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Establishing Quality Metrics for Systems Engineering Process

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Background

- Systems Engineering & Integration process is not unique
- Internally, we looked to standardize our process in concert with program/project management processes
- We wanted to provide a coherent, consistent approach to better address customer requirements

Motivation

Genesis

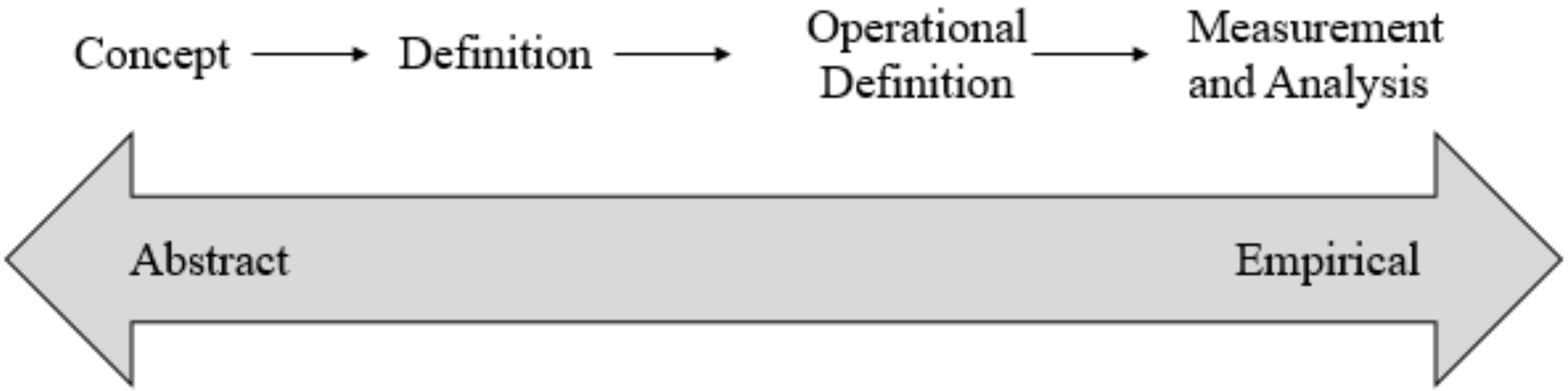
- Responding to RFI/P from a potential customer
- Old – cut & paste same/ similar boilerplate prose & material
- New – present new SE&I process, which is uniquely quantifiable

How to verify process is working

- Need quality metrics
- Assign complexity points
- Manage evolution of complexity through lifecycle
- Realize value through the lifecycle

Motivation

- Maturation through the lifecycle



Solution

- Architectural Decomposition - An architecture is the marriage of form and function to provide functionality greater than the sum of its parts.

- Blend architecture and systems thinking
  - Combination – form + function
  - Unique – social aspect
  - Structural complexity
  - Dynamic complexity
  - Social complexity

