Systems Engineering and Systems Management Transformation

- Ilities Tradespace and Affordability Project (iTAP)
  - Barry Boehm, Jo Ann Lane, Nupul Kukreja, USC
  - David Jacques, Erin Ryan, AFIT
  - Tommer Ender, Mike Curry, Russell Peak, Val Sitterle, GaTech
  - Adam Ross, Donna Rhodes, MIT
  - Ray Madachy, NPS
  - Kevin Sullivan, Xi Wang, U. Virginia
  - Gary Witus, Walt Bryzik, Wayne State University

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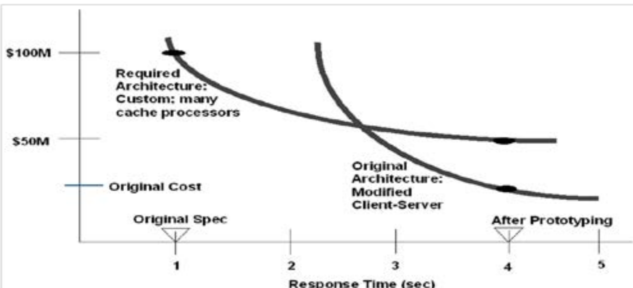
SE and Management Transformation: Ilities Tradespace and Affordability Project (iTAP)

- **System ilities have systemwide impact**
  - —System elements generally just have local impact
- **Ilities often exhibit asymptotic behavior**
  - —Watch out for the knee of the curve
- **Best architecture is a discontinuous function of ility level**
  - —Large system example below
  - —Highly risky to "Build it quickly, tune or fix it later"
    - Complementary RT-40 addresses quantiative risk assessment



Summary: Create, validate, and transition MPTs to make better decisions on affordability and value in systems, particularly for non-functional requirements or -ilities

Funding: pre-2014 $1.0M, 2014-15 $875K, 2016-18 20% annual reduction

Status:

- Tradespace and affordability analysis foundations
  - More precise ility definitions and relationships
  - Stakeholder value-based, means-ends relationships
  - Ility strategy effects, synergies, conflicts
  - U. Virginia, MIT, USC
- Next-generation system cost-schedule estimation models
  - Initially for full-coverage space systems (COSATMO)
  - Extendable to other domains
  - USC, AFIT, GaTech, NPS
- Applied iTAP methods, processes, and tools (MPTs)
  - For concurrent cyber-physical-human systems
  - Experimental MPT piloting, evolution, improvement
  - Wayne State, AFIT, GaTech, NPS, Penn State, USC

Impact:

- Engagements with NAVSEA, Army RDECOM on ility tradespace analysis in set-based design, use of GaTech FACT tradespace analysis capability
- Engagements with USAF/SMC, Aerospace Corp., and aerospace companies on definition and development of next-generation, full-coverage space system cost estimation model family
- Development and iteration with DoD, industry of initial framework and quantification of ility definitions, stakeholder value-based, means-ends relationships, and Ility strategy synergies and conflicts with other ilities

Context: SERC iTAP Initiative Elements

- Tradespace and affordability analysis foundations
  - —More precise ility definitions and relationships
  - —Stakeholder value-based, means-ends relationships
  - —Ility strategy effects, synergies, conflicts
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SERC Value-Based ilities Hierarchy

Based on ISO/IEC 9126, 25030; JCIDS; previous SERC research

- **Individual ilities**
  - **Mission Effectiveness**: Speed, Physical Capability, Cyber Capability, Usability, Accuracy, Impact, Endurability, Maneuverability, Scalability, Versatility
  - **Resource Utilization:** Cost, Duration, Personnel, Scarce Quantities (capacity, weight, energy, …); Manufacturability, Sustainability
  - **Protection:** Security, Safety
  - **Robustness:** Reliability, Availablilty, Maintainability, Survivability
  - **Flexibility:** Modifiability, Tailorability, Adaptability
  - **Composability:** Interoperability, Openness, Service-Orientation

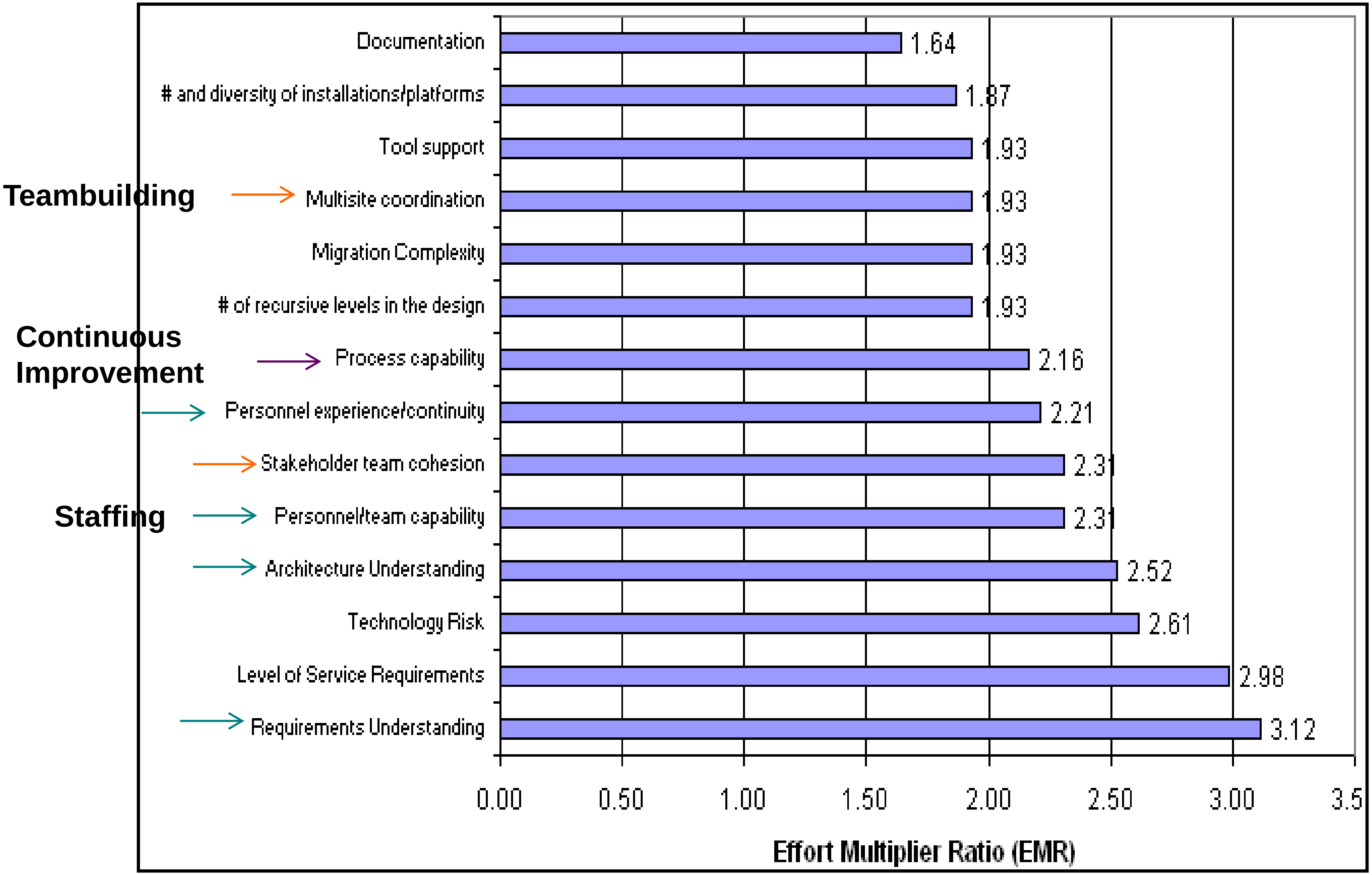
- **Composite ilities**
  - **Comprehensiveness/Suitability:** all of the above
  - **Dependability:** Mission Effectiveness, Protection, Robustness
  - **Resilience:** Protection, Robustness, Flexibility
  - **Affordability:** Mission Effectiveness, Resource Utilization

