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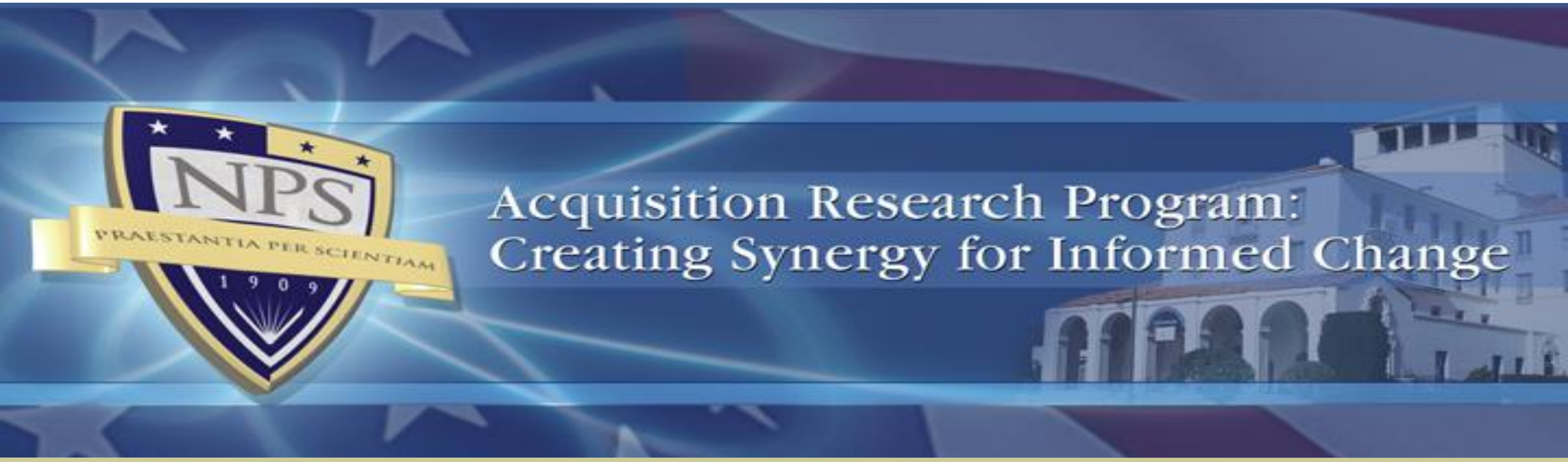

Development and Extension of a Deterministic SoS Performance Prediction Methodology for an Acknowledged Systems of Systems

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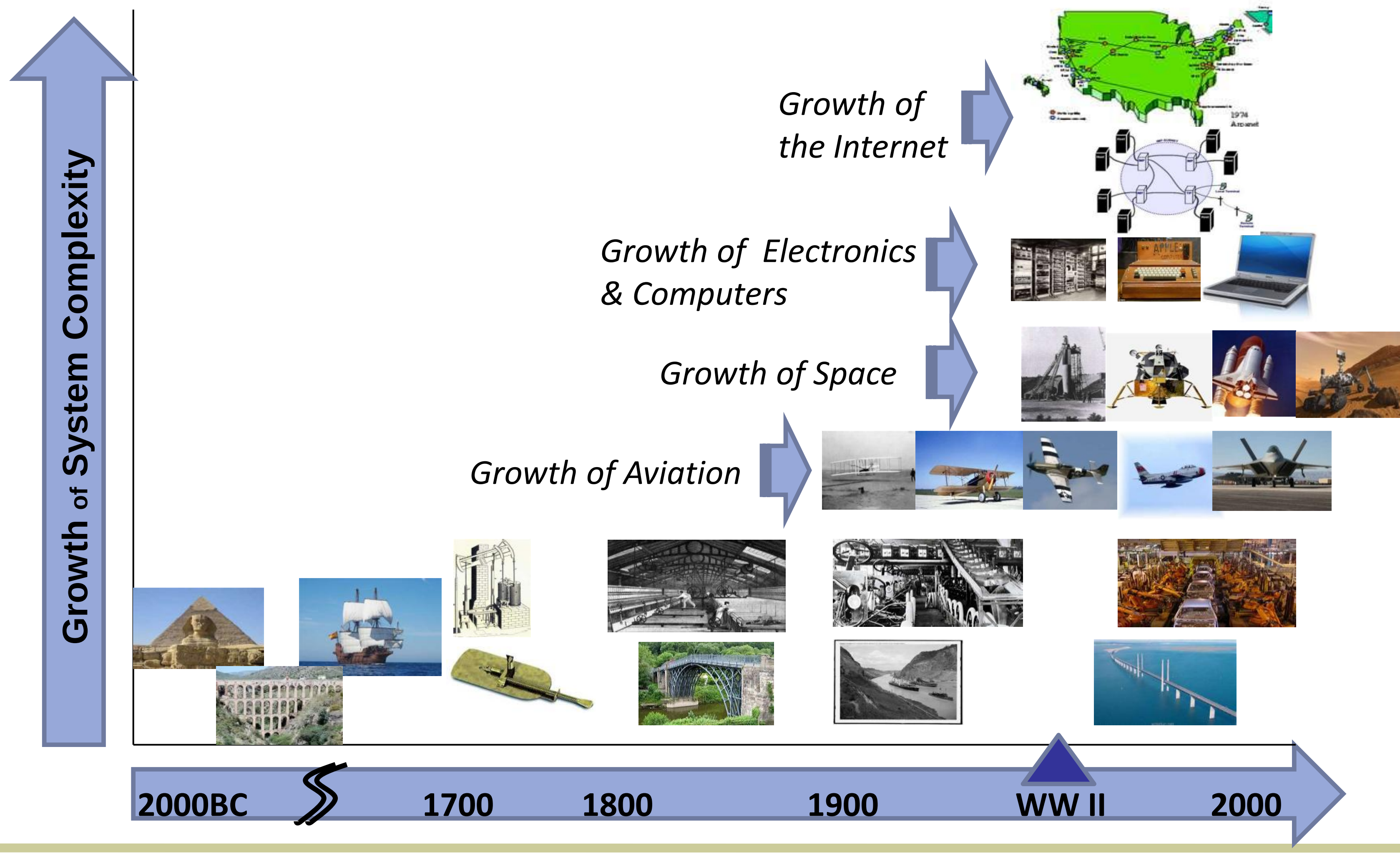
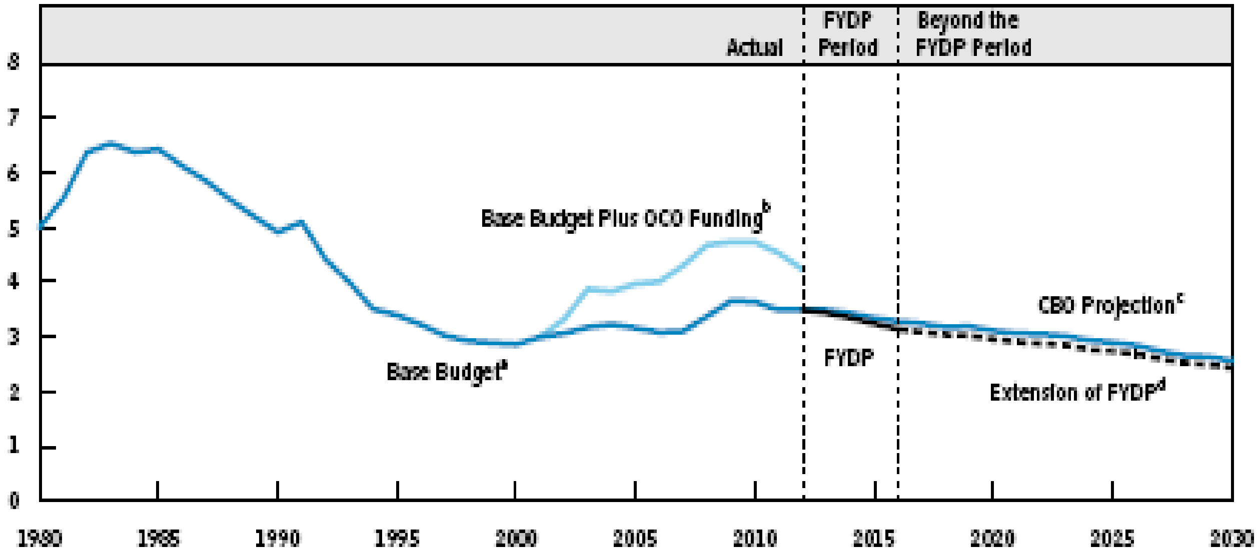
Growth of Systems Complexity into the Systems Century



