Platform Evolution

Extending System Lifecycles Under Uncertainty

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Engineered Resilient Systems Track
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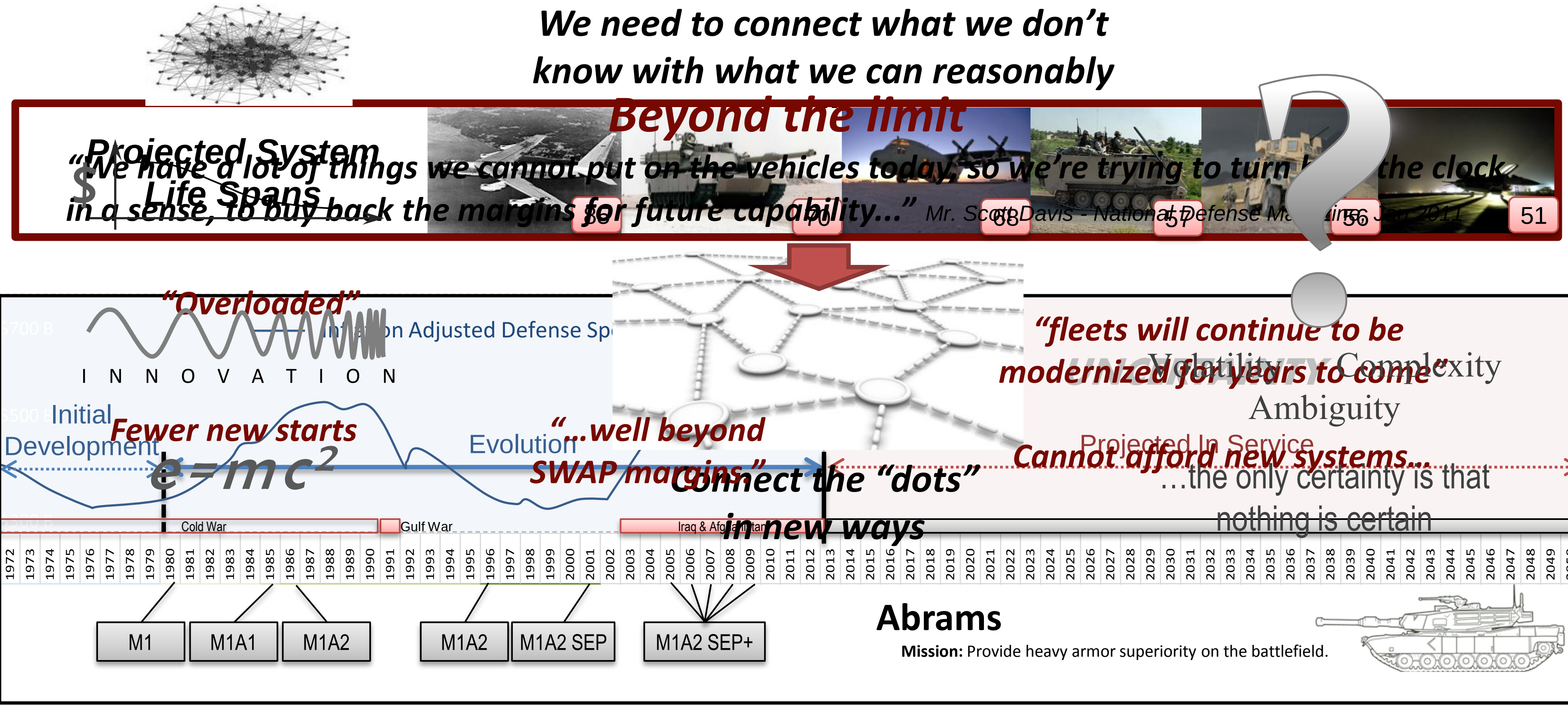
SE&I



"This country is at a strategic turning point, after a decade of war"

Secretary of Defense Leon E. *Panetta*

"It is now time to lift our heads up a bit and look out with a more strategic view..."

Maj. Gen. Kurt Stein - National Defense Magazine, January 2011

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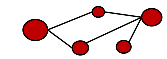
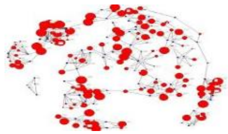
Assertions



- **Clean sheet complex systems development is extremely rare**

  Design process is more middle out than top down or bottom up

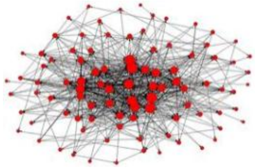


- **Platform Evolution occurs incrementally over an extended period of time**

  Context drives intensity and inactivity

- **Cannot afford new systems – so we must design for change**

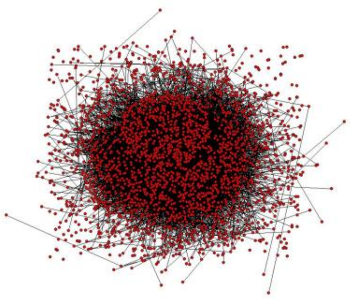
  Design for the new …ilities – agility, flexibility, adaptability, extensibility, insensitivity…



Implications

- **Legacy systems need more efficient and resilient designs**

  Regain lost margins - Simplify designs - Balance modularity and integrality – Absorb change