Means-Ends Framework: Affordability

Affordability Improvements and Tradeoffs

- **Get the Best from People**
  - Staffing, Incentivizing, Teambuilding
  - Facilities, Support Services
  - Kaizen (continuous improvement)
- **Make Tasks More Efficient**
  - Tools and Automation
  - Work and Oversight Streamlining
  - Collaboration Technology
- **Eliminate Tasks**
  - Lean and Agile Methods
  - Task Automation
  - Model-Based Product Generation
- **Eliminate Scrap, Rework**
  - Early Risk and Defect Elimination
  - Evidence-Based Decision Gates
  - Modularity Around Sources of Change
  - Incremental, Evolutionary Development
  - Value-Based, Agile Process Maturity
  - Risk-Based Prototyping
- **Simplify Products (KISS)**
  - Value-Based Capability Prioritization
  - Satisficing vs. Optimizing Performance
- **Reuse Components**
  - Domain Engineering and Architecture
  - Composable Components,Services, COTS
  - Legacy System Repurposing
- **Reduce Operations, Support Costs**
  - Automate Operations Elements
  - Design for Maintainability, Evolvability
  - Streamline Supply Chain
  - Anticipate, Prepare for Change
- **Value- and Architecture-Based Tradeoffs and Balancing**

COSYSMO Sys Engr Cost Drivers



Product Line Engineering and Management: NPS

Preferences

Systems Product Line Flexibility Value Model

Welcome SERC Collaborator

Open | Save | Save As

System Costs

Average Product Development Cost (Burdened $M): 5
Ownership Time (Years): 3
Annual Change Cost (% of Development Cost): 10
Interest Rate (Annual %): 7

Product Line Percentages

Unique %: 40
Adapted %: 30
Reused %: 30

Relative Costs of Reuse (%)

Relative Cost of Reuse for Adapted: 40
Relative Cost of Reuse for Reused: 5

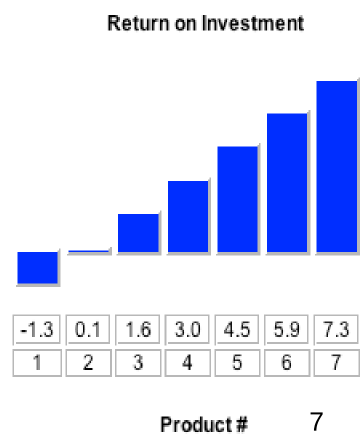
Investment Cost

Relative Cost of Developing for PL Flexibility via Reuse: 1.7

Calculate

Results

# of Products	1	2	3	4	5	6	7
Development Cost ($M)	$7.1	$2.7	$2.7	$2.7	$2.7	$2.7	$2.7
Ownership Cost ($M)	$2.1	$0.8	$0.8	$0.8	$0.8	$0.8	$0.8
Cum. PL Cost ($M)	$9.2	$12.7	$16.2	$19.7	$23.1	$26.6	$30.1
PL Flexibility Investment ($M)	$2.1	$0	$0	$0	$0	$0	$0
PL Effort Savings	($2.7)	$0.3	$3.3	$6.3	$9.4	$12.4	$15.4
Return on Investment	-1.30	0.14	1.58	3.02	4.46	5.90	7.34



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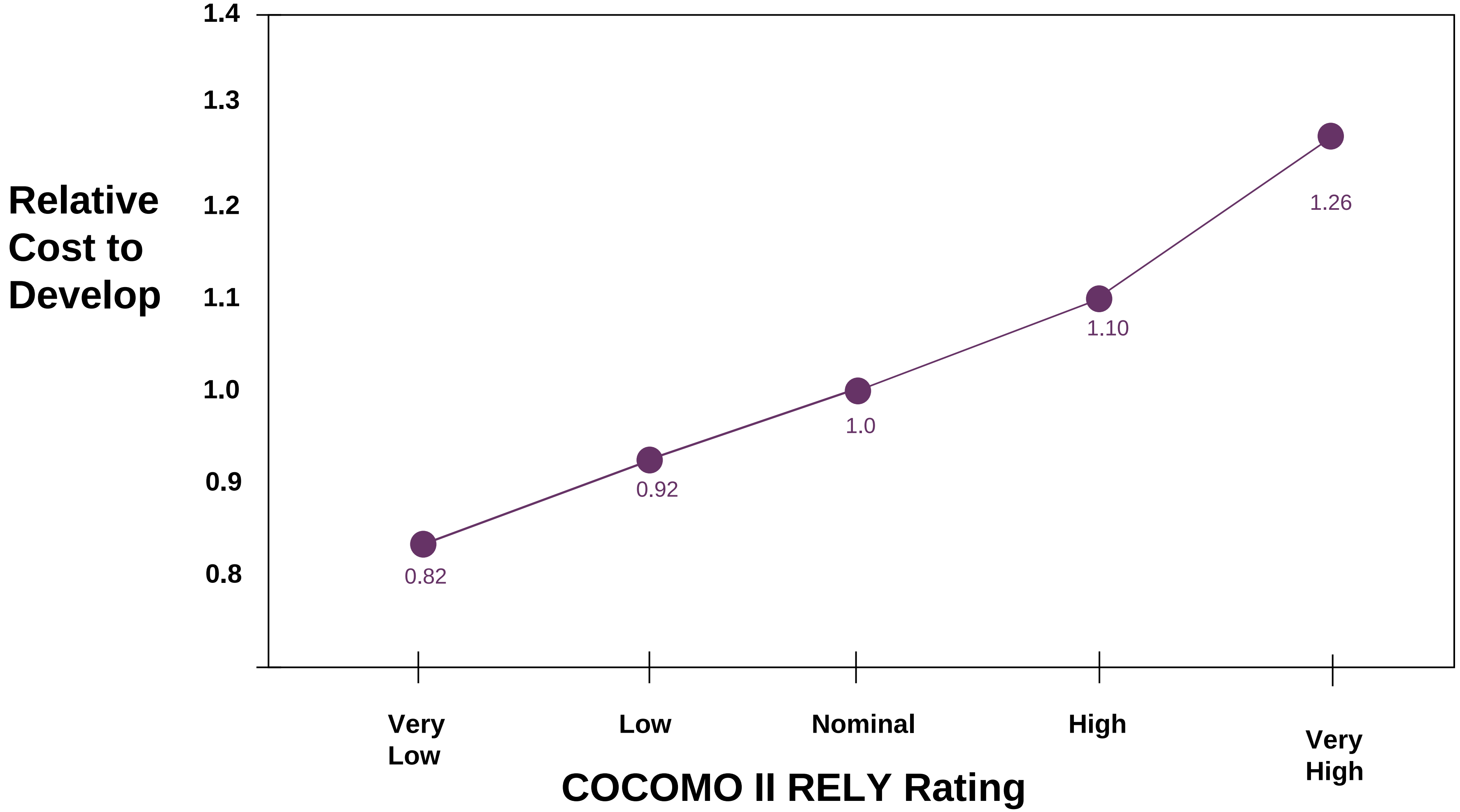
Architecture Strategy Synergy-Conflict Matrix