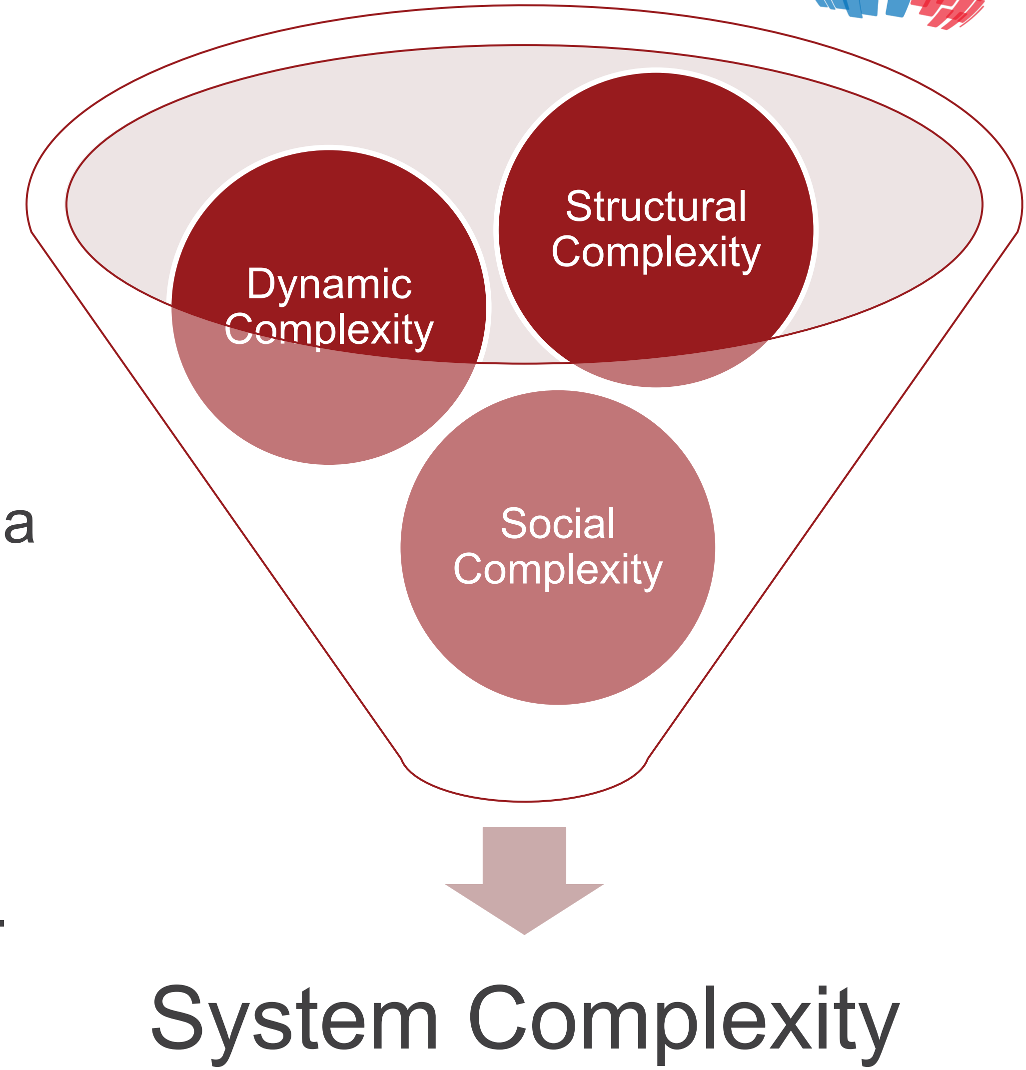
Solution-Space Influencers

Complexity – Defined

- Structural – number of different ways system elements can be combined at a physical level; related to **system's form**.

- Dynamic – complexity which can be observed when systems are used to perform tasks within a particular environment; related to **system's function**.

- Social - considers the effect of individuals or groups of people on complexity; related to perception of complexity and irrational behavior.



Complexity – Categorized

Complexity Driver	Categorization	Example
Structural	Represents the physical and logical connections between system components	Welded or Bolted interfaces, Cabling
Dynamic	Summarized by the number of inputs and outputs to and from the dynamic system	Embedded or Organic Software Functionality
Social	Increased number of stakeholders drives complexity with greater number of communication channels, as provided by the binomial coefficient	Working groups, “design by committee”

Complexity Points - CPs

- Leverages Agile "Story Points"
- Defined within as 3, 5, 8
- Tailorable Fibonacci sequence values
  - Extended to 13
  - Lowered to 1, 2
- Sample sizing
  - Small – 0-250
  - Medium – 251-500
  - Large – >500
- Can vary based on business experience

Complexity Points

CP	Structural	Dynamic
3	Defined by external stakeholder, e.g., Ethernet standard	Logic with two or fewer inputs and outputs, typically off-the-shelf
5	Defined by external stakeholder but not considered a standard	Logic with three to five inputs and outputs, may be off-the-shelf or internally developed
8	Internally developed and not considered a standard	Logic with more than five inputs and outputs