Why shift from system based to capability based acquisitions ?

Decreasing Funding to support Defense Investment in increasingly expensive systems



Decreasing Cost for Adversaries to counter traditional areas of military dominance

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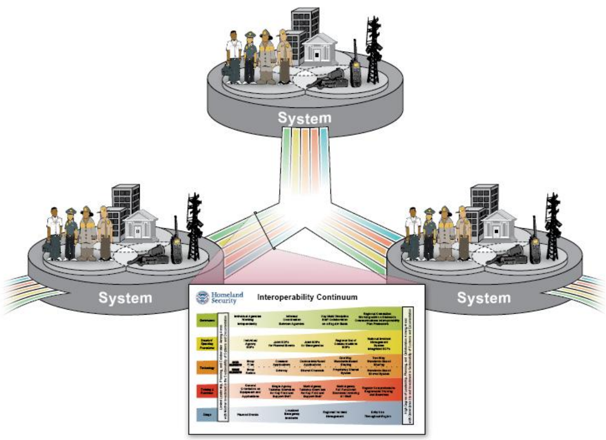
intensifies the desire to obtain greater utility from systems developed & procured

New Paradigm of System of System Acquisition

A SoS is defined as a set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities [DoD, 2004(1)].



Type	Definition
Virtual	Virtual SoS lack a central management authority and a centrally agreed upon purpose for the SoS. Large-scale behavior emerges—and may be desirable—but this type of SoS should rely upon relatively invisible mechanisms to maintain it.
Collaborative	In collaborative SoS, the component systems interact more or less voluntarily to fulfill agreed upon central purposes. The Internet is a collaborative system. The Internet Engineering Task Force works out standards but has no power to enforce them. The central players collectively decide how to provide or deny service, thereby providing some means of enforcing and maintaining standards.
Acknowledged	Acknowledged SoS have recognized objectives, a designated manager, and resources for the SoS; however, the constituent systems retain their independent ownership, objectives, funding, and development and sustainment approaches. Changes in the systems are based on collaboration between the SoS and the system.
Directed	Directed SoS are those in which the integrated SoS is built and managed to fulfill specific purposes. It is centrally managed during long-term operation to continue to fulfill those purposes as well as any new ones the system owners might wish to address. The component systems maintain an ability to operate independently, but their normal operational mode is subordinated to the central managed purpose.

The field of SoS engineering, development, integration, sustainment, and management requires the decision maker to face both the traditional challenges associated with any complex system (Jamshidi, 2006) and the additional challenges associated with having to analyze, organize, and integrate the constituent systems (existing and developmental) into an integrated SoS capability.