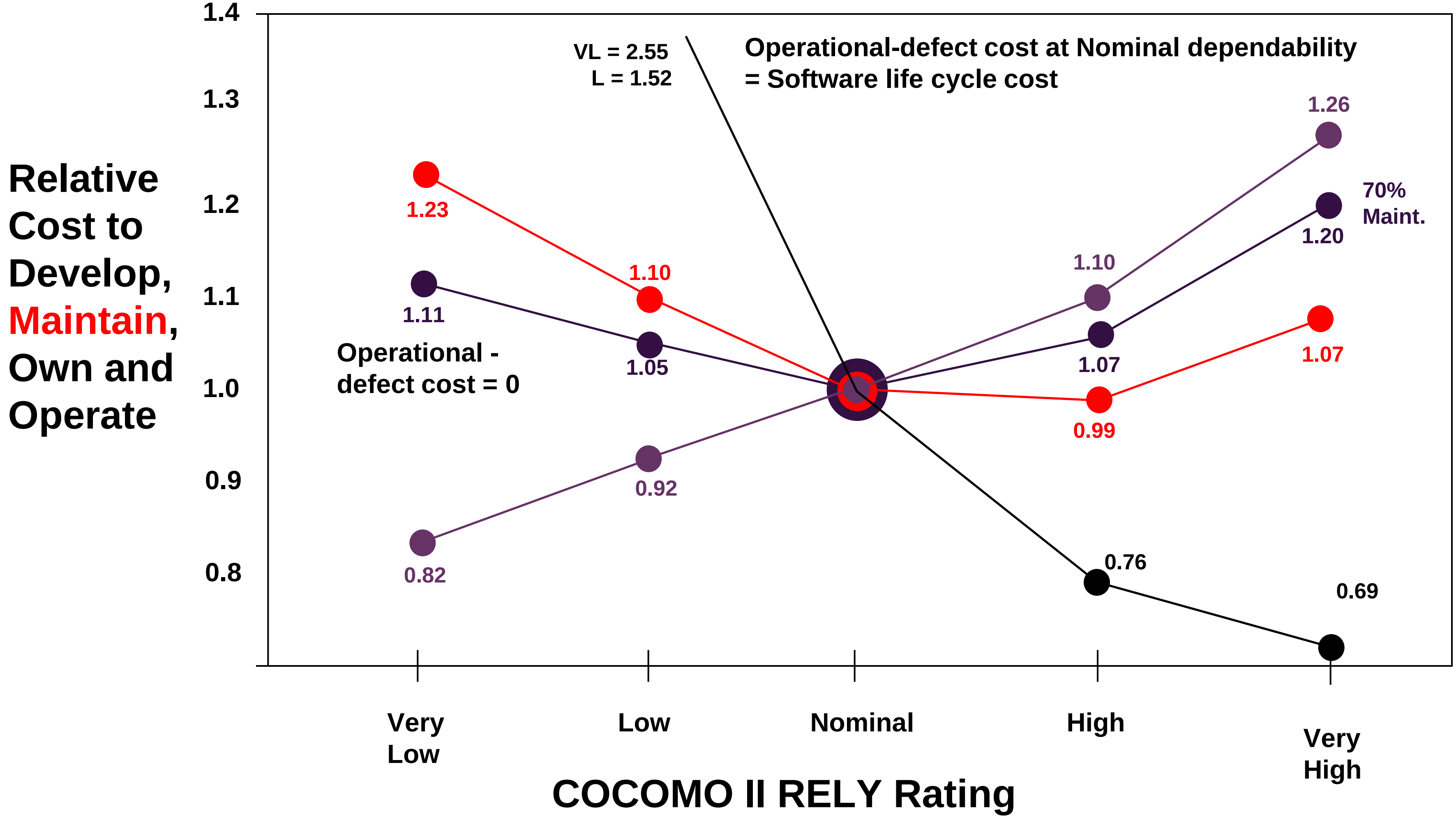
	Reliability	Modifiability	Interoperability	Cost
Reliability		• Nanosensor-based smart monitoring improves reliability, makes mods more effective • Domain architecting (using domain knowledge in defining interfaces) improves reliability and modifiability • Modularity (high module cohesion, low module coupling) improves modifiability and reliability	• Domain architecting improves reliability, interoperability within the domain • High-cohesion, low-coupling modules improve interoperability and reliability • Common, multi-layered services and architecture improve interoperability and reliability	• Automated input, output validation reduces human costs • Increased reliability reduces life cycle ownership costs • Product line architectures reduce cost, increase reliability
Modifiability	• Reliability-optimized designs may complicate fault diagnosis, system disassembly • Domain architecting assumptions complicate multi-domain system modifiability		• Modularization around sources of change improves modifiability and interoperability • High-cohesion, low-coupling modules improve modifiability and interoperability • Open standards, service-oriented architectures improve both modifiability and interoperability	• Modularization around sources of change reduces life cycle costs • High-cohesion, low-coupling modules reduce life cycle costs • Domain architecting enables domain product lines, reducing costs • Providing excess capacity improves modifiability and decreases lifecycle cost
Interoperability	• Data redundancy improves reliability, but updates may complicate distributed real-time systems interoperability • Optimizing on reliability as liveness may degrade message delivery, accuracy	• Domain architecting assumptions complicate multi-domain system interoperability		• Common, multi-layered services and architecture reduce life cycle costs • Product line architecture improves interoperability, reduces cost of later systems
Cost	• Increased reliability increases acquisition costs • Hardware redundancy adds cost • Making easiest-first initial commitments reduces early costs but degrades later reliability, adds later costs • Formal verification adds cost	• Fixed-requirements, fixed-cost contracts generally produce brittle, hard-to-modify systems • Domain architecting increases multi-domain system costs • Providing excess capacity improves modifiability but increases acquisition cost	• Neglecting or deferring interfaces to co-dependent systems will reduce initial costs, but degrade interoperability • Product line architecture increases cost of initial system	

Software Development Cost vs. Quality



MTBF (hours)	**1**	**10**	**300**	**10,000**	**300,000**

Software Ownership Cost vs. Quality



MTBF (hours) 1 10 300 10,000 300,000

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AFIT: CEVLCC Methodology

Current Expected Value of Life Cycle Cost

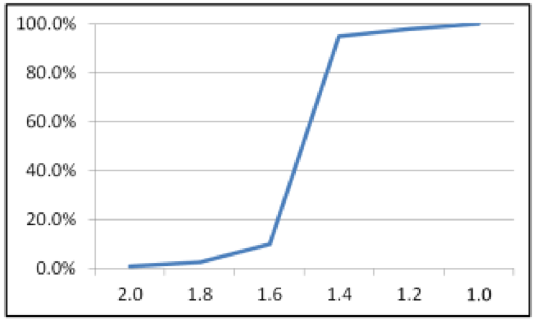
1. Establish system design options
1. Construct time-phased PDFs associated w/ all existing key cost, schedule, & tech performance parameters of program
2. Estimate costs associated with mods (consistent w/ PDFs) to baseline cost, schedule, & tech performance parameters
3. Assign time-phased probabilities for potential new capabilities of the system
4. Estimate costs associated w/ the addition of new capabilities
5. Calculate standard (i.e., traditional) LCC estimate
6. Calculate CEVLCC for each system design option and select alternative with the lowest CEVLCC

AFIT: CEVLCC Tool

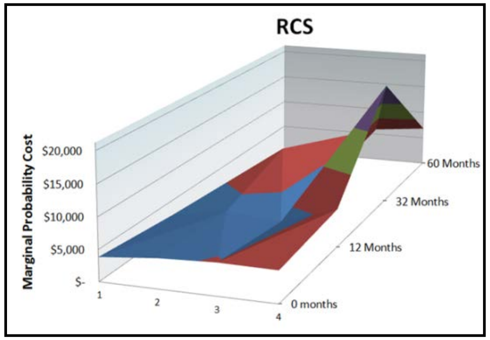
1. Specify design options

2. Identify reqmnts that will be useful for discriminating between designs

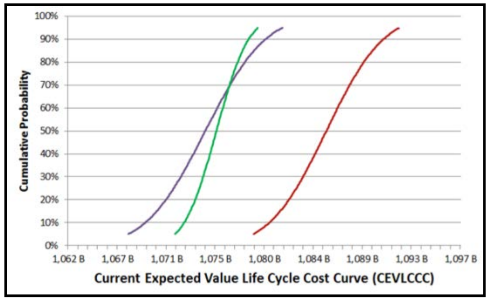
3. Estimate probabilities of threshold value changes in each reqmnt