- **Must take advantage of every incremental upgrade**

  "…Aim at eternity" - Avoid Architectural "Lock In" - Total life cycle cost

- **Must identify, assess and prioritize future needs and know constraints**

  Accommodate future upgrades - Technology Forecasting

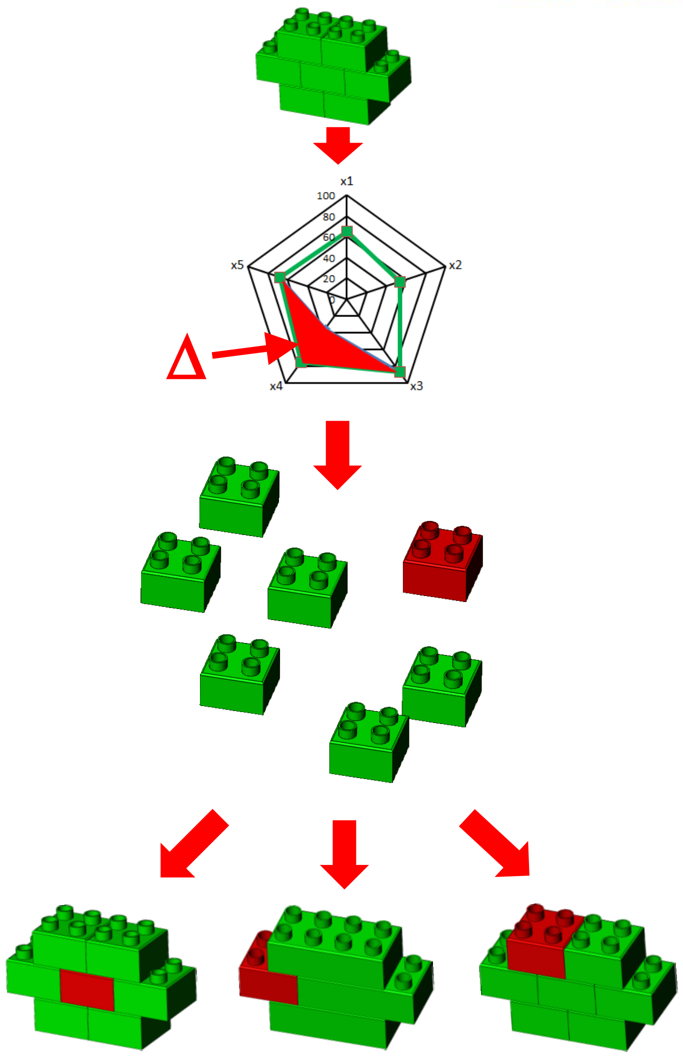
"We can't solve problems by using the same kind of thinking we used when we created them."

Albert Einstein

Life span data obtained from wikipedia.com, globalsecurity.org and ndia.org

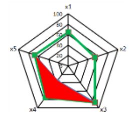
Platform Evolution Involves:

- **Uncertainty Management**
  - Understanding how requirements might change
  - Eliminating the cause of the uncertainty
  - Delaying design decisions until uncertain variables are known
- **Architecture Management**
  - Reducing system sensitivity to uncertainty
  - Purposefully isolating anticipated change
  - Planning for subsystem and/or technology insertion
  - Leveraging platform engineering methodologies
- **Decision Analysis**
  - Optimizing system level performance , growth, risks etc.
  - Conducting performance and risk tradeoffs
  - Making decisions to optimize this tradeoff



"Curiosity begins as an act of tearing to pieces or analysis." - Samuel Alexander

Uncertainty Management Involves



- **Clarifying Issues**

  Envisioning alternate futures for operational context, mission, technologies, etc.

  Identifying key issues and categorizing them as Criteria, Chances, Choices & Constituencies

  Tools: Wargaming, Brainstorming, Delphi, Affinity Diagrams…

- **Describing the potential uncertainties, decisions and criteria**

  Assessing probability of occurrence and how that probability changes over time

  Understanding how uncertainties may be driven by more fundamental ones

  For each criteria perform Five Whys to infer the primary criteria/needs

  Tools: SME and Stakeholder Interviews, Five Whys, Root Cause Analysis…

- **Identifying the drivers of performance on each criteria**

  Define a deterministic multi-objective measure of performance

  Relate multi-objective measure to the uncertainties and decisions (Influence Diagrams)

  Analyze the end-point uncertainties of the influence diagram to determine which uncertainties, when varied over their range, cause the greatest change in value

  Tools: Multi-attribute Utility, Influence Diagrams, Design of Experiments, Pareto Charting…

"For all of its uncertainty, we cannot flee the future." - Barbara Jordan

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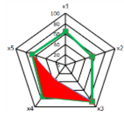
Influence Diagrams

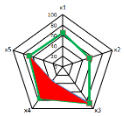


- Influence diagrams were developed by the decision-analysis community as a compact visual representation of a decision problem
- They provide an intuitive approach to modeling:
  - Uncertainty
  - Risk
  - Cost
- Influence diagram software couples the development of a visual and analytical model
- Influence diagrams are helpful in identifying factors affecting the probability of system elements requiring
  - A hierarchy of modules can be used to manage complexity and to create holistic models
  - Variables can be multidimensional arrays
  - Users can define functions

Symbol	Element	Description
What do we do?	Decision	A variable that can be modified directly
What's the outcome?	Chance Variable	A value which cannot be controlled directly, is uncertain
What's the situation?	General Variable	A deterministic fuction of the quantities is depends on
How do we like it?	Objective	A measure of satisfaction with an outcome, utility
⟶	Arrow	An influence