System of Systems Challenges

- SoS acquisition management - a significant increase in complexity over traditional system acquisition
- Development requires that significant numbers of technologies be integrated to one another
- Challenges traditional development monitoring tools and cost models
  - need to capture integration complexity
  - level of effort required to connect individual components
- Unintended Consequences - high degree of inter-linkage between components can cause unintended impacts to overall system performance
  - components are modified from original use
  - Technology change: replaced throughout the system life cycle

"Large, complex systems development has always been challenging, even when the "only" thing a program manager had to worry about were cost, schedule, and performance within a single program". **Smith and Meyers (2008),**

System of Systems Tools- an emerging field of study

Technical Risk Index (TRI)/Generalized Performance Risk Measure. The index shows the degree of performance risk presently in the SoS, supports identifying risk-driving TPMs, and can reveal where management should focus on improving technical performance and, thereby, lessen risk. [1]

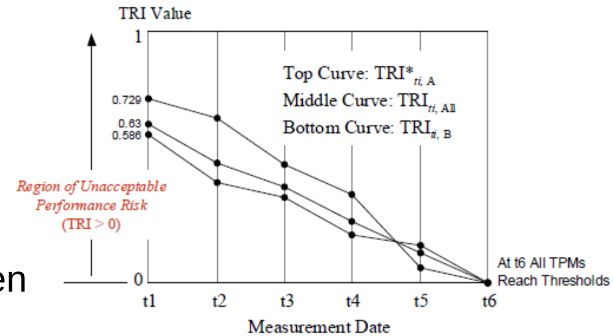


Figure 4. Illustrative TPM Risk Index Time History Trend

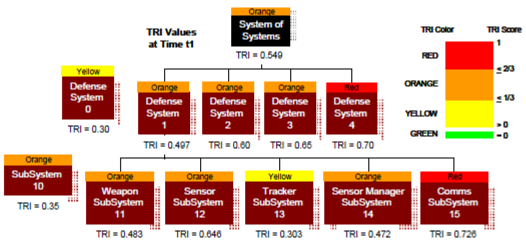
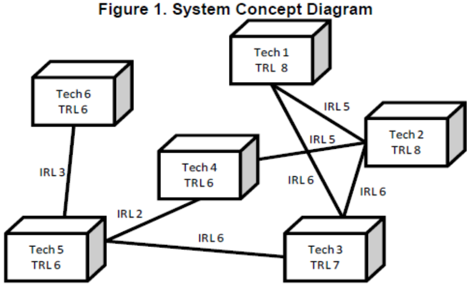


Figure 6. An Illustrative SoS Hierarchy, TRI Values, and Associated Colors

Figure 1. System Concept Diagram



Process Modeling. A methodology for performing architectural analyses of complex systems of systems. [2]

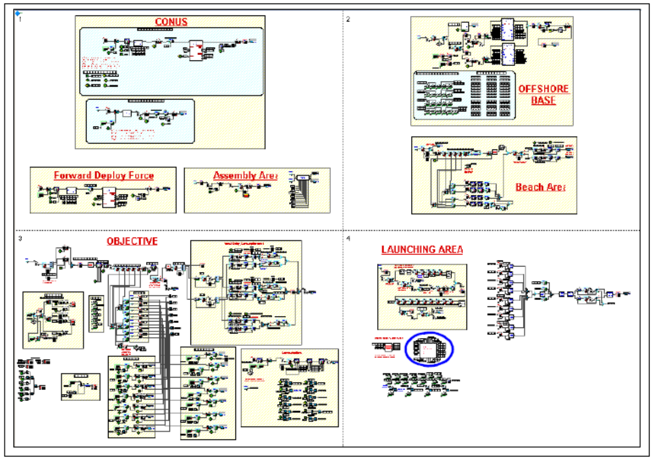


Figure 2. Top-level view of the EXTEND™ Expeditionary Warfare Model for Sea Basing.

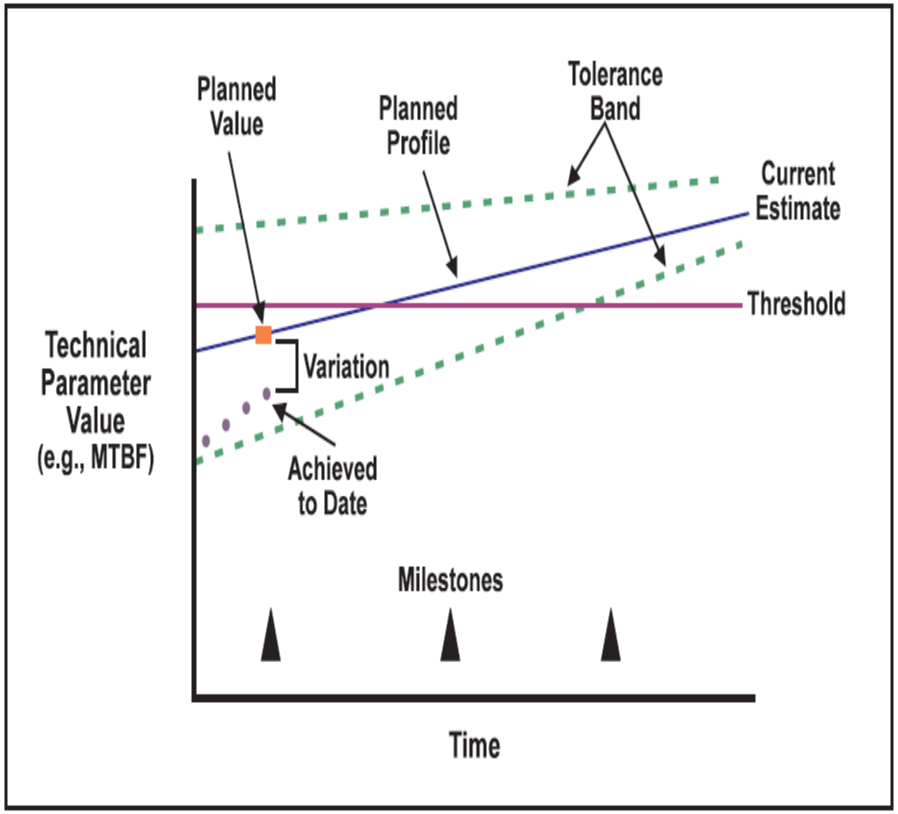
System Earned Readiness Management (SERM). A monitoring and evaluation tool for the planning and monitoring the progress of the system development effort using SRL (combination of TRL and IRL) combined with the prescribed strategy for developing the SoS and an appropriately constrained optimization model to formulate the optimal development plan.[3]