Metrics

- Collecting to prove that the SE&I process is functioning and managed in a closed-loop manner

- Overall goal – improve SE quality by gathering **and** analyzing metrics

- *Can be gathered by phase (e.g., resulting in Systems Requirements Review), but this is tailorable based on user-defined, time-boxed increments*

Overall Goals

Goals

- Improve Project Planning
- Increase Defect Containment
- Decrease Fault Density
- Improve Customer Service
- Reduce Cost of Nonconformance
- Increase SE Productivity

Metric Focus

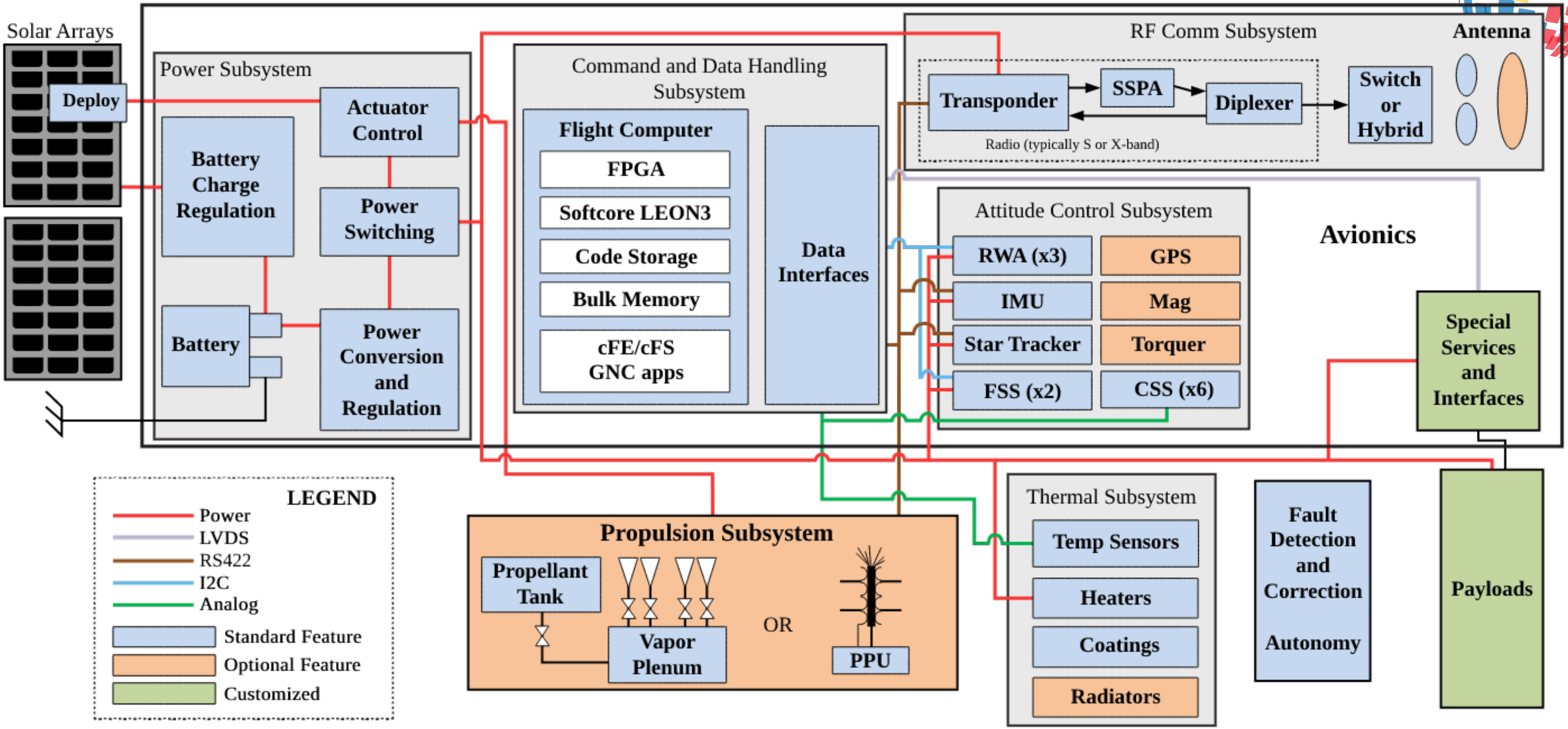
- Schedule and Effort Estimation
- Containment Effectiveness
- When Detected (phase)
- Number of open faults – how responsive in adressing issues
- Cost of Fixing Faults
- System Productivity Index