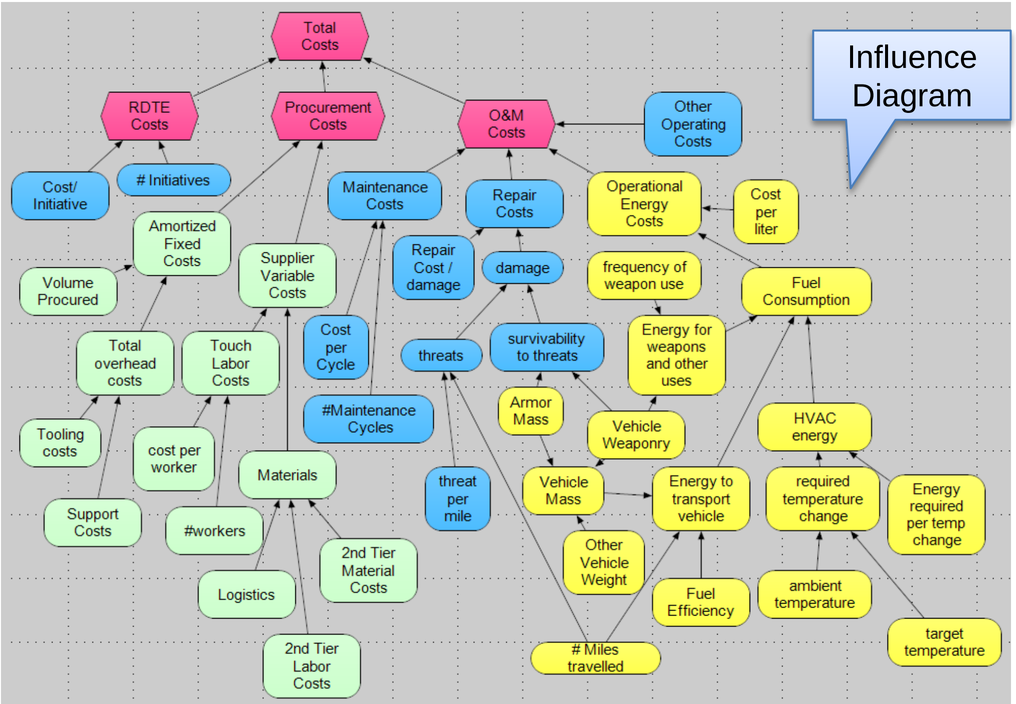
Table definitions derived from and graphics obtained from http://www.lumina.com/technology/influence-diagrams/

Sensitivity & Criticality



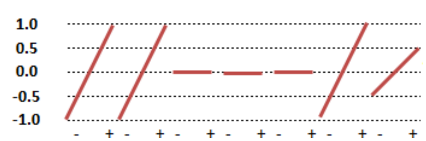
- Influence Diagrams –great tool for identifying cost drivers in complex systems
- The adjacent example models total cost as an aggregate or RDT&E, Procurement and O&M.
- With this model we can conduct a sensitivity analysis, via a DOE, to identify the impact of different uncertainties.
- This DOE also allows for the estimation of interaction effects
- Use a tornado chart (two-sided vertical Pareto chart) to identify the most critical uncertainties

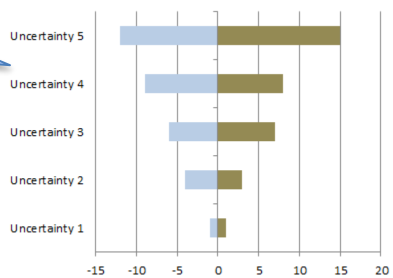
Influence Diagram



Design Of Experiments

Tornado Chart





"Information is the resolution of uncertainty." - Claude Shannon

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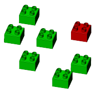
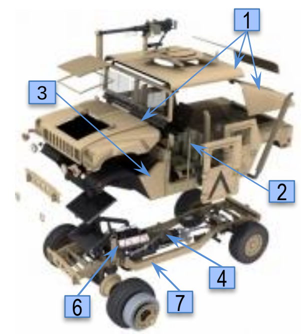
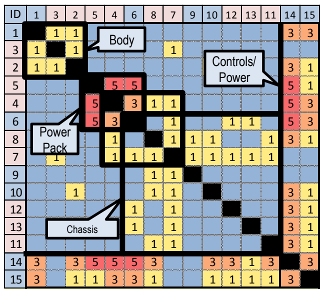
Architectural Management Involves



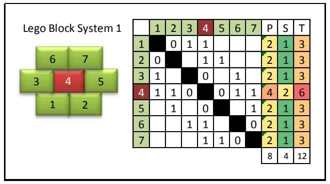
- Identifying and characterizing system interactions
- Providing analytical rigor around how system elements interact to maximize system value
- Understanding how system elements and interactions are affected by change
- Performing analysis and appropriately modifying the architecture to decrease cost sensitivity to change

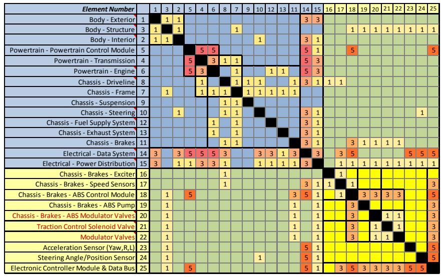




Attributes and methods to consider:

- Modularity and Integrality
- Change Propagation
- Technology Integration
- Platform Engineering