1 Garvey, P. and Cho, C. (2005). "An Index to Measure and Monitor a System-of-Systems' Performance Risk", *MITRE Technical Paper*
2 Osmundson, J., and Huynh, T., (2005), 'A Systems Engineering Methodology for Analyzing System of Systems', *Proceedings of the 1st Annual Systems of Systems Engineering Conference*
3 Sauser, B., Ramirez-Marquez, J., Magnaye, R., (2009), "Using a System Maturity Scale to Monitor and Evaluate the Development of Systems", Proceedings of the 6th Annual NPS Acquisition Symposium

Performance Prediction within a SoS -
the need for a TPM Equivalent

Technical Performance Measurements[1,2] provide insight as to the parameters of the specific design elements of the system and are used by project management to define the measures of performance and acceptable variables during project implementation.

Technical Performance Measurement values are implemented at the beginning of a project, as to ensure that projected performance values, within tolerable variance ranges, are met. Throughout the project, the actual performance is tracked and compared by project management to the Technical Performance Measurement that was deemed acceptable at the project's outset.–*PMBOK (online 4/17/12)*

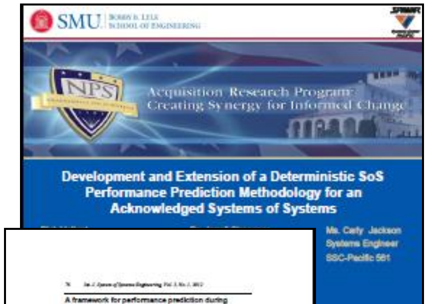


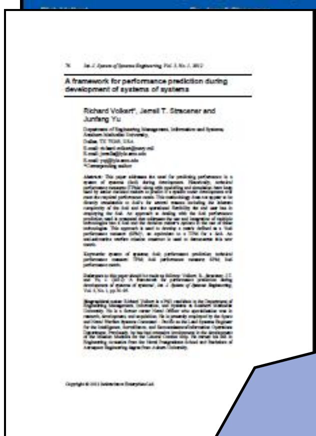
An equivalent metric for SoS's does not seem to exist

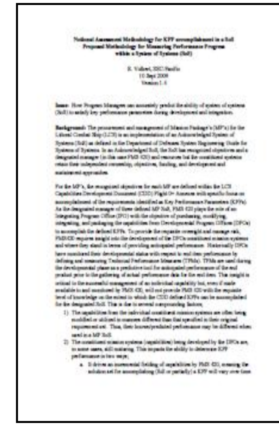
1 Pisano, N., (1995), "Technical Performance Measurement Earned Value, and Risk Management: An Integrated Diagnostic Tool for Program Management", *Paper presented at Defense Acquisition University Acquisition Research Symposium.*,

2 Roedler, G. and Jones, C. (2005) 'Technical measurement', A collaborative project of PSM, INCOSE, and industry, ver. 1.0, *INCOSE Technical Report No. INCOSETP-2003- 020-01.*

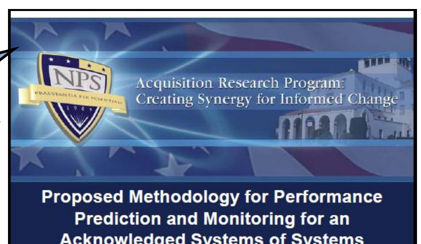
Development of the SoS Performance Measure (SPM) Metric

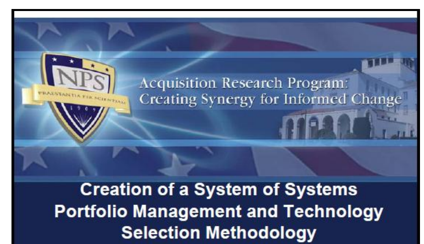


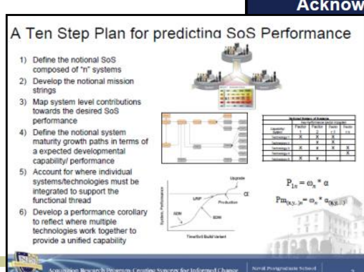


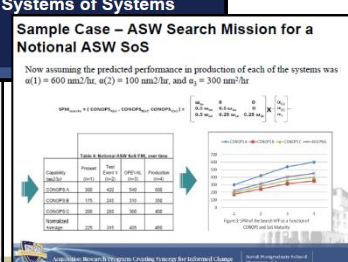


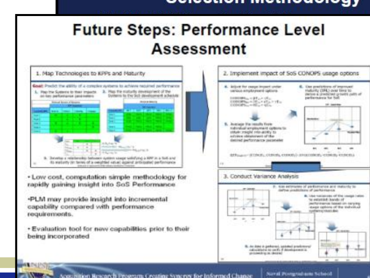
the SoS systems engineer needs to establish metrics and methods for assessing performance of the SoS capabilities which are independent of alternative implementation approaches. A part of effective mission capability assessment is to identify the most important mission threads and focus the assessment effort on end-to-end performance. [1]