4. Relative to each design, estimate cost impacts for each potential threshold value change



5. Evaluate expected LCC curve (CDF) and choose design that corresponds to most favorable curve



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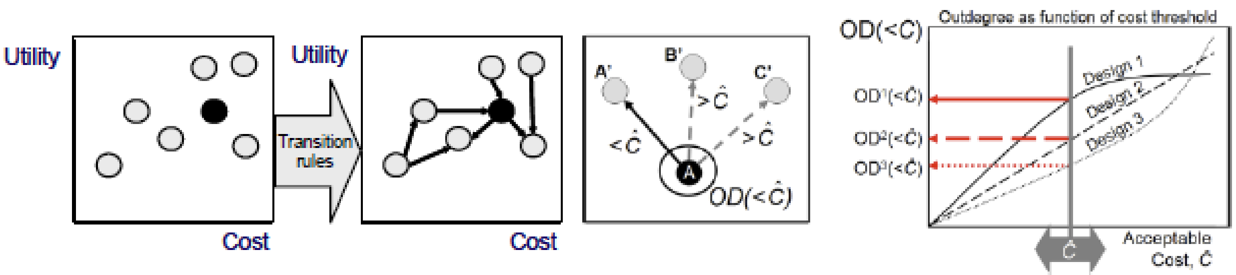
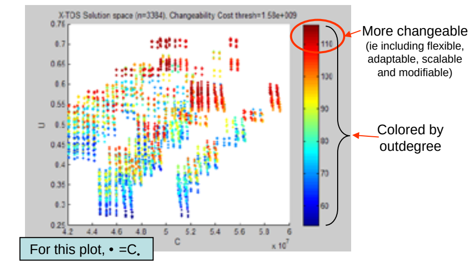
MIT: ilities in Tradespace Exploration

Based on SEAri research

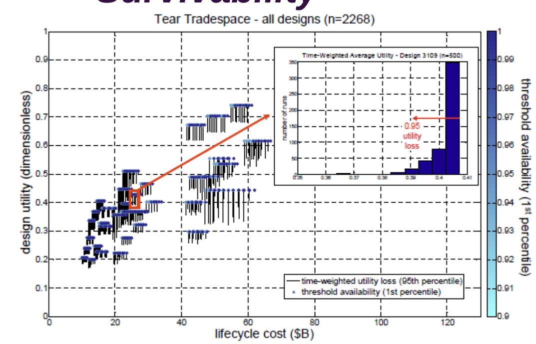
Enabling Construct: Tradespace Networks



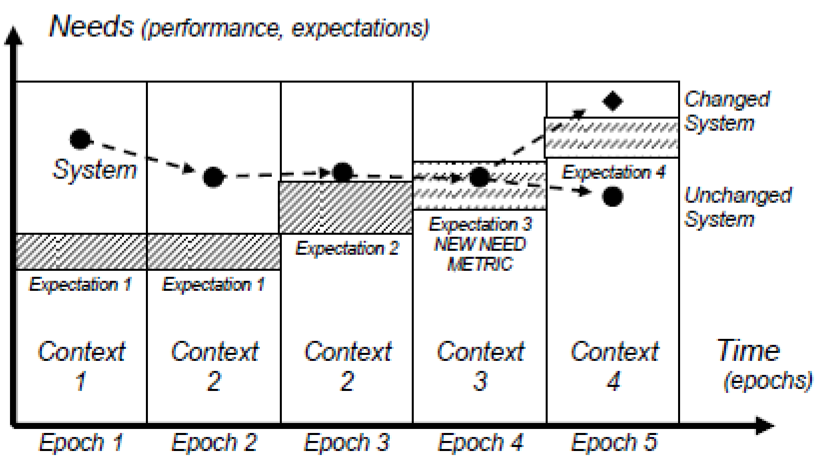
Changeability



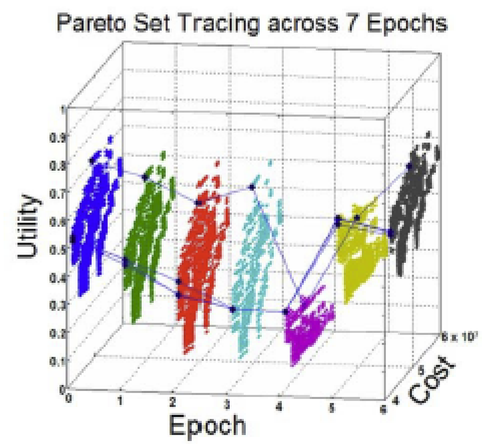
Survivability



Enabling Construct: Epochs and Eras



Value Robustness



Set of Metrics

Value Aspect	Acronym	Stands For	Definition
Robustness via "no change"	NPT	Normalized Pareto Trace	% epochs for which design is Pareto efficient in utility/cost
Robustness via "no change"	fNPT	Fuzzy Normalized Pareto Trace	Above, with margin from Pareto front allowed
Robustness via "change"	eNPT, efNPT	Effective (Fuzzy) Normalized Pareto Trace	Above, considering the design's end state after transitioning
"Value" gap	FPN	Fuzzy Pareto Number	% margin needed to include design in the fuzzy Pareto front
"Value" of a change	FPS	Fuzzy Pareto Shift	Difference in FPN before and after transition
"Value" of a change	ARI	Available Rank Increase	# of designs able to be passed in utility via best possible change
Degree of changeability	OD	Outdegree	# outgoing transition arcs from a design
Degree of changeability	FOD	Filtered Outdegree	Above, considering only arcs below a chosen cost threshold
Survivability	TWAUL	Time-weighted Average Utility Loss	Measure of central tendency of value losses over time for a design, as a result of experienced disturbances
Survivability	AT	Threshold Availability	% of lifetime for which design delivers utility above minimum acceptable levels before, during, and after a disturbance

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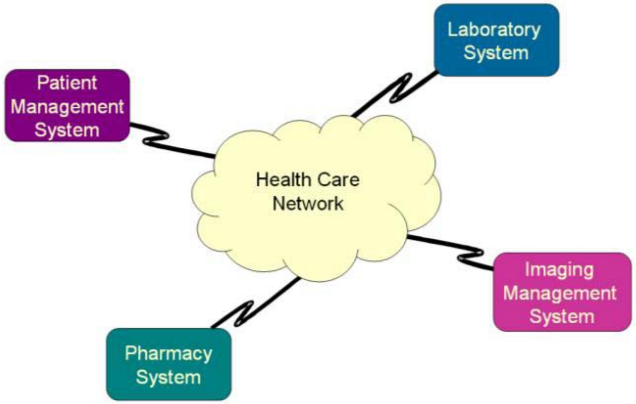
COSATMO Concept

- Co-sponsored by OSD, USAF/SMC
- Focused on current and future satellite systems
  - Accommodating rapid change, evolutionary development, Net-Centric SoSs, families of systems, future security and self-defense needs, microsats, satellite constellations, model-based development
  - Recognizes new draft DoDI 5000.02 process models
    - Hardware-intensive, DoD-unique SW-intensive, Incremental SW-intensive, Accelerated acquisition, 2 Hybrids (HW-, SW-dominant)
  - Covers full life cycle: definition, development, production, operations, support, phaseout
  - Covers full system: satellite(s), ground systems, launch
  - Covers hardware, software, personnel costs
- Extensions to cover systems of systems, families of systems
- Several PhD dissertations involved (as with COSYSMO)
  - Incrementally developed based on priority, data availability
- Upcoming workshop at Aerospace Ground Systems Architectures Workshop Feb 26