See paper for complete list and defintions

Sample System – description

- Technology demonstrator – cubesat solar panel deployment
- Maximum payload mass – 1.33 kg
- Volume – 10 cm x 10 cm x 10 cm
- Deployment via standard interface (P-POD)
- Battery
- Attitude determination

ArraySat Block Diagram



Sample System – Decomposition Overview

	Chassis	Solar Panels	Battery Charge Regulation	Actuator Control	Power Switching	Battery	Power Control Regulator	Flight Computer	Data Interfaces	Transponder	SSPA	Diplexer	Hybrid	Reaction Wheel	IMU	Star Tracker	FSS	GPS	Mag	Torquer	CSS	Temp Sensors	Heaters	Coatings	Radiators	Fault Detection	Propellant Tank	Vapor Plenum	Flight Computer
Chassis		3																						3	3		3	3	3
Solar Panels			3	3																									
Battery Charge Regulation						3																							
Actuator Control																							3					3	
Power Switching							3	3		3				3	3	3	3	3	3	3	3								
Battery							3																						
Power Control Regulator																													
Flight Computer									8																				
Data Interfaces										5				5	5	5	5	5	5	5	5	5				5			
Transponder											3	3	3																
SSPA												3	3																
Diplexer													3																
Hybrid																													
Reaction Wheel Assembly																													
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Coatings																													
Radiators																													
Fault Detector																													
Propellant Tank																												3	
Vapor Plenum																													
Flight Computer																													

Form-Form

	Control Attitude	Communicate With Ground	Control Antenna	Switch Power	Control Propulsion	Control Temperature	Monitor Processing	Monitor Payload
Chassis								
Solar Panels								5
Battery Charge Regulation								
Actuator Control	5	5	5		5	5		
Power Switching				5				
Battery								
Power Control Regulator								
Flight Computer	8		5	5			5	
Data Interfaces	8							
Transponder		5						
SSPA		5						
Diplexer		5						
Hybrid		5						
Reaction Wheel Assembly	5							
IMU	5							
Star Tracker	5							
Fine Sun Sensor (FSS)	5							
GPS	5							
Mag	5							
Torquer	5							
Course Sun Sensor (CSS)	5							
Temp Sensors								
Heaters								
Coatings								
Radiators								
Fault Detector								
Propellant Tank								
Vapor Plenum								
Flight Computer								

Form-Function

	Control Attitude	Communicate With Ground	Control Antenna	Switch Power	Control Propulsion	Control Temperature	Monitor Processing	Monitor Payload
Control Attitude					5			
Communicate With Ground								
Control Antenna								
Switch Power					5	5		
Control Propulsion								
Control Temperature								
Monitor Processing		8						
Moni[illegible]		[illegible]						

Function-Function

Decomposition of System Architecture

Sample System – Decomposition

- Function-function excerpt
- Attitude control connected to propulsion control

	Control Attitude	Communicate With Ground	Control Antenna	Switch Power	Control Propulsion	Control Temperature	Monitor Processing	Monitor Payload
Control Attitude					5			
Communicate With Ground								
Control Antenna								
Switch Power					5	5		
Control Propulsion								
Control Temperature								
Monitor Processing		8						
Monitor Payload		8						

Sample System – Decomposition (2)

- Form-form excerpt from Complete Matrix
- Solar panels regulating battery charging

	Chassis	Solar Panels	Battery Charge Regulation	Actuator Control	Power Switching
Chassis		3			
Solar Panels			3	3	
Battery Charge Regulation					
Actuator Control					