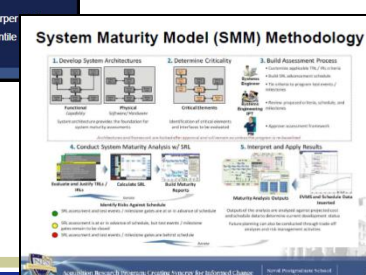








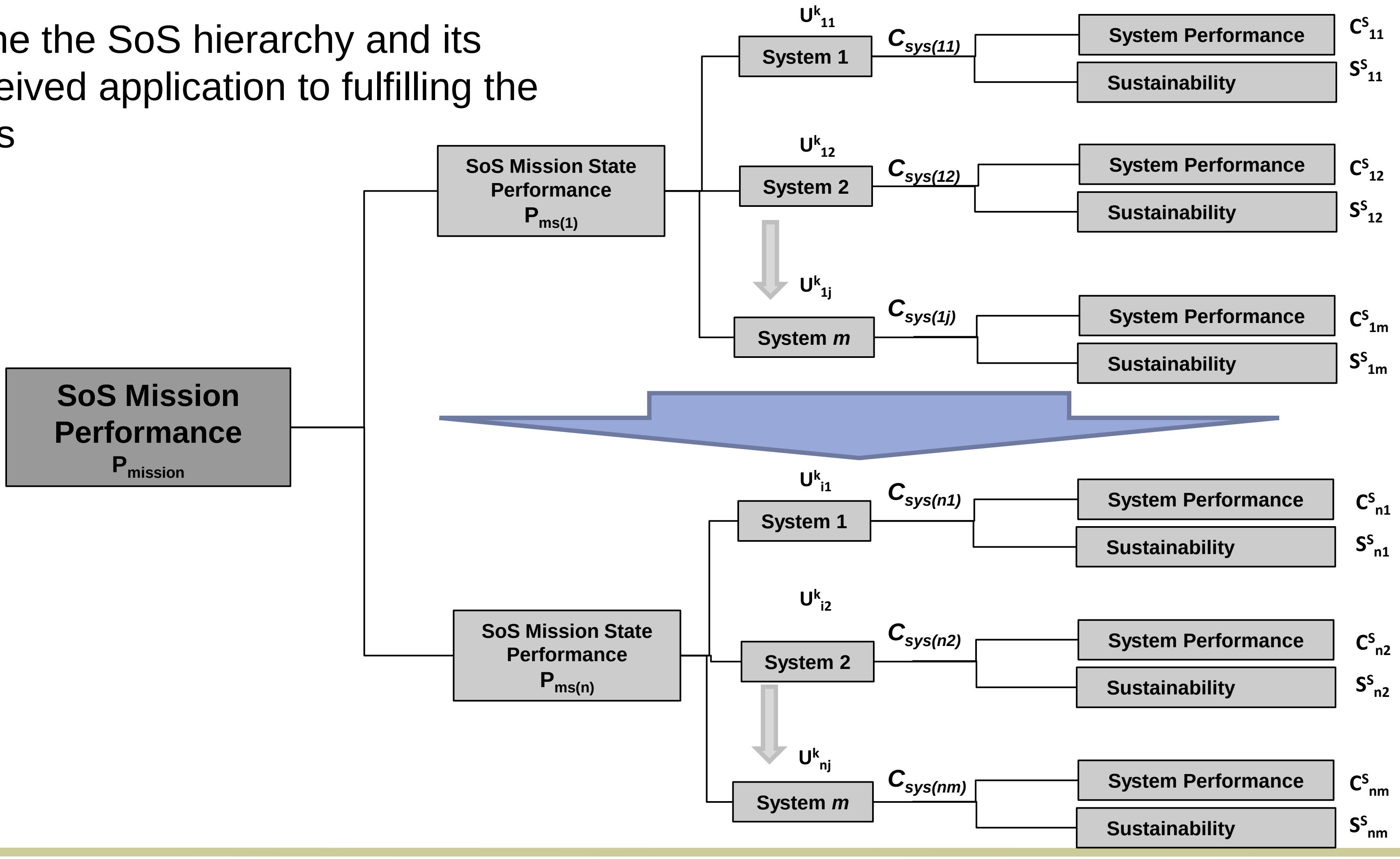




1. Systems Engineering Guide (ODUSD (A&T) SSE, 2008)

What can the SoS PM know, obtain, or predict at the system of system level?

Define the SoS hierarchy and its perceived application to fulfilling the KPPs



What can the SoS PM know, obtain, or predict at the system level?

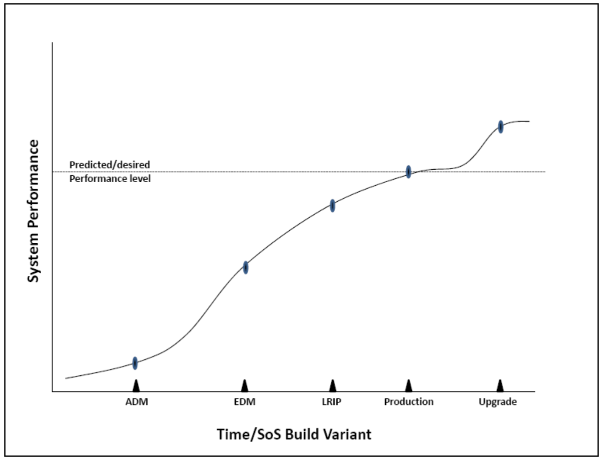


Figure 4: Notional Technology S-Curve mapped to Developmental Events

Performance and schedules of known systems, predictions for those under development or where knowledge is limited. Input from the potential users