SysML Building Blocks for Cost Modeling

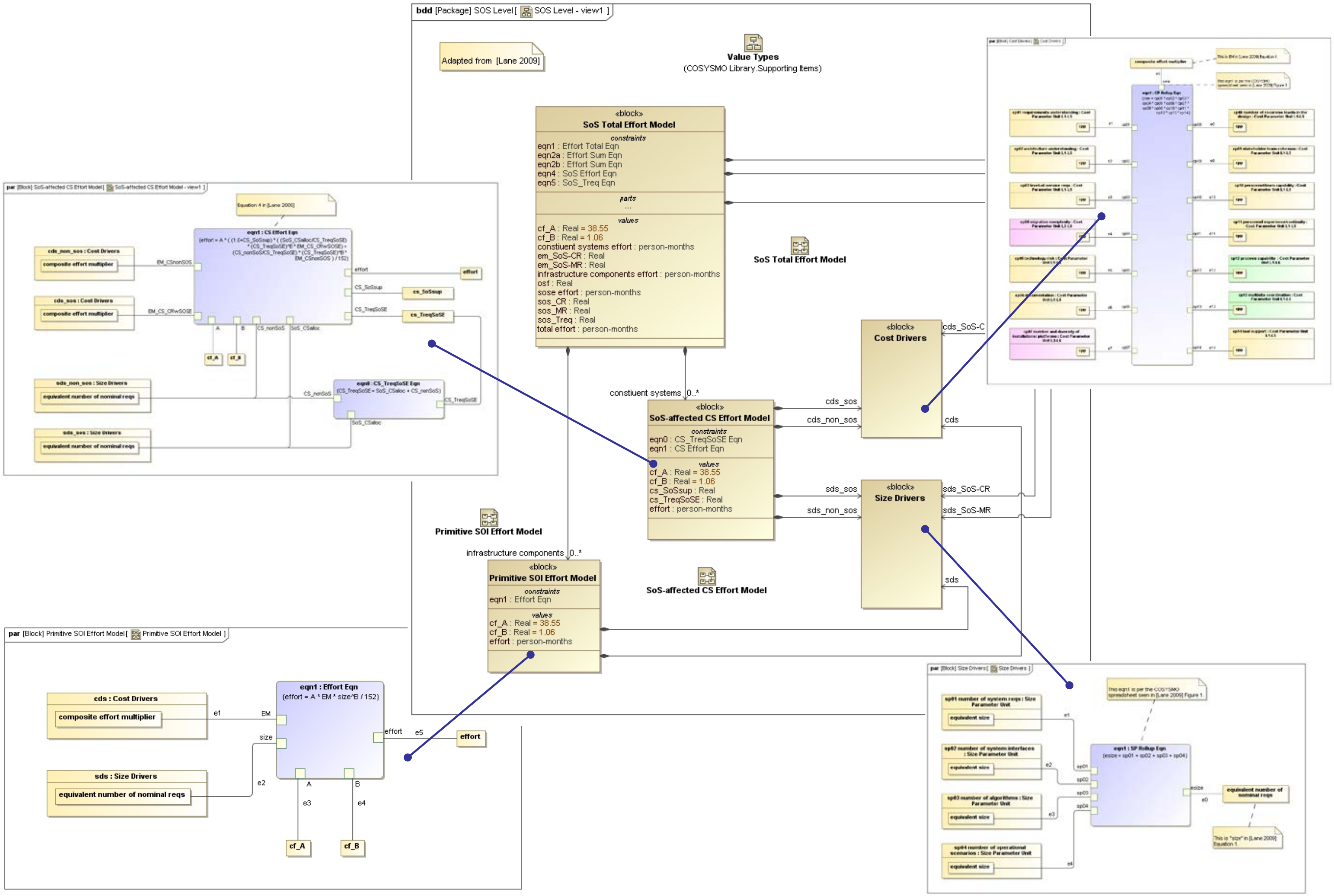
GaTech-USC Work in RT46 Phase 2 (Oct-Dec 2013)

- Implemented reusable SysML building blocks
  - Based on SoS/COSYSMO SE cost (effort) modeling work by Lane, Valerdi, Boehm, et al.
- Successfully applied building blocks to healthcare SoS case study from [Lane 2009]
- Provides key step towards affordability trade studies involving diverse "-ilities" (*see MIM slides*)