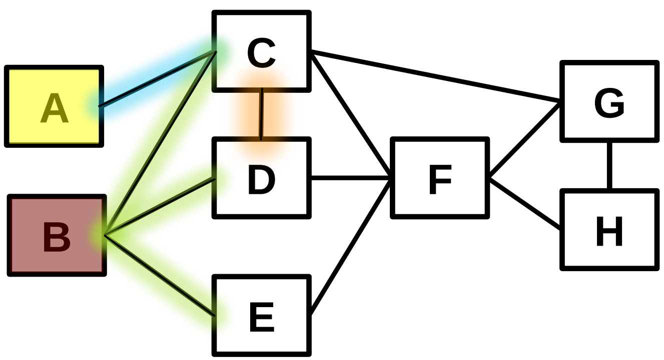




"Each new situation requires a new architecture." - Jean Nouvel

Matrices provide a powerful way to analyze architectures

- The diagrams below provide two different views of a generic system with interrelationships
- Interrelationships could be physical/forces, information flows, energy transfer or material/mass exchange
- Diagrams are necessary to gain a better understanding of how systems elements interact



Graph (Network) View

Lines indicate connectivity between elements

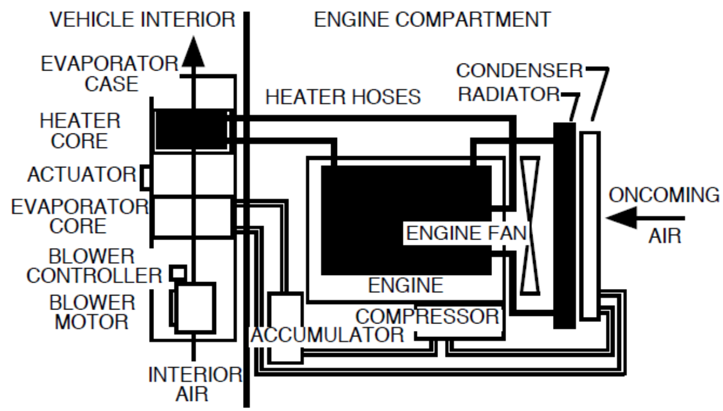
	A	B	C	D	E	F	G	H
A			X					
B			X	X	X			
C	X	X		X		X	X	
D		X	X			X		
E		X				X		
F			X	X	X		X	X
G			X			X		X
H							X	

Matrix View

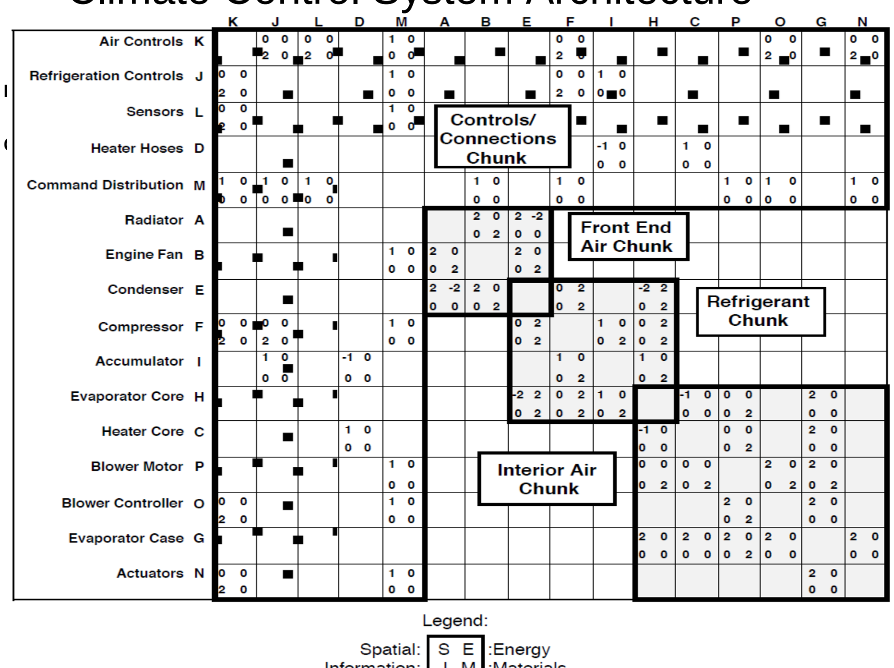
X's indicate connectivity between elements

The benefit of the matrix is that it provides a compact visual of the system and it enables holistic integration modeling, analysis and optimization

System Architecture Analysis Example Using Matrices

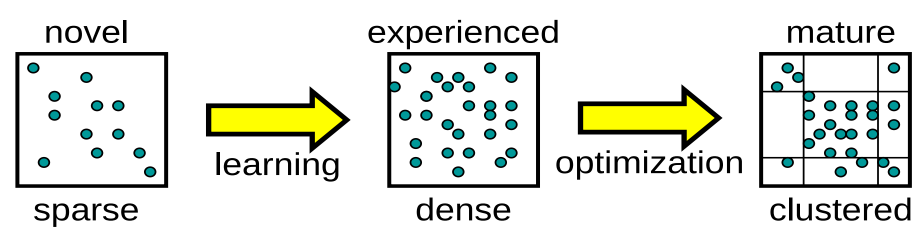


Climate Control System Architecture



		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Radiator	A	A	X			X											
Engine Fan	B	X	B			X								X			
Heater Core	C			C	X			X	X								X
Heater Hoses	D			X	D					X							
Condenser	E	X	X			E	X		X								
Compressor	F					X	F		X	X	X	X		X			
Evaporator Case	G			X				G	X						X	X	X
Evaporator Core	H			X		X	X	X	H	X							X
Accumulator	I				X		X		X	I	X						
Refrigeration Controls	J						X			X	J	X		X			
Air Controls	K						X				X	K	X	X	X	X	
Sensors	L											X	L	X			
ommand Distribution	M		X				X				X	X	X	M	X	X	X
Actuators	N							X				X		X	N		
Blower Controller	O							X				X		X		O	X
Blower Motor	P			X				X	X					X		X	P