Sample System – Decomposition (3)

- Function-form excerpt from Complete Matrix
- Actuator control for attitude control

	Control Attitude	Communicate With Ground	Control Antenna
Chassis			
Solar Panels			
Battery Charge Regulation			
Actuator Control	5	5	5

Sample System – Reduce Complexity

- Utilize GOTS/COTS solutions
  - Favor Standard Solutions
- Lower complexity systems can be more robust/reliable
  - Reduced number of components/parts

Sample System – Metrics

	SRR	SDR	PDR	CDR	IA&T	SAR	ORR
Forecast (days)	30	30	30	30	30	30	15
Actual (days)	45	33	28	30	33	29	21
Forecast (cost)	$500	$750	$1,000	$750	$1,000	$500	$300
Actual (cost)	$491	$700	$1,214	$487	$784	$490	$270
Internal Defects Found	47	91	83	44	91	19	0
Internal Defects Closed	14	34	92	60	65	68	1
Internal Errors Found	19	21	19	34	19	3	0
Internal Errors Closed	8	4	6	30	34	9	0
External Errors Found	4	12	7	9	7	4	1
External Errors Closed	0	9	4	3	18	9	1
Cost to Correct Defects	$1,000	$750	$ 850	$1,200	$ 950	$2,000	$1,000
System Engineering Cost	$1,200	$1,300	$4,000	$2,500	$1,900	$1,000	$500

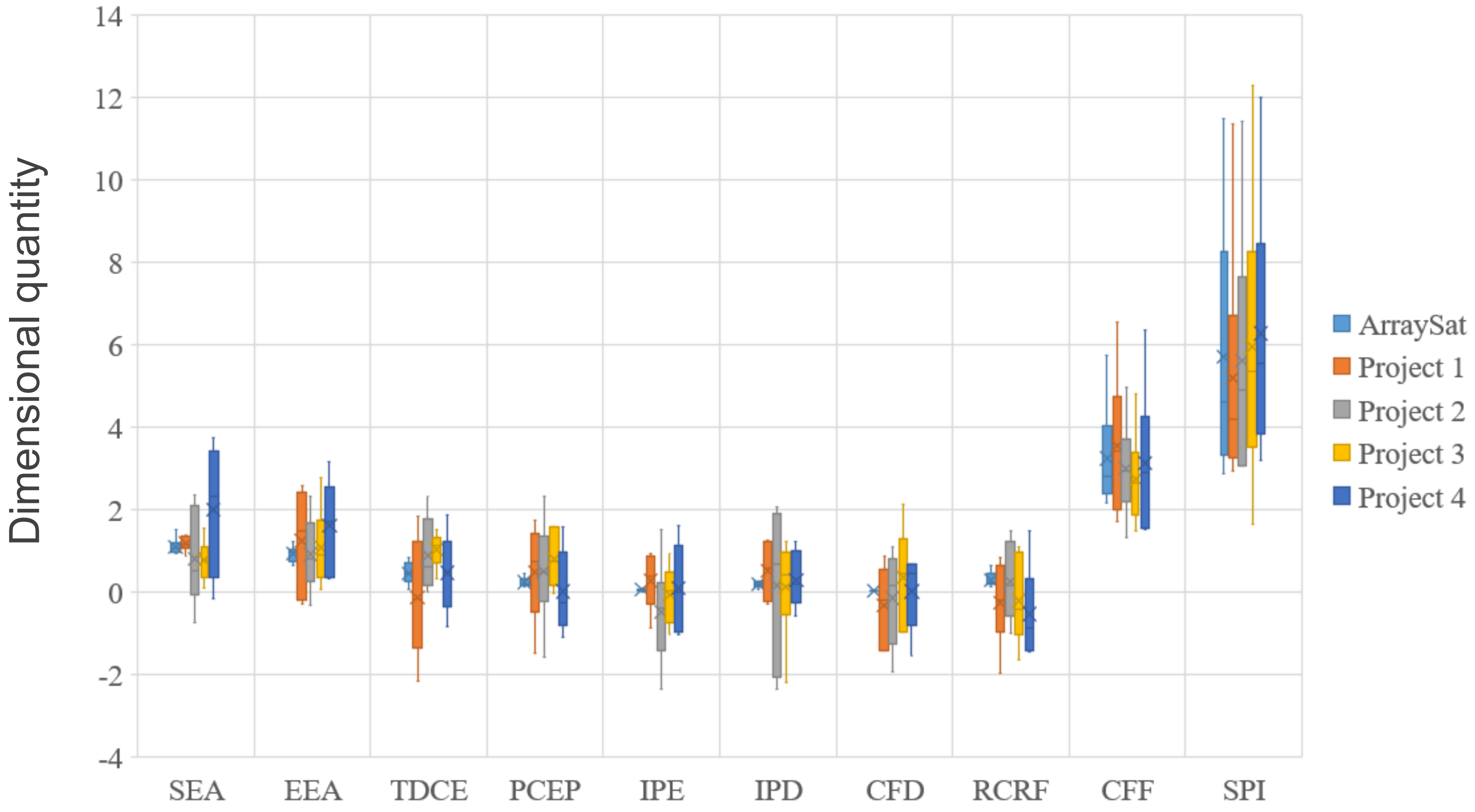
- Metrics gathered per identified phase for ArraySat