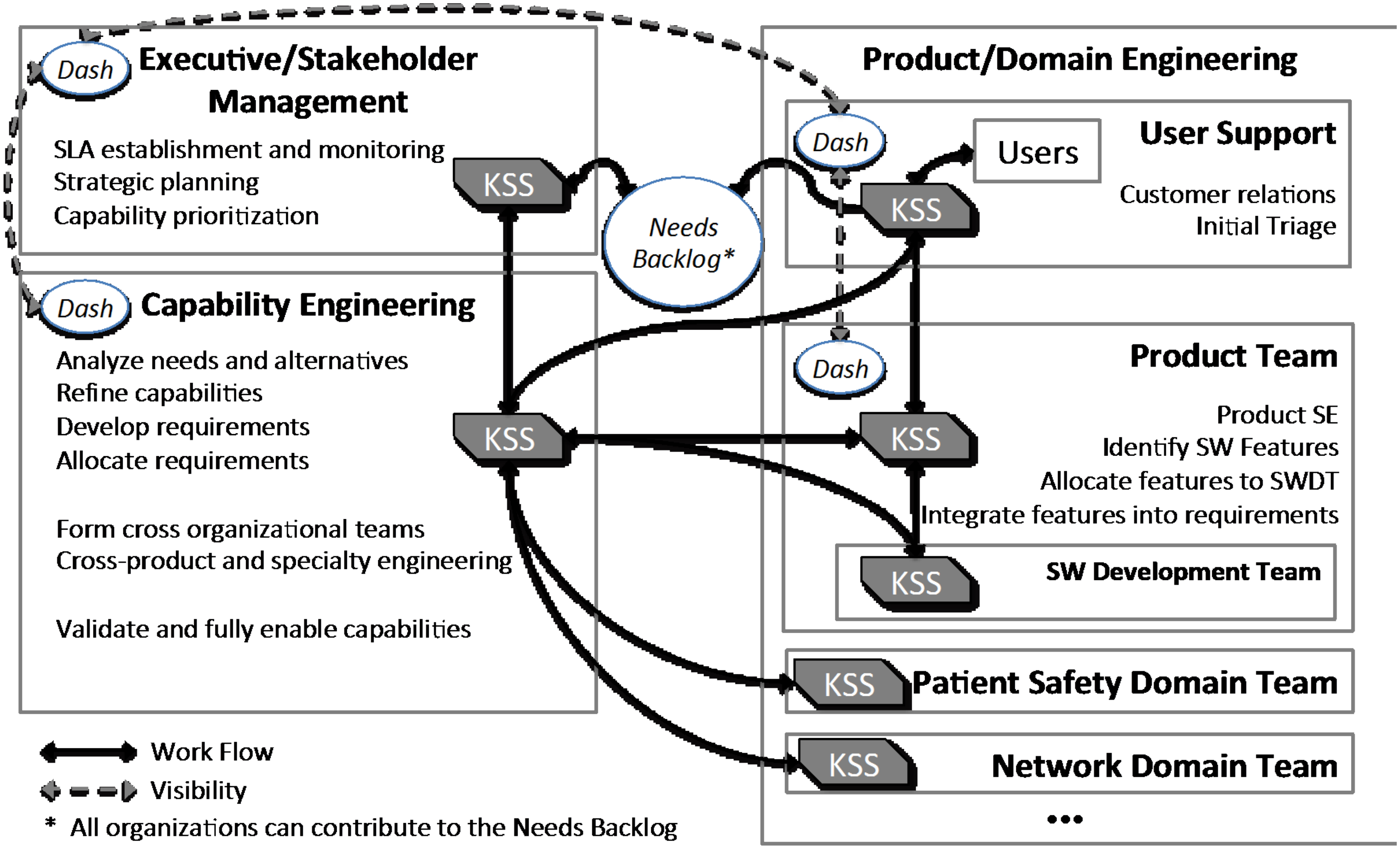


Aspect	Formula	Calculated Effort
SoSE effort (Equation 5)	$Effort = 38.55*[((SoS_{CR} / SoS_{Treq})*(SoS_{Treq})^{1.06} * EM_{SOS-CR}) + ((SoS_{MR} / SoS_{Treq})*(SoS_{Treq})^{1.06} * EM_{SOS-MR}*OSF)] / 152$ $= 38.55*[((50 / 52) * (52)^{1.06} * 2.50) + (20/52)*(52)^{1.06} * 0.47 * 10\%)] / 152$	40.41
Pharmacy System effort (Equation 4)	$Effort = 38.55*[(1.0+CS_{SoSsup}) * ((SoS_{CSalloc}/CS_{TreqSoSE})*(CS_{TreqSoSE})^{1.06} * EM_{CS-CRwSOSE}) + (CS_{nonSoS}/CS_{TreqSoSE}) * (CS_{TreqSoSE})^{1.06} * EM_{CSnonSOS}] / 152$ $= 38.55 *[(1.15) * ((50/70)*(70)^{1.06} * 1.06 + (20/70) * (70)^{1.06} * 0.72] / 152$	22.02
Laboratory System effort (Equation 4)	$Effort = 38.55*[(1.0+CS_{SoSsup}) * ((SoS_{CSalloc}/CS_{TreqSoSE})*(CS_{TreqSoSE})^{1.06} * EM_{CS-CRwSOSE}) + (CS_{nonSoS}/CS_{TreqSoSE}) * (CS_{TreqSoSE})^{1.06} * EM_{CSnonSOS}] / 152$ $= 38.55 *[(1.15) * ((50/50)*(50)^{1.06} * 1.06 + 0] / 152$	19.55
Imaging System effort (Equation 4)	$Effort = 38.55*[(1.0+CS_{SoSsup}) * ((SoS_{CSalloc}/CS_{TreqSoSE})*(CS_{TreqSoSE})^{1.06} * EM_{CS-CRwSOSE}) + (CS_{nonSoS}/CS_{TreqSoSE}) * (CS_{TreqSoSE})^{1.06} * EM_{CSnonSOS}] / 152$ $= 38.55 *[(1.15) * ((50/50)*(50)^{1.06} * 1.06 + 0] / 152$	19.55
New infrastructure component effort (Equation 1)	$Effort = 38.55*EM*(size)^{1.06}/152$ $= 38.55 * 1.0 * (100)^{1.06} / 152$	33.43
	Total Effort:	134.96

Healthcare SoS Case Study [Lane 2009] Implemented Using SysML Building Blocks: *Selected SysML Diagrams*

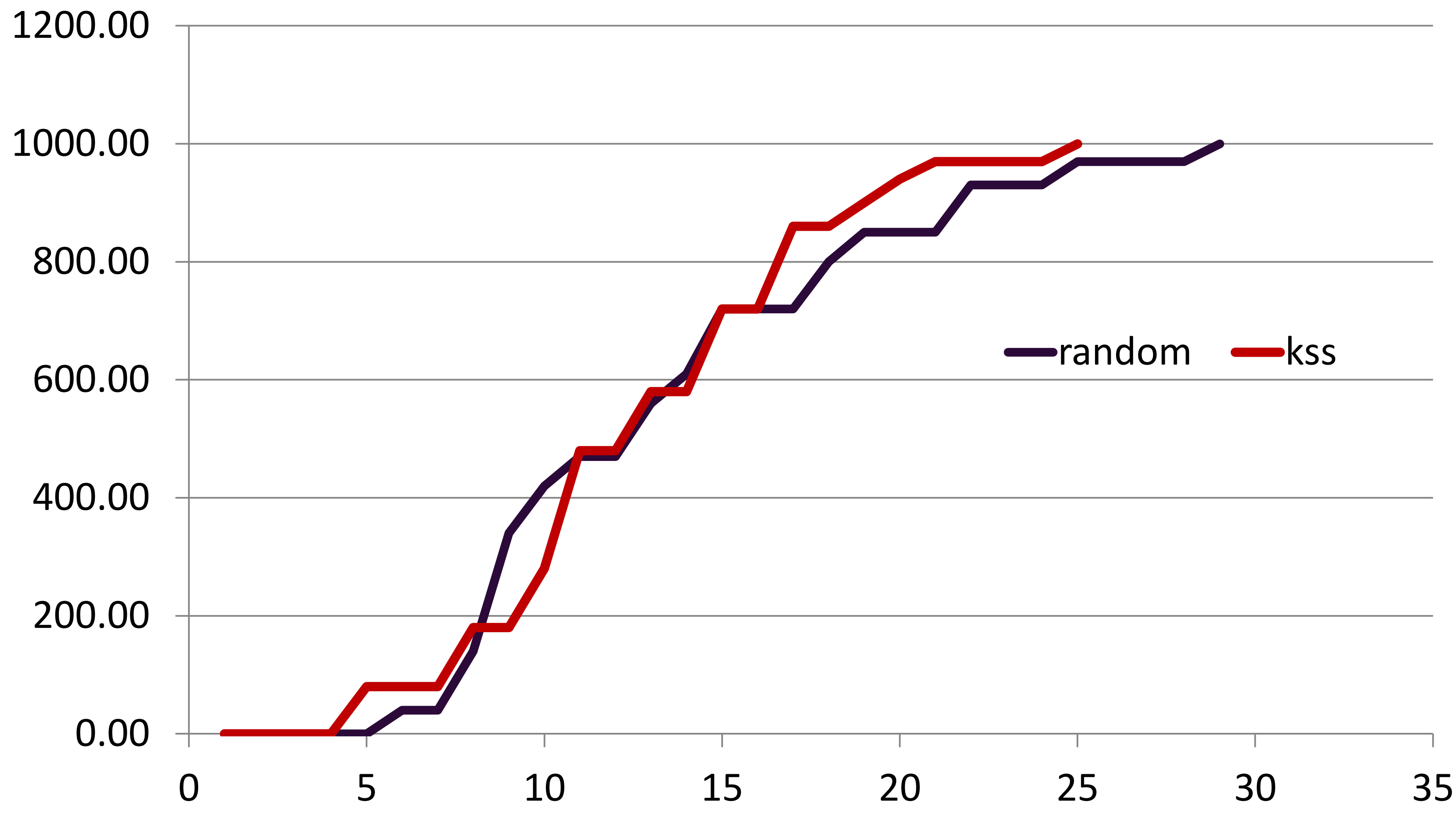


Health care example of Kanban Scheduling System (KSS) Network



Example: KSS simulation result analysis

Value:



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SE and Management Transformation: Agile SE Enablers