Levels of understanding of System Architectures



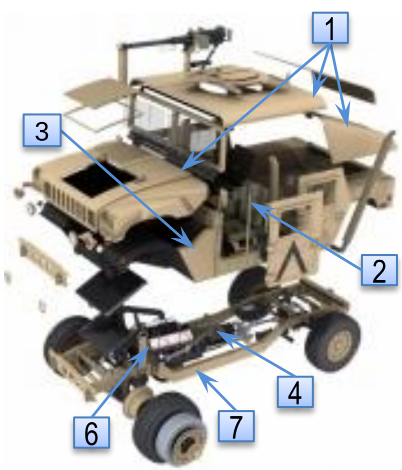
Steven Eppinger, MIT – ESD36j – Systems & Project Management
Fall 2002 Class Lecture notes

Modularity and Integrality

- Modularization is the grouping of system elements that are mutually exclusive or minimally interacting subsets (absorb interactions internally) – minimizing external connections
- Can minimize change propagation, enable technology insertion and platform based engineering methods making systems less sensitive to the uncertainties
- Applied at various levels of decomposition can aid to regain margins through combination: apply function sharing and axiomatic principles

"Bolt On" Mission Equipment Integration

Graphic Source: AUSA ILW Sustainment Symposium Technology Panel Resetting for the Future:, K. Griffith-Brown –24-Jun-2010



Element Number		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Body - Exterior	1		X	X											X	X
Body - Interior	2	X		X											X	X
Body - Structure	3	X	X					X								
Powertrain - Transmission	4					X	X	X	X						X	X
Powertrain - Powertrain Control Module	5				X		X							X	X	X
Powertrain - Engine	6				X	X		X	X		X		X	X	X	X
Chassis - Frame	7			X	X		X		X	X	X		X	X		
Chassis - Driveline	8				X		X	X		X	X	X	X		X	
Chassis - Suspension	9							X	X							
Chassis - Steering	10						X	X	X						X	X
Chassis - Brakes	11								X						X	X
Chassis - Fuel Tank	12						X	X	X						X	X
Chassis - Exhaust	13					X	X	X							X	X
Electrical - Data System	14	X	X		X	X	X		X		X	X	X	X		X
Electrical - Power Distribution	15	X	X		X	X	X				X	X	X	X	X	

	1	3	2	5	4	6	8	7	9	10	12	13	11	14	15
1		1	1											3	3
3	1		1					1							
2	1	1												3	1
5					5	5								5	1
4				5		3	1	1						5	3
6				5	3			1			1	1		5	3
8					1			1	1	1			1	3	1
7		1			1	1	1		1	1	1	1	1		
9							1	1							
10			1				1	1						3	1
12						1		1						3	1
13						1		1						3	1
11							1	1						3	1
14	3		3	5	5	5	3			3	3	1	3		3
15	3		1	1	3	3	1			1	1	1	1	3	

Body
Controls/ Power
Power Pack
Chassis

Change Propagation

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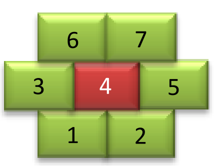
- Changes can easily balloon in an uncontrolled fashion
- Knowing how changes propagate so 2nd, 3rd, and 4th order impacts are know is very powerful
- Early discovery of "propagation paths" can have a significant impact on total life cycle cost.[1]
- Architectural analysis and planning helps to control change propagation due to upgrades.

Multipliers	Generate more changes [1] than they absorb
Carriers	Absorb a similar number of changes to those they cause
Absorbers	Absorb more change they themselves cause
Constants	Unaffected by change

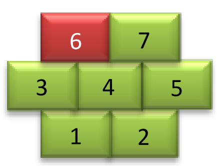
Realized uncertainties often drive engineering changes

Block System 1



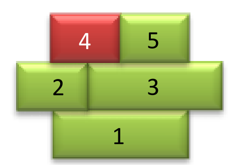
	1	2	3	4	5	6	7	P	S	T
1		0	1	1				2	1	3
2	0			1	1			2	1	3
3	1			0		1		2	1	3
4	1	1	0		0	1	1	4	2	6
5		1		0			1	2	1	3
6			1	1			0	2	1	3
7				1	1	0		2	1	3
								8	4	12

Block System 2



	1	2	3	4	5	6	7	P	S	T
1		0	1	1				2	1	3
2	0			1	1			2	1	3
3	1			0		1		2	1	3
4	1	1	0		0	1	1	4	2	6
5		1		0			1	2	1	3
6			1	1			0	2	1	3
7				1	1	0		2	1	3
								8	4	12

Block System 3



	1	2	3	4	5	P	S	T
1		1	1			2	0	2
2	1		0	1		2	1	3
3	1	0		1	1	3	1	4
4		1	1		0	2	1	3
5			1	0		1	1	2
						5	2	7

P=1 = Primary Interface (snap fit) S=0 = Secondary Interface (non-snap fit)

"All change is not growth, as all movement is not forward. " - Ellen Glasgow

1. Eckert C, (2004) Change and Customization in Complex Engineering Domains, Research in Engineering Design

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Technology Integration

- Analyzing integration risks and transition readiness to improve technology insertion or subsystem integration
- Reveal which elements pose complexity, risk and may become likely cost drivers
- Combine system and subsystem matrixes to forms a multi-domain matrix (MDM)