Sample System – Metrics (2)

	SRR	SDR	PDR	CDR	IA&T	SAR	ORR
Schedule Estimation Accuracy (SEA)	1.50	1.10	0.93	1.00	1.10	0.97	1.40
Effort Estimation Accuracy (EEA)	0.98	0.93	1.21	0.65	0.78	0.98	0.90
Phase Containment Effectiveness for Phase (PCEP)	1.00	0.60	0.48	0.74	0.83	0.75	0.00
In-Process Errors (IPE)	0.05	0.06	0.05	0.10	0.05	0.01	0.00
In-Process Defects (IPD)	0.00	0.04	0.06	0.03	0.01	0.00	0.00
Customer-Found Defects (CFD)	0.01	0.03	0.02	0.03	0.02	0.01	0.00
Ratio of Captured and Released Faults (RCRF)	4.75	0.81	0.68	1.62	1.73	0.60	1.70
New Opened Faults (NOF)	23.00	47.00	47.00	55.00	30.00	8.00	1.00
Total Opened Faults (TOF)	31.00	51.00	43.00	84.00	80.00	23.00	1.00
Mean Age of Closed Faults (MACF)	2.50	9.15	8.21	15.40	8.40	8.20	8.20

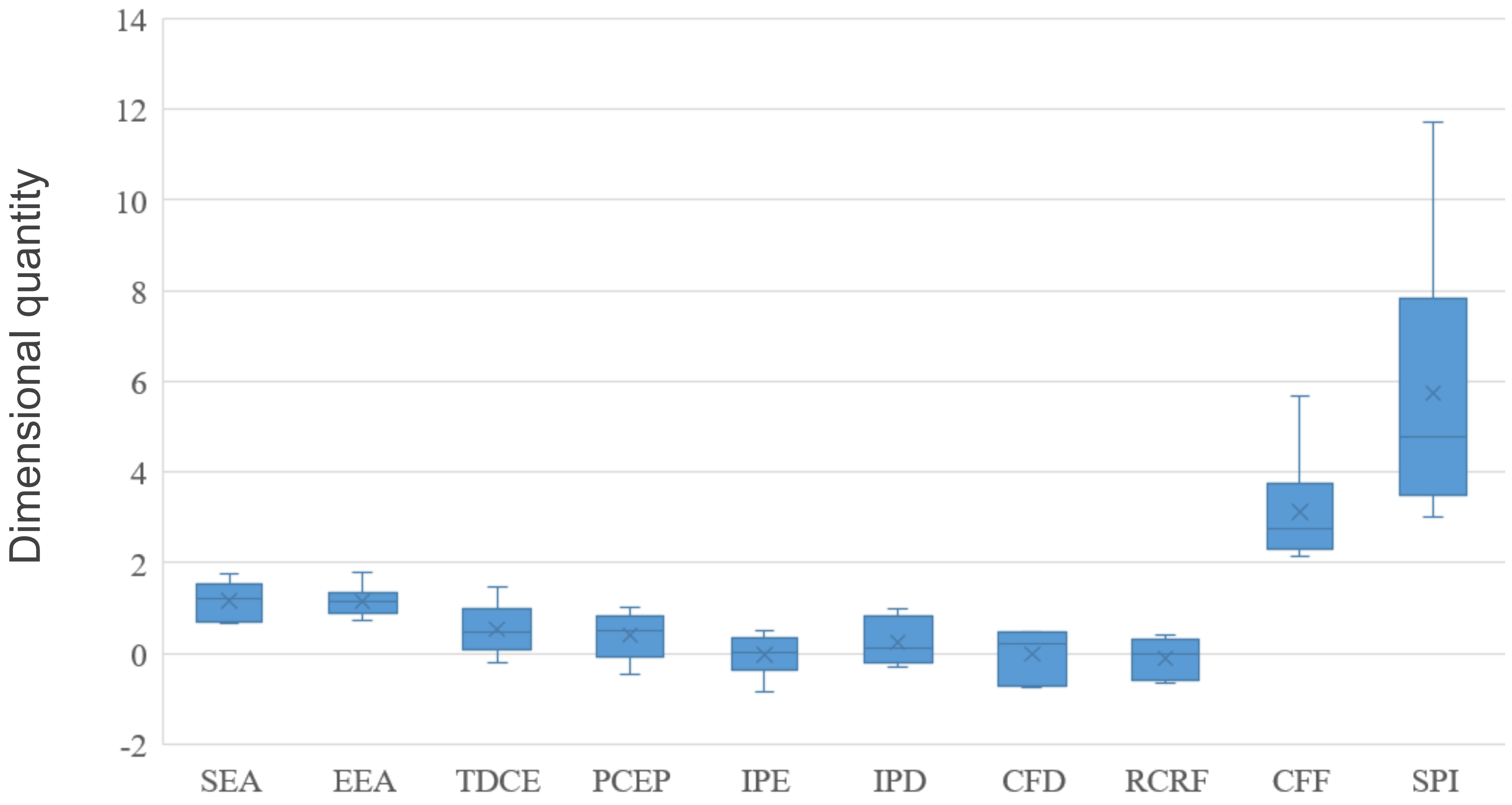
- Metrics captured after a hypothetical year of SE&I support

Sample System – Comparison



- Projects of differing size and complexity
- Abscissa – calculated metrics

Sample System – Comparison (2)



- Statistical analysis
- Projects of differing size and complexity
- Abscissa – calculated metrics

Sample System – Comparison (3)

- SEA and EEA – Since they hover near zero, they show good agreement between forecast and actual.

- PCEP – This is the phase captured faults. Depending on the organization, the PM may allocate more funds to mitigation of in-phase faults.

- SPI – This is system complexity and is the big takeaway. The organization's system complexity level can be multiplied by the cost per complexity point to get an understanding of SE&I costs for other projects. This is statistically rigorous and is based on historical metrics.

- There are some other metrics that hover near zero (e.g. CFD); these are acceptable.

Conclusion

- SE&I metrics, when captured and analyzed incrementally, form a robust statistical approach of the underlying model an organization uses to synthesize systems.

- Metrics tethered on an SE&I process have insight into all aspects of the system development lifecycle and can exceed the ability of canonical estimating processes, which are typically focused on a specific lifecycle phase or domain.

Future Work

- Automation using a lifecycle management tool can aid in the minimization of complex systems and the incremental realization of value throughout the process.

