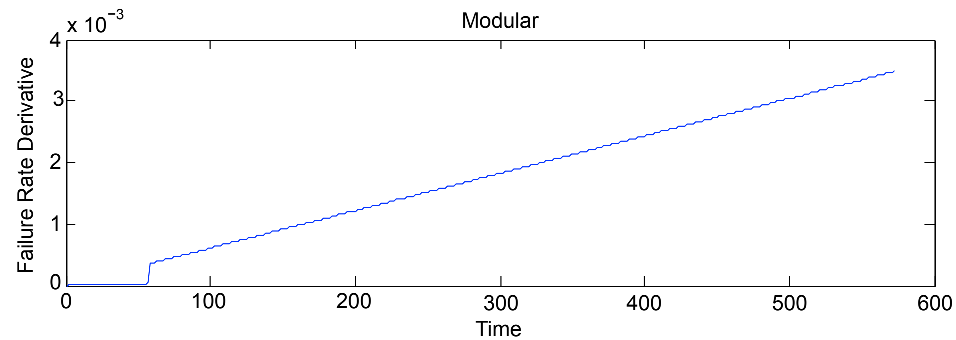


Failure Propagation: Results and Insights

Failure detection in modular structure is easier







Insights:

Failure propagation and detection in various F6 architecture vs. a monolith

•In monoliths, failure propagates at a very slow rate initially and after a certain level, it grows exponentially

• In modular systems, failure propagates rather faster initially, but grows steadily

•If detectability of failure is defined at x% (e.g, 10%), Fractionated systems show partial failure sooner, as well as provide decision-makers with time to react (window of opportunity) to exercise an option to address the problem. In many monoliths, when the failure becomes detectable that its already too late

Expanding the Capabilities of Requirements to Promote the Design of Affordable Systems

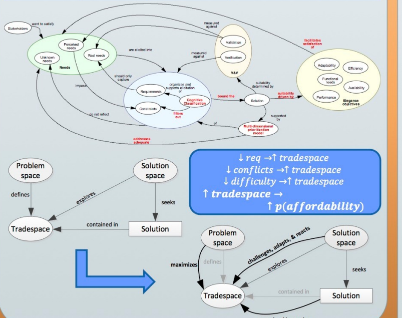
Alejandro Salado
Stevens Institute of Technology

STEVENS INSTITUTE of TECHNOLOGY — THE INNOVATION UNIVERSITY — 1870

SYSTEM AFFORDABILITY

	AFFORDABILITY			
	PERCEIVED VALUE			BUDGET
	Perceived benefit	Actual benefit	Cost	
Business processes	Marketing	Technology push	Process improvement Labor Outsourcing Procurement strategies	Investment
Product development	N/A	Value-based design strategies DtX DfX Adaptability Use cases Pugh matrices Other tradit. SE	Cost-effective design strategies DtX DfX De-scope needs Use cases Pugh matrices Other tradit. SE	N/A
Context/ Environment	Awareness Lobby	Market change	Economic situation Laws and regulations	Awareness Lobby Competition

Tradespace exploration — Tradespace definition — Tradespace maximization/adaptation



ABSTRACT

Economic situation all over the world stresses a need to provide society more with less. Systems engineering is expected to be the solution to effectively develop complex systems, yet cost and schedule are often out of control during system development. The present research proposes that current capabilities of requirements engineering are one of the limiting factors against system affordability and questions if and how requirements could be actively used to drive system affordability instead of playing a passive role against it.

Requirements are used in the problem domain to define the boundaries wherein a satisfactory solution exists: the solution tradespace. In the solution domain the solution tradespace is explored against requirements and their relative importance levels to find a satisfactory or in some cases optimal solution.

The present research proposes a conceptual change in using requirements to promote affordability: use elicitation supporting mechanisms to maximize the solution tradespace for a given set of needs and prioritization mechanisms that adapt to a varying environment as the system development evolves. By maximizing and adapting the solution tradespace instead of merely defining it at a given point in time, chances to find "good" solutions are maximized, facilitating as well finding solutions that are contained in varying solution tradespaces.