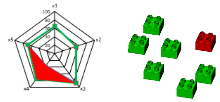
Identify which technology elements affect multiple system level elements

Element Number		1	3	2	5	4	6	8	7	9	10	12	13	11	14	15	16	17	18	19	20	21	22	23	24	25
Body - Exterior	1		1	1											3	3										
Body - Structure	3	1		1					1										1	1	1	1	1	1	1	1
Body - Interior	2	1	1								1				3	1										
Powertrain - Powertrain Control Module	5					5	5								5	1			5							5
Powertrain - Transmission	4				5		3	1	1						5	3										
Powertrain - Engine	6				5	3			1			1	1		5	3										
Chassis - Driveline	8					1			1	1	1			1	3	1	1	1								
Chassis - Frame	7		1			1	1	1		1	1	1	1	1												
Chassis - Suspension	9							1	1																	
Chassis - Steering	10			1				1	1						3	1									1	
Chassis - Fuel Supply System	12						1		1						3	1										
Chassis - Exhaust System	13						1		1						3	1										
Chassis - Brakes	11							1	1						3	1			3	1	1	1	1			
Electrical - Data System	14	3		3	5	5	5	3			3	3	1	3		3		3	5					5	5	5
…ical - Power Distribution	15	3		1	1	3	3	1			1	1	1	1	3			1	1	1	1	1	1	1	1	1
Chass… …kes - Exciter	16							1										1								
Chassis - Brakes - Speed Sens…	17							1							3	1	1		1							3
Chassis - Brakes - ABS Control Module	18		1		5									3	5	1		1		3	3	3	3			5
Chassis - Brakes - ABS Pump	19		1											1		1			3							3
Chassis - Brakes - ABS Modulator Valves	20		1											1		1			3			1	1			3
Traction Control Solenoid Valve	21		1											1		1			3		1		1			
Modulator Valves	22		1											1		1			3		1	1				3
Acceleration Sensor (Yaw,R,L)	23		1												5	1										5
Steering Angle/Position Sensor	24		1								1				5	1										5
Electronic Controller Module & Data Bus	25		1		5										5	1		3	5	3	3	3	3	5	5	

Identify high impact areas to a particular system element

Assess multiple technologies to determine Technology Invasiveness (*Technology Infusion – Oli de Weck*)

Platform Engineering

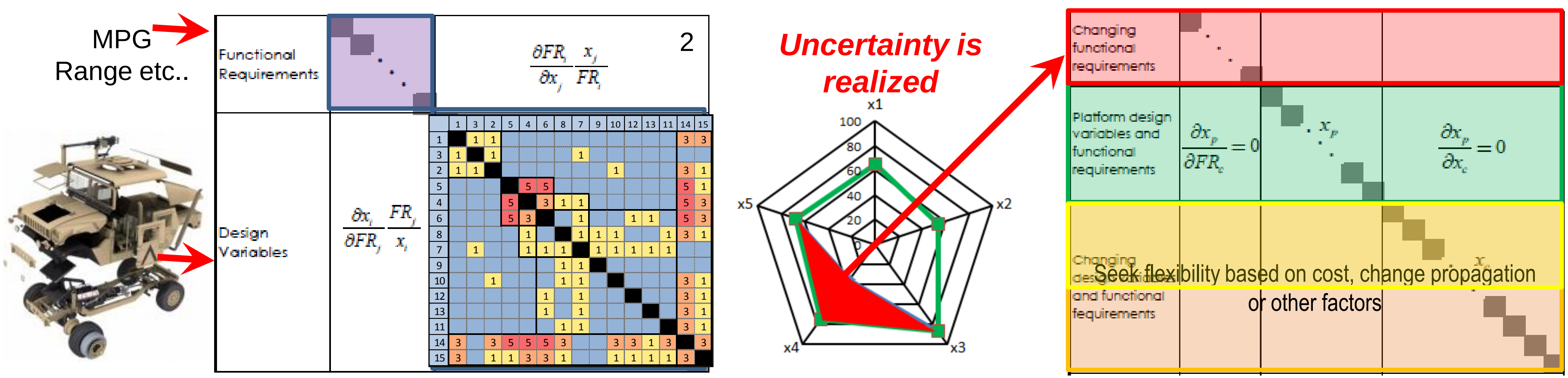


Platform: A core infrastructure (system) that consists of ***common*** *and* ***flexible elements*** (components, processes and interfaces), which enable production of distinctive product variants and product families by adding ***unique elements***.[1]

Common Elements: Common across variants - less sensitive to changes over time.

Flexible Elements: Interchangeable at a lower cost to accommodate uncertainties

Unique Elements: Not easily changed without redesign.