Accelerators/Ratings	Very Low	Low	Nominal	High	Very High	Extra High
Product Factor: Multipliers	**1.09**	**1.05**	**1.0**	**0.96**	**0.92**	**0.87**
Simplicity	Extremely complex	Highly complex	Mod. complex	Moderately simple	Highly simple	Extremely simple
Element Reuse	None (0%)	Minimal (15%)	Some (30%)	Moderate (50%)	Considerate (70%)	Extensive (90%)
Low-Priority Deferrals	Never	Rarely	Sometimes	Often	Usually	Anytime
Models vs Documents	None (0%)	Minimal (15%)	Some (30%)	Moderate (50%)	Considerate (70%)	Extensive (90%)
Key Technology Maturity	>0 TRL 1,2 or >1 TRL 3	1 TRL 3 or > 1 TRL 4	1 TRL 4 or > 2 TRL 5	1-2 TRL 5 or >2 TRL 6	1-2 TRL 6	All > TRL 7
Process Factor: Multipliers	**1.09**	**1.05**	**1.0**	**0.96**	**0.92**	**0.87**
Concurrent Operational Concept, Requirements, Architecture, V&V	Highly sequential	Mostly sequential	2 artifacts mostly concurrent	3 artifacts mostly concurrent	All artifacts mostly concurrent	Fully concurrent
Process Streamlining	Heavily bureaucratic	Largely bureaucratic	Conservative bureaucratic	Moderate streamline	Mostly streamlined	Fully streamlined
General SE tool support CIM (Coverage, Integration, Maturity)	Simple tools, weak integration	Minimal CIM	Some CIM	Moderate CIM	Considerable CIM	Extensive CIM
Project Factors: Multipliers	**1.08**	**1.04**	**1.0**	**0.96**	**0.93**	**0.9**
Project size (peak # of personnel)	Over 300	Over 100	Over 30	Over 10	Over 3	≤ 3
Collaboration support	Globally distributed weak comm. , data sharing	Nationally distributed, some sharing	Regionally distributed, moderate sharing	Metro-area distributed, good sharing	Simple campus, strong sharing	Largely collocated, Very strong sharing
Single-domain MMPTs (Models, Methods, Processes, Tools)	Simple MMPTS, weak integration	Minimal CIM	Some CIM	Moderate CIM	Considerable CIM	Extensive CIM
Multi-domain MMPTs	Simple; weak integration	Minimal CIM	Some CIM or not needed	Moderate CIM	Considerable CIM	Extensive CIM
People Factors: Multipliers	**1.13**	**1.06**	**1.0**	**0.94**	**0.89**	**0.84**
General SE KSAs (Knowledge, Skills, Agility)	Weak KSAs	Some KSAs	Moderate KSAs	Good KSAs	Strong KSAs	Very strong KSAs
Single-Domain KSAs	Weak	Some	Moderate	Good	Strong	Very strong
Multi-Domain KSAs	Weak	Some	Moderate or not needed	Good	Strong	Very strong
Team Compatibility	Very difficult interactions	Some difficult interactions	Basically cooperative interactions	Largely cooperative	Highly cooperative	Seamless interactions

Summary: Research, package, and deploy the most valuable SE enablers, based primarily on the enablers and risk factors identified in the RT-34 Expediting SE study

Funding: pre-2014 $500K, 2014 $100K, 2015 $100K, 2016-2018 20% annual reduction

Status:

- Identified people, process, product, and project enablers as well as risk factors
- Delivered prototype quantitative schedule acceleration model; Plan to calibrate and evolve

Impact:

- Cooperation and coordination with ongoing non-SERC agile SE work (INCOSE, NDIA, LSS, FFRDC)
- Leveraging results of other SERC tasks

Case Study: From Plan-Driven to Agile

Initial Project: Focus on Concurrent SE

Accelerators/Ratings	VL	L	N	H	VH	XH
Product Factors	1.09	1.05	1.0	0.96	0.92	0.87
Simplicity			X			
Element Reuse	X					
Low-Priority Deferrals	X					
Models vs Documents		X				
Key Technology Maturity			X			
Process Factors	1.09	1.05	1.0	0.96	0.92	0.87
Concurrent Operational Concept, Requirements, Architecture, V&V				X		
Process Streamlining		X				
General SE tool support CIM (Coverage, Integration, Maturity)				X		
Project Factors	1.08	1.04	1.0	0.96	0.93	0.9
Project size (peak # of personnel)				X		
Collaboration support				X		
Single-domain MMPTs (Models, Methods, Processes, Tools)				X		
Multi-domain MMPTs		X				
People Factors	1.13	1.06	1.0	0.94	0.89	0.84
General SE KSAs (Knowledge, Skills, Agility)			X			
Single-Domain KSAs				X		
Multi-Domain KSAs		X				
Team Compatibility			X			
Risk Acceptance Factor	1.13	1.06	1.0	0.94	0.89	0.84
			X			

Expected schedule reduction of 1.09/0.96 = 0.88 (green arrow)
Actual schedule delay of 15% due to side effects (red arrows)
Model prediction: 0.88*1.09*1.04*1.06*1.06 = 1.13

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Case Study: From Plan-Driven to Agile

Next Project: Fix Side Effects; Reduce Bureaucracy

Accelerators/Ratings	VL	L	N	H	VH	XH
Product Factors	**1.09**	**1.05**	**1.0**	**0.96**	**0.92**	**0.87**
Simplicity			X			
Element Reuse	X					
Low-Priority Deferrals	X					
Models vs Documents		X				
Key Technology Maturity					X	
Process Factors	**1.09**	**1.05**	**1.0**	**0.96**	**0.92**	**0.87**
Concurrent Operational Concept, Requirements, Architecture, V&V					X	
Process Streamlining				X		
General SE tool support CIM (Coverage, Integration, Maturity)				X		
Project Factors	**1.08**	**1.04**	**1.0**	**0.96**	**0.93**	**0.9**
Project size (peak # of personnel)				X		
Collaboration support				X		
Single-domain MMPTs (Models, Methods, Processes, Tools)				X		
Multi-domain MMPTs		X				
People Factors	**1.13**	**1.06**	**1.0**	**0.94**	**0.89**	**0.84**
General SE KSAs (Knowledge, Skills, Agility)				X		
Single-Domain KSAs				X		
Multi-Domain KSAs		X				
Team Compatibility				X		
Risk Acceptance Factor	**1.13**	**1.06**	**1.0**	**0.94**	**0.89**	**0.84**
			X			

Model estimate: 0.88*(0.92/0.96)*(0.96/1.05) = 0.77 speedup
Project results: 0.8 speedup
Model tracks project status; identifies further speedup potential