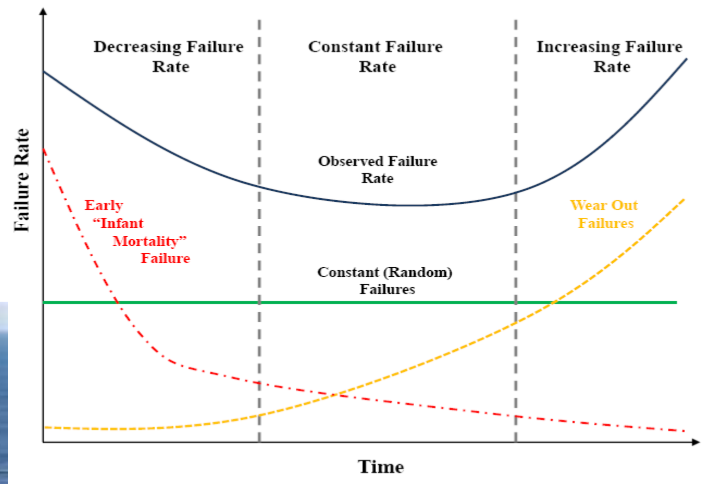


Figure 5: Reliability Bathtub Curve

"Nothing succeeds in war except in consequence of a well prepared plan." - Napoleon

Putting it together into a generic methodology

Define the mission as a function of its mission stages ⇒ $P_{mission} = g(P_{ms(1)}, P_{ms(2)}, \ldots, P_{ms(n)})$

Decompose the mission stages to their constituent elements ⇒ $P_{ms(i)} = f_i(C_{i1}^S, \ldots, C_{im}^S;\ S_{i1}^S, \ldots, S_{im}^S;\ U^k{}_{i1}, \ldots, U^k{}_{im})$

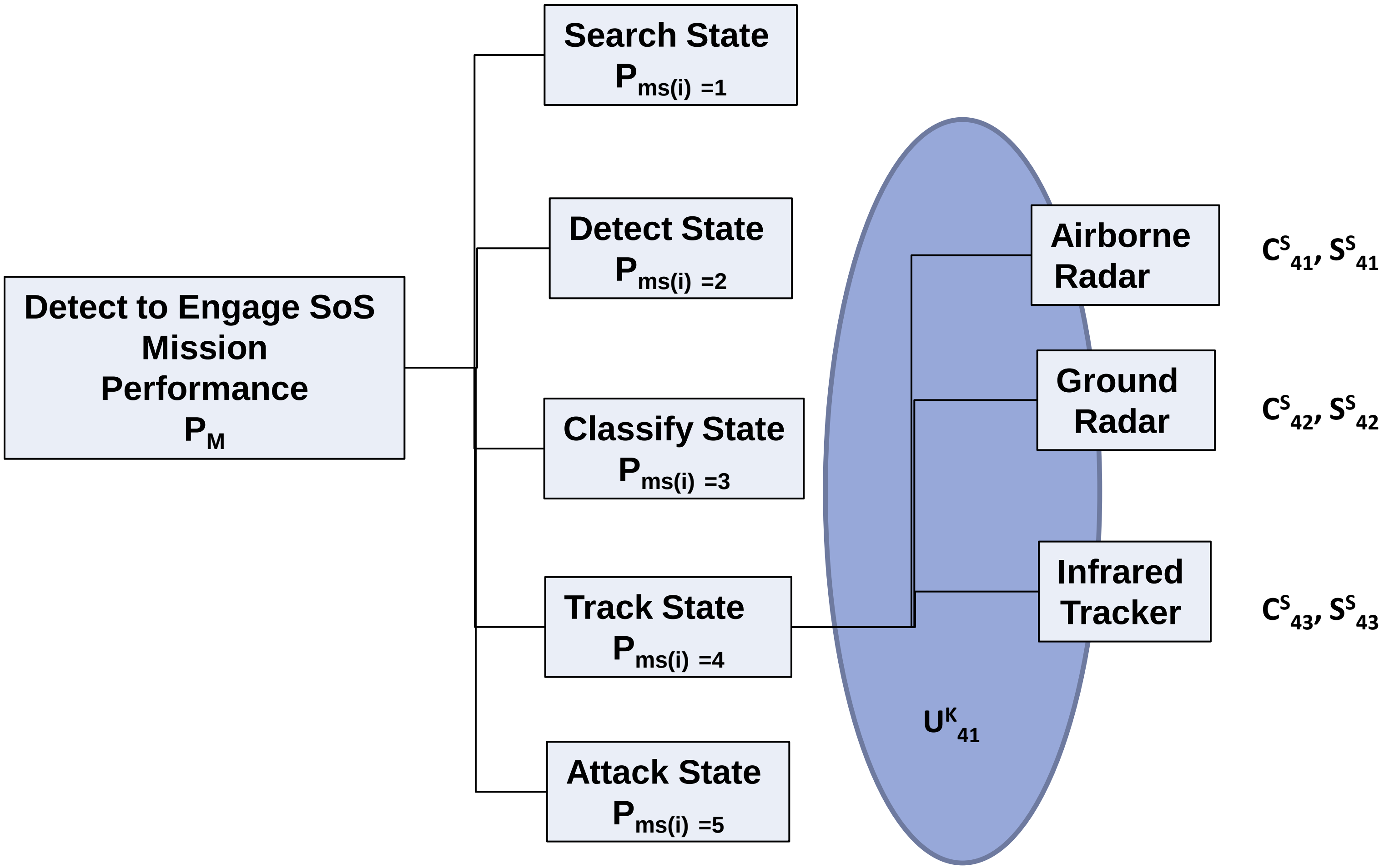
Adjust the constituent elements for inclusion in a SoS ⇒ $C_{ij}^S(t) = \omega_{ij} \times C_{ij}^B(t)$ $\quad S_{ij}^S(t) = \beta_{ij} \times S_{ij}^B(t)$

Incorporate system usage within SoS and determine system level performance within a mission state ⇒ $P_{ij} = C_{sys(ij)} \times U_{ij}^k = C_{ij}^S \times S_{ij}^S \times U_{ij}^k$