1. deWeck, Oli, Strategic Engineering: Designing Systems for an Uncertain Future, Flexible Product Platforms: Framework and Case Study
2. Kalligeros K., de Weck O., de Neufville R., Luckins A., "Platform Identification using Design Structure Matrices", *Sixteenth Annual International Symposium of the International Council On Systems Engineering (INCOSE)*, Orlando, Florida, 8 - 14 July 2006

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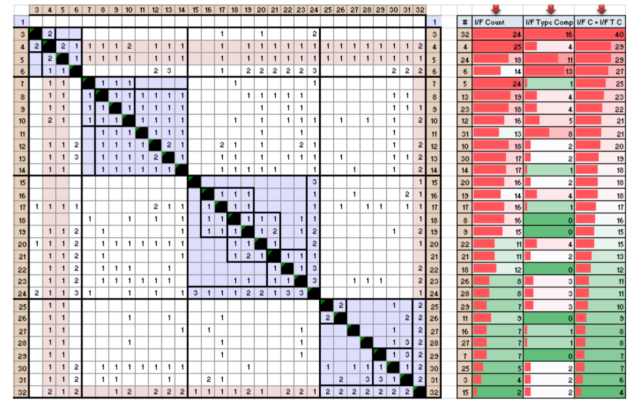
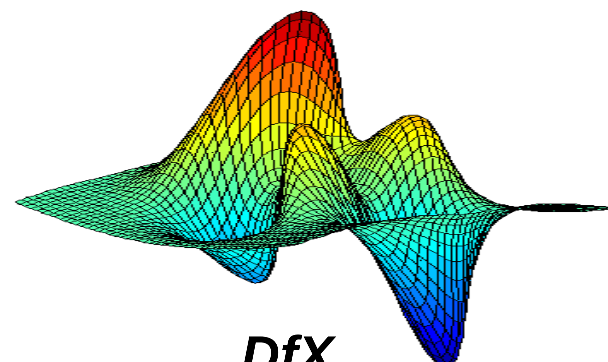
Whole System Trades Analysis Involves:

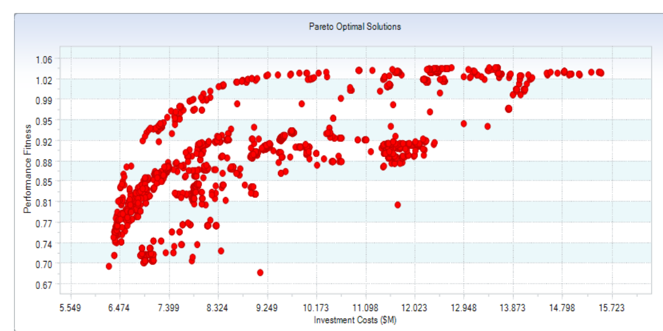
Assessing system level performance through understanding of subsystem level options and contributions across configuration options

- Establish system and data structures as well as architectural options; must fits, fits and misfits
- Develop understanding and selection of criteria to be considered including the interactions of these criteria
- Leverage SMEs and physics based models as inputs for weighting of criteria or attributes to assess value
- Provide a means to evaluate and graphically display alternatives under multiple criteria
- Enable data visualizations from multiple perspectives and filtering for DfX analysis
  - Aid with economic evaluation and architectural options valuation, establish growth metrics
  - Conduct performance and risk tradeoffs



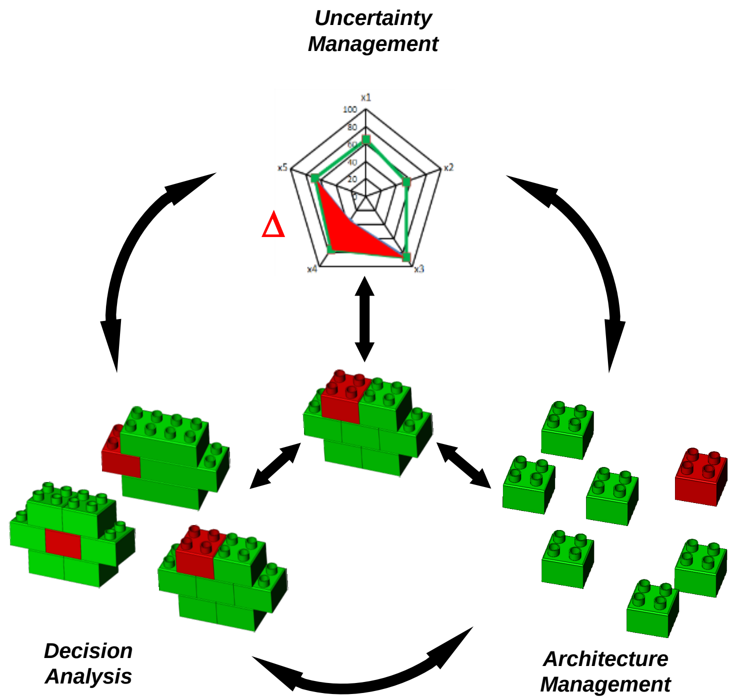


DfX



Uncertainty Management - Architecture Management - Decision Analysis

- Uncertainty management reduces and prioritizes the uncertainties affecting the architecture
- Architecture management minimizes the overall impact of uncertainty
- Decision Analysis seeks the optimal solutions given uncertainty and constraints
- These three disciplines are best used iteratively as part of an integrated approach to engineering resilient systems



"Get the habit of analysis - analysis will in time enable synthesis to become your habit of mind."
Frank Lloyd Wright

Conclusions

- Understanding future changes is not easy but analyzing the potential futures is necessary to reduce total life cycle cost
- Reduced cost in complex systems is ultimately achieved by architecting for change creating more flexible, agile, robust and adaptable systems
- Developing system models will establish a documented knowledge base for quickly making decisions and recording key design rules
- Methods presented have been successfully employed within government and industry programs. (Automotive, Aerospace, Oil, Healthcare, Telecom electronics and others)