- Potential expansion to an entirely digital domain

Backups

CP	Structural Definition	Dynamic Definition
3	A low-complexity system form is a physical or data connection defined by an external stakeholder and is considered industry standard. An example of this is IEEE 802.3, which defines the Ethernet network standard.	A low-complexity system function is logic with two or fewer inputs and outputs. Low complexity systems often use off-the-shelf software or firmware packages to provide the desired system behavior. Simple functions or classes written by the organization for custom processing are also considered low complexity. An example of a low complexity system behavior may be an αβ filter which uses a simplified observer for estimation, and data smoothing for control systems. The αβ filter converts an input signal to a corrected output signal. Per the definition above, this filter would be considered low complexity.
5	A medium-complexity system form is a physical or data connection defined by an external stakeholder but is not considered a standard (e.g., custom/proprietary adaptor plate between two hardware components or Microsoft® Word *.docx format). The reason this is more complex is because system engineers need to verify that the formats are compatible, and this may increase required testing rigor.	A medium-complexity system function is logic with three to five inputs and outputs. Medium complexity system function may use off-the-shelf or internally developed software or firmware packages to provide the desired system behavior. The practicing SE is encouraged to use engineering judgement and relevant domain knowledge to categorize the system functionality. An example of a medium-complexity system behavior could be a cubic spline interpolation, in which vectors of independent and dependent variables are represented using an underlying mathematical model.
8	A high-complexity system form is a physical or data connection defined by internal stakeholders that is not considered standard or a high complexity interface. The underlying assumption here is that a proprietary or purpose-built interface will require increased testing rigor, solicitation with external stakeholders and adjacent component makers, and design reviews and iterations.	A high-complexity system function is logic with greater than five inputs and outputs. High complexity system function may use off-the-shelf or internally developed software or firmware packages to provide the desired system behavior. The practicing SE is encouraged to use engineering judgement and relevant domain knowledge to categorize the system functionality. At this level, high-complexity functionality can often be decomposed into several medium or low complexity system elements. For example, a Guidance, Navigation, and Control (GNC) algorithm may decompose into several elements focused on processing of external sensors states (e.g., Navigation Camera, Star Trackers, Sun Sensors, Accelerometers, or Gyroscopes), filtering and assembling the final navigation solution, and then exerting positive control over the various attitude management or orbital control thrusters. The complicated GNC behavior is the holistic representation of all sub-routines, data handling, filtering, and integration activities. The practicing SE is encouraged to use systems thinking to decompose complex system behavior into relevant system elements

Metric	Formula
Schedule Estimation Accuracy	$SEA = \frac{Actual\ Phase\ Duration}{Estimated\ Phase\ Duration}$
Effort Estimation Accuracy	$EEA = \frac{Actual\ Phase\ Effort}{Estimated\ Phase\ Effort}$
Total Defect Containment Effectiveness	$TDCE = \frac{Number\ Prerelease\ Defects}{(Number\ Prerelease\ Defects + Number\ Postrelease\ Defects)}$
Phase Containment Effectiveness for Phase	$PCEP = \frac{Number\ Phase\ Errors}{(Number\ Phase\ Errors + Number\ Phase\ Defects)}$
In-Process Errors	$IPE = \frac{Number\ of\ Prerelease\ Errors}{System\ Complexity\ Points}$
In-Process Defects	$IPD = \frac{Number\ of\ Prerelease\ Defects}{System\ Complexity\ Points}$
Customer Found Defects	$CFD = \frac{Number\ of\ Customer\ Found\ Defects}{System\ Complexity\ Points}$

Metric	Formula
Ratio of Captured and Released Faults	$RCRF = \frac{IPE}{IPD + CFD}$
Total Open Faults	N/A
Mean Age of Open Faults	N/A
Mean Age of Closed Faults	N/A
Cost of Fixing Faults	$CFF = \frac{Cost\ of\ Defect\ Correction}{System\ Complexity\ Points}$
Systems Productivity Index	$SPI = \frac{Systems\ Engineering\ Effort}{System\ Complexity\ Points}$

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Actuator Control																							3					3	
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Propellant Tank								
Vapor Plenum	5							
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