NEED-BASED CATEGORIZATION (NbC)

Value level	Functions (Do)	Performance (Being)	Resources (Have)	Interaction (Interact)
Break-event	Req. 1 Req. 2 Req. 3	Req. 4	Req. 5 Req. 6	Req. 7
Goal	Req. 8	Req. 9		
Wish		Req. 10	Req. 11 Req. 12	

A partition!

Functional requirements (*Do*)
What the system does in essence, i.e. what it accepts and what it delivers
Performance requirements (*Being*):
How well the system does it, which includes performance related to functions the system performs or characteristics of the system on its own, such as –ilities
Resource requirements (*Have*):
What the system uses to transform what it accepts in what it delivers
Interaction requirements (*Interact*):
Where the system does it, which includes any type of operation during its life-cycle.

Categ.	Requirement
Mission reqs.	**Req. 1.** The instrument shall take images of the Earth surface and transmit them to ground.
	Req. 2. The instrument shall be compatible with a LEO.
Operat. reqs.	**Req. 3.** The instrument shall be powered on by the platform.
	Req. 4. The instrument shall be depressurized during its ascent phase.
Funct. reqs.	**Req. 5.** The instrument shall image the Earth surface in UV spectral range.
	Req. 6. The instrument shall image the Earth surface in VNIR spectral range.
	Req. 7. The instrument shall move a mirror to select the redundant channel.
	Req. 8. The instrument shall power itself. Note: when receiving power according to Req. 12.
I/F reqs.	**Req. 9.** The instrument shall transmit image data according to IF-Def-1.
	Req. 10. The instrument shall be compatible with the platform payload carrying capability.
	Req. 11. The instrument shall have a thermal coupling at its mechanical interface lower than 2 units.
	Req. 12. The instrument shall accept power according to IF-Def-2.
Perf. reqs.	**Req. 13.** The instrument shall have a resolution better than 1 unit.
	Req. 14. The instrument shall have a FOV greater than 2°.
Integr. logistic support	**Req. 15.** The instrument GSE shall be compatible to instrument cleanliness requirements.
	Req. 16. The instrument contractor shall provide a transport container compatible with transport requirements to transport the instrument to the prime contractor facilities.
	Req. 17. The instrument EGSE shall provide no less than 400 W.

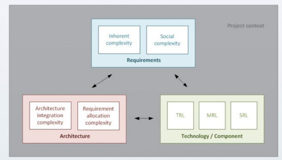
Categ.	Requirement
Physical reqs.	**Req. 18.** The instrument shall fit within 1 m x 1m x 1 m.
	Req. 19. The instrument shall have a mass lower than 900 kg.
Config. reqs.	**Req. 20.** The instrument reference frame shall be according to RD02.
	Req. 21. The instrument MICD shall include the mass of the represented element.
Design reqs.	**Req. 22.** The instrument mass budget shall use the margin philosophy specified in RD01.
	Req. 23. The instrument shall use independent detectors for both spectral ranges.
	Req. 24. The instrument shall have a reliability higher than 0.90.
	Req. 25. The instrument shall be thermally decoupled from the platform.
	Req. 26. The instrument shall use redundant power supplies.
	Req. 27. The instrument shall provide venting provisions.
	Req. 28. The instrument shall be designed to operate in LEO.
	Req. 29. The instrument shall use a focal length of 3 units: Note: in order to achieve resolution requirement Req. 13.
	Req. 30. The instrument shall use mirrors of XYZ material.
	Req. 31. The optical elements of the instrument shall be aligned with a precision of 10 units.
Environ. reqs.	**Req. 32.** The instrument shall fulfill its performance requirements in the thermal environment specified in RD04.
	Req. 33. The instrument shall fulfill its performance requirements in vacuum.
Verif. reqs.	**Req. 34.** The instrument shall fulfill its performance after being subjected to 4thermal cycles between -50°C and +100°C.
	Req. 35. The instrument performance shall be verified at 10 °C.