Key Questions	*Disciplines & Methodologies*
What future upgrades will be needed?	**Uncertainty Management**
–What uncertainties are likely to be realized?	–Wargaming, Brainstorming, Delphi, Affinity…
–What are some of the fundamental cost drivers?	–Interviews, Five Whys, Root Cause Analysis…
–To which uncertainties are we highly sensitive?	–Multi-attribute Utility, Influence Diagrams, DOE, Pareto…
How do I plan to implement future upgrades?	**Architecture Management**
–How do I minimize the time and cost to upgrade?	–Modularization, Change Propagation…
–How do I prepare for new technologies?	–Technology Insertion and Transition…
–Where do I pursue commonality or design in flexibility?	–Platform Engineering…
Given constraints what is the optimal solution?	**Decision Analysis**
–What is the business case for building in flexibility?	–Decision Tree, Expected Value of Information Analysis,
–How do I optimally make trades in the face of uncertainty?	Expected Utility, Reliability Based Design Optimization,

"The future is uncertain… but this uncertainty is at the very heart of human creativity. - Ilya Prigogine

Thank You

&

Questions

About the Presenter

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Troy Peterson is a Senior Associate at Booz Allen Hamilton with over 19 years' experience in systems development and management. He has led several distributed teams in delivery of large-scale complex systems and has instituted numerous organizational processes to improve efficiency and effectiveness. His consulting experience spans academic, commercial and government sectors across all development lifecycle phases

Troy leads Booz Allen's support to the U.S. Army TARDEC and the firm's engineering support across the TACOM LCMC. Prior to Booz Allen Troy worked at Ford Motor Company and Peterson & Associates, Inc., which he founded and operated in support to academic research labs and small engineering firms.

Troy completed advanced graduate studies at Massachusetts Institute of Technology in System Design and Management, obtained a MS in Business and Technology Management from Rensselaer Polytechnic Institute and holds a BS in Mechanical Engineering from Michigan State University. He Michigan State University's Mechanical Engineering Department Advisory Board Secretary and is the INCOSE Michigan Chapter Past President. Troy is an INCOSE Certified Systems Engineering Professional, PMI Project Management Professional, and ASQ Certified Six Sigma Black Belt.

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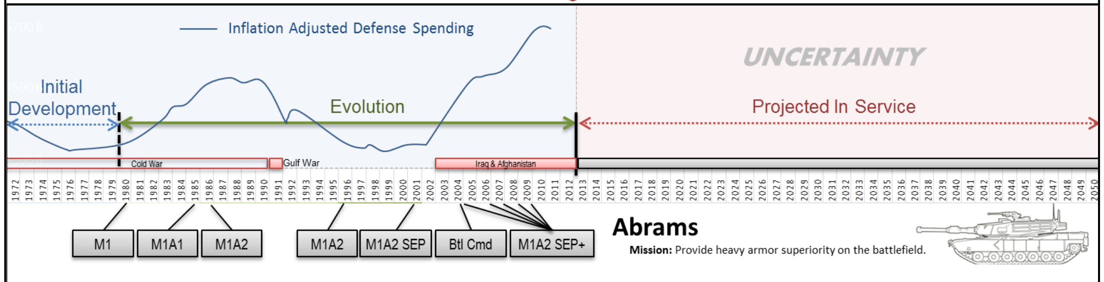
Projected System Life Spans



"It is now time to lift our heads up a bit and look out with a more strategic view as we determine the true and enduring requirements for the future." *Maj. Gen. Kurt Stein - National Defense Magazine, January 2011*

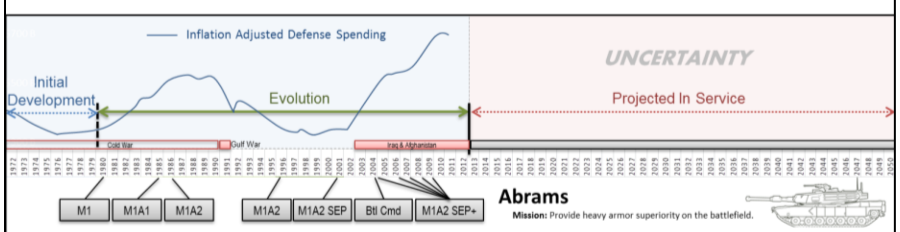
Beyond the limit

"We have a lot of things we cannot put on the vehicles today, so we're trying to turn back the clock in a sense, to buy back the margins for future capability..." *Mr. Scott Davis - National Defense Magazine, Jan 2011*

"Overloaded"

"...well beyond SWAP margins."

"fleets will continue to be modernized for years to come"



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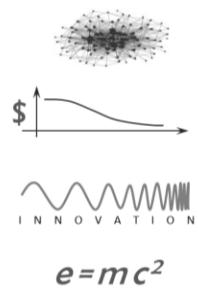
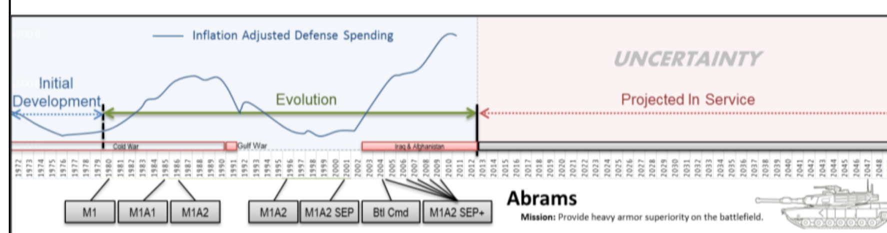


"We can't solve problems by using the same kind of thinking we used when we created them."
Albert Einstein

Connect the "dots" in new ways

Volatility Complexity
Uncertainty Ambiguity



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