Determine the performance level of the mission state for a specific usage scenario ⇒ $P_{ms(i)} = \sum_{j=1}^{m} P_{ij} = \sum_{j=1}^{m} C_{sys(ij)} \times U_{ij}^k = \sum_{j=1}^{m} C_{ij}^S \times S_{ij}^S \times U_{ij}^k$

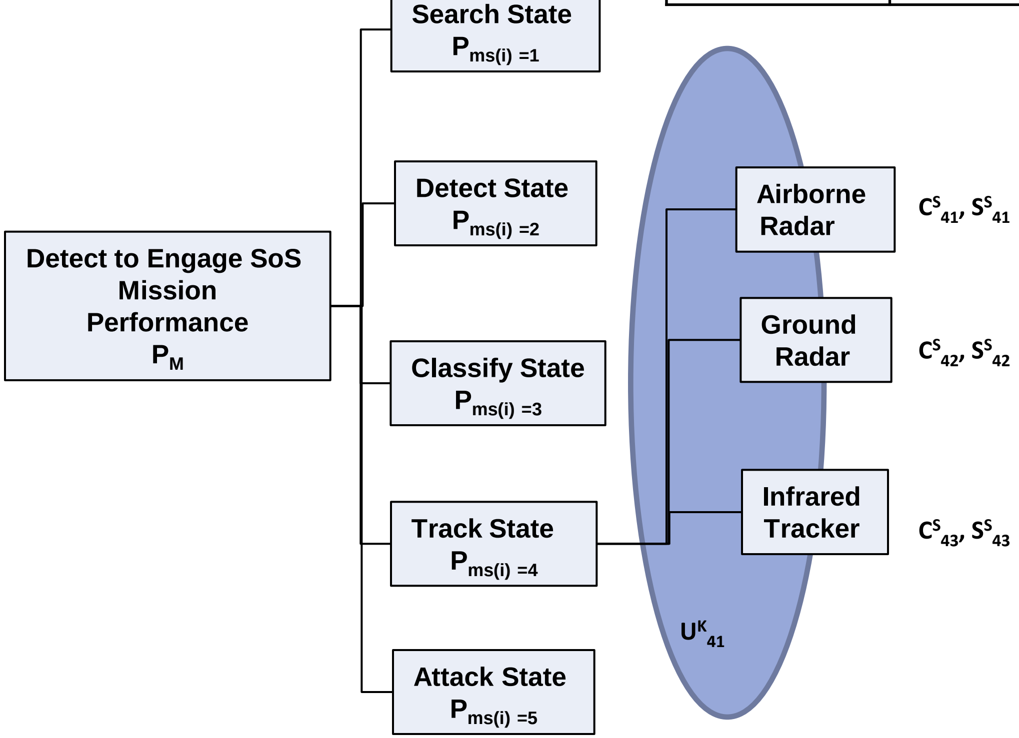
Adjust for the range of usage scenarios being evaluated To determine the mean value ⇒ $\overline{P}(t)_{ms(i)set} = \sum_{k=1}^{o} \gamma_k P_{ms(i)} = \sum_{k=1}^{o} \sum_{j=1}^{m} \gamma_k C_{sys(ij)} U^k{}_{ij}$

An example application- establish the hierarchy



An example application- define the parameters

Capability (integrated w/C&C)	Max. Base Capability	Units	Max. Base Sustainability	Performance Adjustment due to SoS Inclusion/ Integration (ω_{ij})	Sustainability Adjustment due to SoS inclusion (β_{ij})
Infrared Sensor	300	tracks/hr	1	0.6	0.8
Airborne Radar	500	tracks/hr	1	0.8	0.9
Ground Radar	1000	tracks/hr	1	0.9	1.0



Capability	CONOPS 1 (U^1_{4j})	CONOPS 2 (U^2_{4j})	CONOPS 3 (U^3_{4j})
Infrared Sensor	20	50	20
Airborne Radar	10	10	10
Ground Radar	20	10	10
C&C System	30	25	50

An example application- calculate performance @ system level

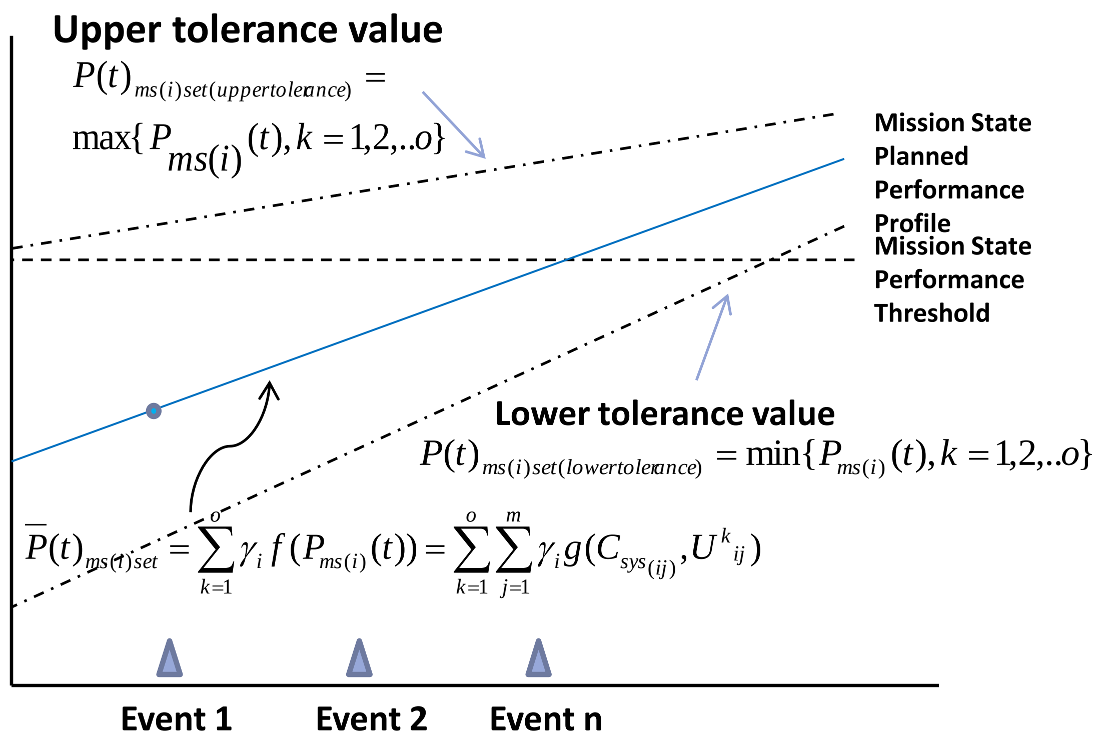
Capability	$C^S_{ij}(t_1)$	$S^S_{ij}(t_1)$	$C^S_{ij}(t_2)$	$S^S_{ij}(t_2)$	$C^S_{ij}(t_3)$	$S^S_{ij}(t_3)$	$C^S_{ij}(t_4)$	$S^S_{ij}(t_4)$
Infrared Sensor	0.5	0.2	0.6	0.4	0.7	0.6	0.8	0.8
Airborne Radar	0.6	0.5	0.7	0.6	0.8	0.7	0.9	0.8
Ground Radar	1	1	1	1	1	1	1	1