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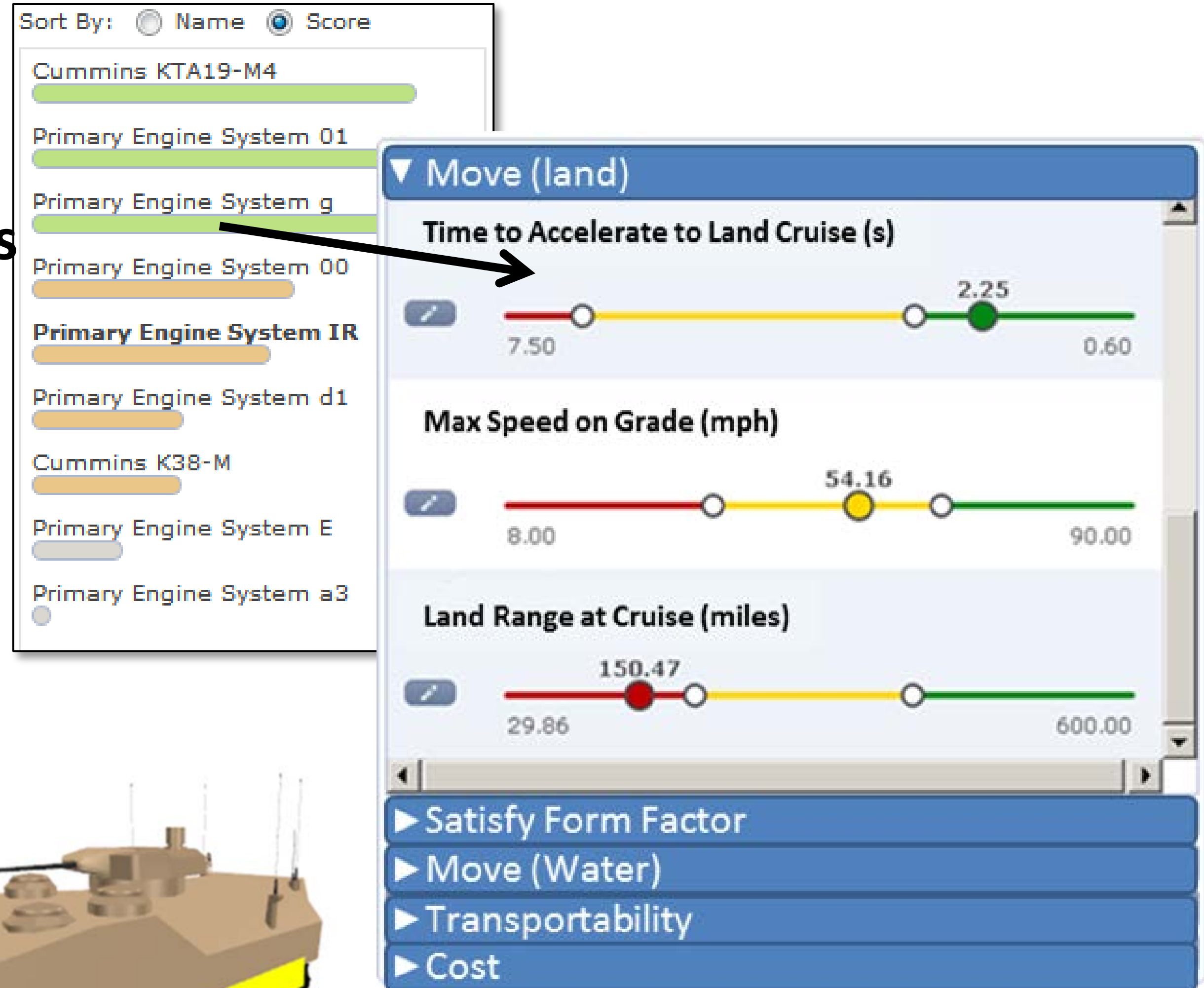
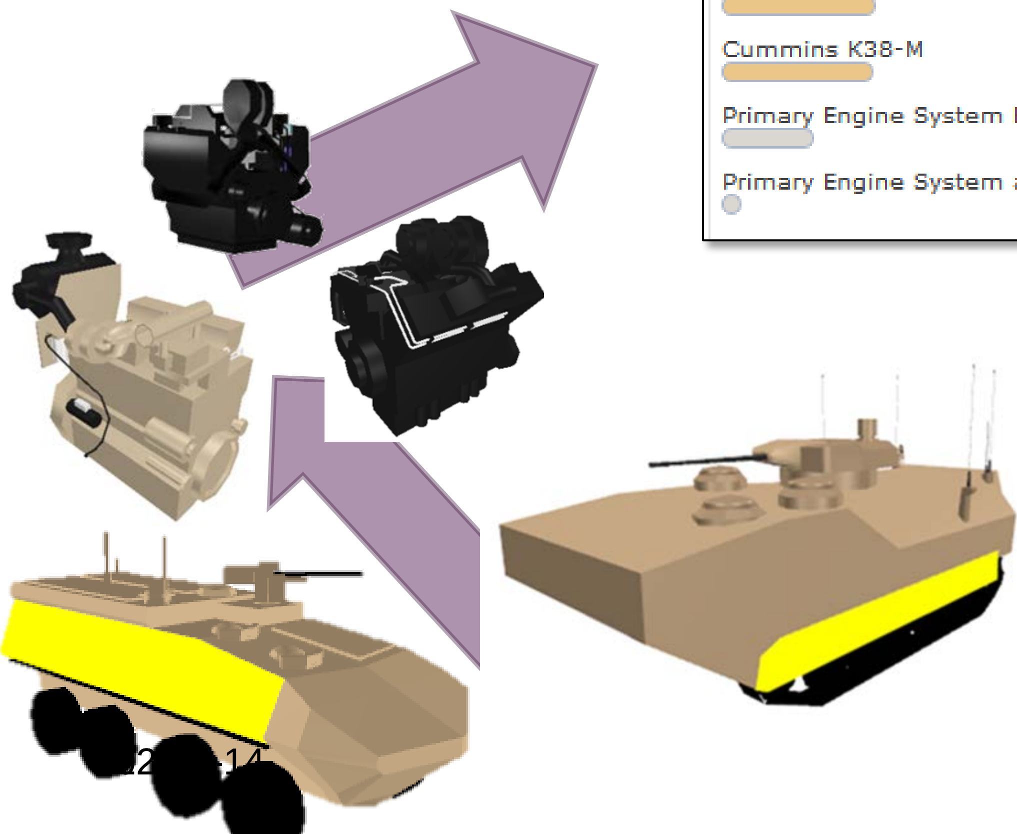
GaTech – FACT Tradespace Tool

Being used by Marine Corps

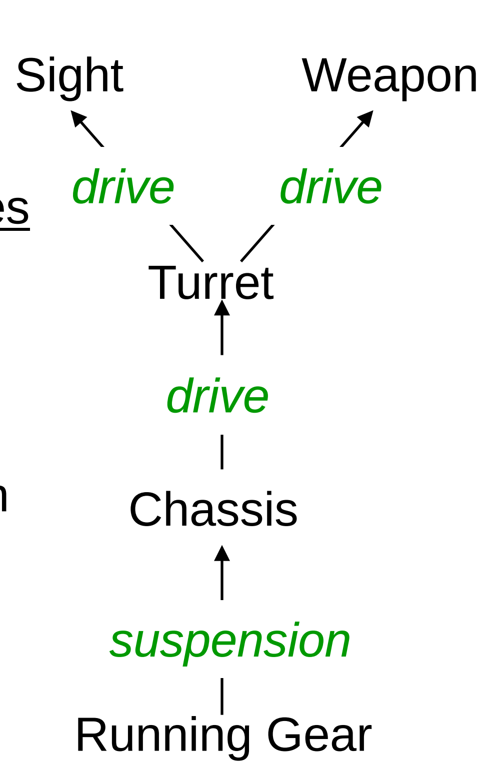
- **Configure vehicles from the "bottom up"**
- **Quickly assess impacts on performance**

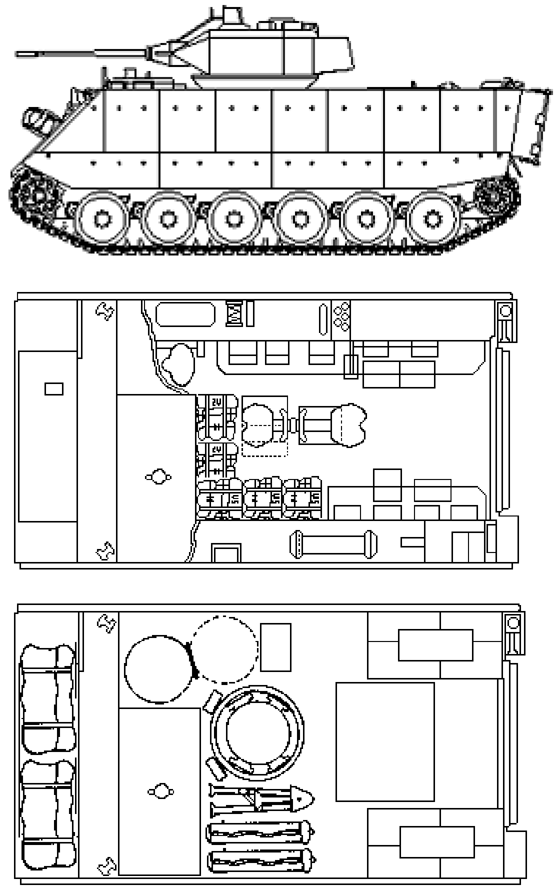




WSU: Versatility Factors and Physical Organization

Components that Can be in Different Positions or Orientations
Isolated or Separated Compartments





<u>Mass & Structure Properties</u>

- Mass
- Angular moments
- Imbalances*
- Load bearing wall strength
- Deck surface area
- Interior volumes**
- Interior surface areas**

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*Angular moments of the CG about axes of rotation

** By crew station and compartment