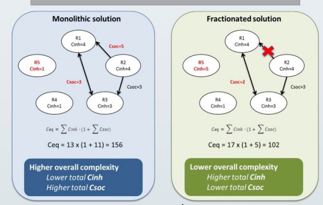
ECSS categorization of requirements

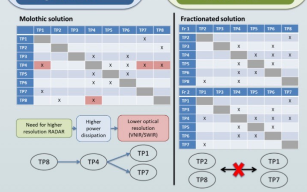
Value level to stakeh.	Requirements: Functions (Do)	Performance (Being)	Resources (Have)	Interaction (Interact)
Break-even	**Req. 5.** The instrument shall image the Earth surface in UV spectral range. **Req. 6.** The instrument shall image the Earth surface in VNIR spectral range. **Req. 8.** The instrument shall power itself. Note: when receiving power according to Req. 12. **Req. 9.** The instrument shall transmit image data according to IF-Def-1. **Req. 11.** The instrument shall have a thermal coupling at its mechanical interface lower than 2 units. **Req. 12.** The instrument shall accept power according to IF-Def-2.	**Req. 13.** The instrument shall have a resolution better than 1 unit. **Req. 14.** The instrument shall have a FOV greater than 2°. **Req. 24.** The instrument shall have a reliability higher than 0.90.	**Req. 18.** The instrument shall fit within 1 m x 1m x 1 m. **Req. 19.** The instrument shall have a mass lower than 900 kg.	**Req. 32.** The instrument shall fulfill its performance requirements in the thermal environment specified in RD04. **Req. 33.** The instrument shall fulfill its performance requirements in vacuum.
Goal		**Req. 36** The instrument shall have a resolution better than 2 unit.	**Req. 37** The instrument shall have a mass lower than 750 kg.	
Wish		**Req. 38** The instrument shall have a FOV greater than 5°.		

15 requirements!

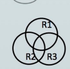
COMPLEXITY-BASED REQUIREMENTS (CbR)







$$d(R1 \wedge R2) = d(R1|R2) = \frac{1}{Size(R1) \cap Size(R2)} = d(R2|R1)$$



$$d(Ri) = \frac{k}{Size\ tradespace}$$

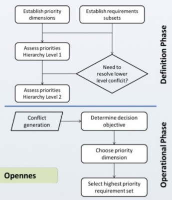
$d = \infty \rightarrow size = 0$
$d = 0 \rightarrow size = \infty$

$d(R1|R2) \geq d(R1)$
$d(R2|R1) \geq d(R2)$

Levels of "accuracy" tension points:
- Order 1. $d(Ri)$
- Order 2. $d(Ri|Rj)$
- Order 3. $d(Ri|Rj \wedge Rk)$
- Order n. $d(Ri|Rj \wedge Rk \wedge \cdots \wedge Rj+n)$

OBJECTIVE-BASED PRIORITIZATION (ObP)

Req	Value stakeh	Imp Busin	Diff	Cost	Risk
Set A	5	2	3	N/A	2
Req. 1			4		
Req. 2			3		
Req. 3					
Req. 4					
Set B	4	1	2	N/A	2
Set C	2	4	2	N/A	1
Set D	1	1	5	N/A	4
Req. 8					
Req. 9					



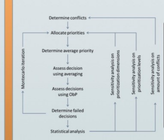
Dimensionality — Hierarchy — Opennes

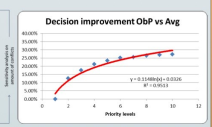
Req	Value stakeh	Imp Busin	Diff	Cost	Risk
Set A	5	2	3	N/A	2
Req. 1			4		
Req. 2			3		
Req. 3					
Req. 4					
Set B	4	1	2	N/A	2
Set C	2	4	2	N/A	1
Set D	1	1	5	N/A	4
Req. 8					
Req. 9					

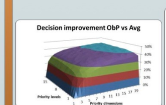
Req	Imp Busin	Value stakeh	Conn	Avg
Subs. 1	1	3	1	0.56
Subs. 2	3	1	3	0.78

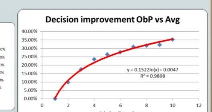
In Case 1 the company is competing against different competitors to actually get a contract for developing the system, but can only implement one of the subsets in order to remain within cost targets.
In Case 2 the project is at the middle of the development and the customer has been forced to cut the budget. As a consequence the company has been asked to propose a de-scoping of requirements at this stage of the project.

Case	Avg	Specific priority
C1	Subset 2	Subset 1. Using value to stakeholder in order to secure the contract.
C2	Subset 2	Subset 2. Using value to business in order to secure maximum profit as the contract has already been secured.