Capability	$C^S_{ij}(t_1)$	$S^S_{ij}(t_1)$	$C^S_{ij}(t_2)$	$S^S_{ij}(t_2)$	$C^S_{ij}(t_3)$	$S^S_{ij}(t_3)$	$C^S_{ij}(t_4)$	$S^S_{ij}(t_4)$
Infrared Sensor	90	0.16	108	0.32	126	0.48	144	0.64
Airborne Radar	240	0.45	280	0.54	320	0.63	360	0.72
Ground Radar	900	1	900	1	900	1	900	1

	t_1			t_2			t_3			t_4		
Capability	$P_4(t)$ for (U^1_{1j})	$P_4(t)$ for (U^2_{1j})	$P_4(t)$ for (U^3_{1j})	$P_4(t)$ for (U^1_{1j})	$P_4(t)$ for (U^2_{1j})	$P_4(t)$ for (U^3_{1j})	$P_4(t)$ for (U^1_{1j})	$P_4(t)$ for (U^2_{1j})	$P_4(t)$ for (U^3_{1j})	$P_4(t)$ for (U^1_{1j})	$P_4(t)$ for (U^2_{1j})	$P_4(t)$ for (U^3_{1j})
Infrared	2.9	7.2	2.9	6.9	17.3	6.9	12.1	30.2	12.1	18.4	46.1	18.4
Airborne	10.8	10.8	10.8	15.1	15.1	15.1	20.2	20.2	20.2	25.9	25.9	25.9
Ground	180.0	90.0	90.0	180.0	90.0	90.0	180.0	90.0	90.0	180.0	90.0	90.0
$P_4(t)$=	193.7	108.0	103.7	202.0	122.4	112.0	212.3	140.4	122.3	224.4	162.0	134.4

An example application- calculate performance @ mission system level & draft SPM chart

	U^1_{4j}	U^2_{4j}	U^3_{4j}	$\sum P/k$	P_{min}	P_{max}
$P_4 @ t_1$	193.7	108.0	103.7	135.1	103.7	193.7
$P_4 @ t_2$	202.0	122.4	112.0	145.5	112.0	202.0
$P_4 @ t_3$	212.3	140.4	122.3	158.3	122.3	212.3
$P_4 @ t_4$	224.4	162.0	134.4	173.6	134.4	224.4



Incorporating variability to represent the real world - the next step forward

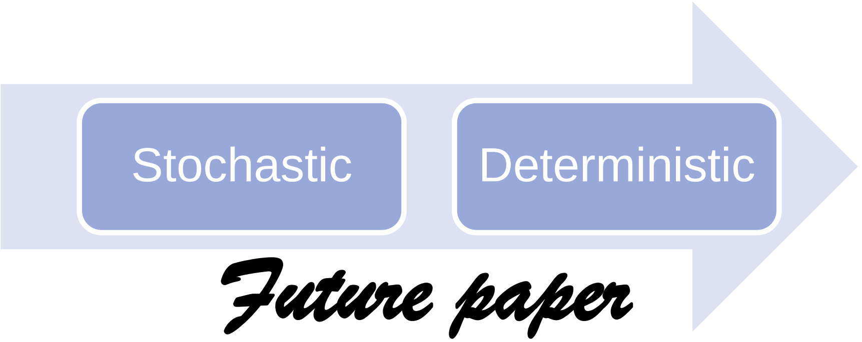
Need to realize that predictions with respect to achievement of performance, usage of systems, etc. are seldom met exactly. How do we deal with this variability?

The starting point, incorporating a probability function for the system drivers

$$C_{ij}^{ES}(t) = f(c_{ij}^{S}(t), P(c_{ij}^{S}(t))$$

$$S_{ij}^{ES}(t) = f(s_{ij}^{S}(t), P(s_{ij}^{S}(t))$$

$$U_{ij}^{Ek} = f(u_{ij}^{k}, P_k(u_{ij}^{k}))$$



Future paper

Conclusion

• System of Systems Development are an increasing trend within Defense & pose significant challenges in management & performance prediction/monitoring

• The development of new tools and metrics for SoS is an ongoing field of research but seems to be missing a TPM equivalent for a SoS

• The SoS Performance Metric (SPM) is a potential tool for addressing this area

  - Potential to operate within the constrained knowledge that a SoS PM may have
  - Expansion of the tool to account for variability should enhance its usability in quantifying the risk to achieving performance
  - Requires verification against real world data

Back Up Material