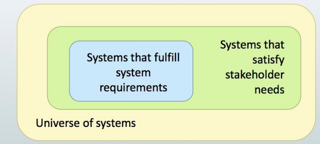








DEFINITION



VALIDATION PLAN

- How can the probability of finding a "good" solution increase?
- How can the size of the tradespace increase & adapt?

Effectiveness NbC:
- Elicit requirements → Field test + survey.
- Filter constraints → Field test + survey.

Effectiveness ObP:
- Decision errors wrt Avg method → Simulation.

Effects constraints & conflicts on chances of "good" solutions:
- Time to find satisfactory solution → Simulation.
- Time to find "good" solution → Simulation.

WANT TO PARTICIPATE IN THIS RESEARCH?

As a company:
Run internal test on using the NbC model.
Survey employees on knowledge and usage of reqs.
Assess level of constraints within your req documents.
As an individual:
Participate to online surveys on using these models.
Participate to online surveys on your knowledge on reqs.
Participate to online surveys on your usage of reqs.
Give your opinion and feedback!

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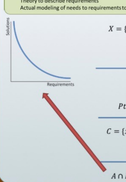
MATHEMATICAL MODELING, ELEGANCE, AND OTHER IN-PROGRESS OR FUTURE WORK

PURPOSE
Theory to link solutions, needs, and requirements
Theory to describe requirements
Actual modeling of needs to requirements to solutions to affordability



$X = \{x \in U : x \text{ is bounded by laws of physics}\}$
$A = \{x \in X : x \text{ fulfills Req. } 1\}$
$B = \{x \in X : x \text{ fulfills Req. } 2\}$

$L = \{x \in X : x \text{ is legal}\}$
$Ct = \{x \in X : C(x) < \text{cost target}\}$
$Tt = \{x \in X : T(t) < \text{schedule target}\}$
$Pt = \{x \in X : P(x) > \text{performance target}\}$

$C = \{x \in X : x \text{ fulfulls Req. } 1 \wedge x \text{ fulfills Req. } 2\}$
$C = A \cap B$

$A \cap B \subseteq A \wedge B \longrightarrow C = \{x \in X : x < 1 \wedge x < 10\}$

Formal Theory: Qualities of Reqs.

$A = \{x \in X : x \text{ satisfies stakeholder needs}\}$
$B = \{x \in X : x \text{ fulfills system requirements}\}$

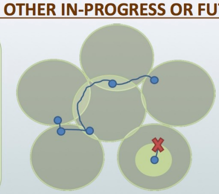
$Rr = \{x \in R : \exists x E(n \in N)\}$
$Rc = \{x \in R : \nexists x E(n \in N)\}$ $E: N \rightarrow R$

$Rc = \emptyset$
$R = Rr = \{r \in R : I(r) = A\}$

$C = \{x \in X : x < 1 \wedge x > 1\} = \emptyset$	Conflicting requirements
$r1, r2 \in R; Y = \{x \in X : r1(x)\}, Z = \{x \in X : r2(x)\}; r1, r2 \in CR \rightarrow Y \cap Z \ll Y \wedge Z$	
$A \subset B \Leftrightarrow \nexists (r \in Rr) F(x \in B)$	Incomplete requirements
$B \subset A \Leftrightarrow \exists (r \in Rc) F(x \in B$	Constrained design
$A \cap B = \emptyset \Leftrightarrow Rr = \emptyset$	Incorrect requirements
$(A \cap B) \subset (A \wedge B)$	f(constraint, incomplete, incorrect)

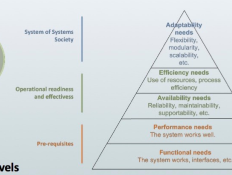
Flexibility in four dimensions:
- Functional reqs
- Performance reqs
- Resource reqs
- Interaction reqs

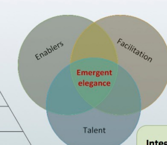
Order of flexibility:
- Order 1. Adapt(dRx)
- Order 2. Adapt(dRx,dRy)
- Order 3. Adapt (dRx,dRy,dRz)
- Order 4. Adapt (dRx,dRy,dRz,dRk)



Flexibility modeled as electron energy levels

Elegant systems





Integration with COSYSMO:
- Constraints and cost?
- Conflicts and cost?