A modelling approach for integration of systems engineering and project/program management

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Never Stand Still

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About the approach

A way forward for bottom up integration of project management and systems engineering, by probabilistic and Bayesian modeling of systems engineering activities.

The focus here is on the most time and budget consuming activities: *Integration and Test*.

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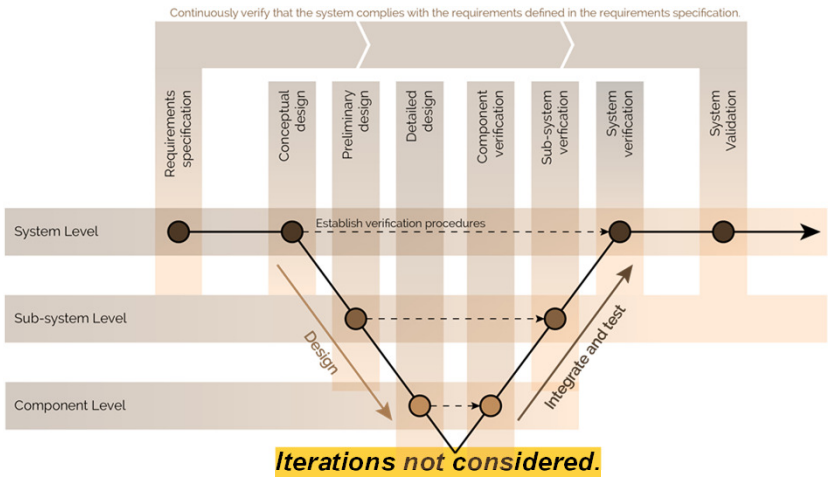
Systems engineering process



Iterations not considered.

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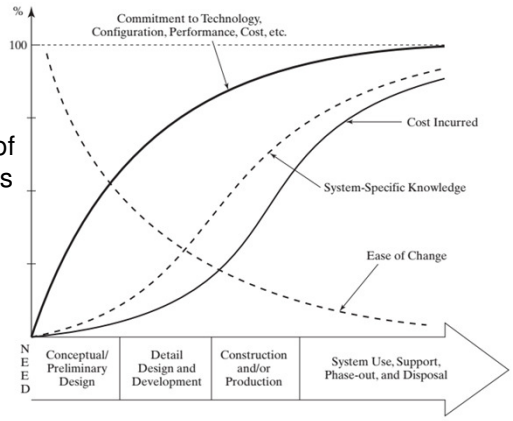
Integration and test process

From the project perspective most of the time and budget is spent at the integration phase thus more rigorous modelling of the integration and test process is essential for project management viability.



Blanchard, Benjamin S; Fabrycky, Wolter J. Systems Engineering and Analysis: Pearson New International Edition.

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Integration and test modeling approach

- Modeling *integration and test processes* with Bayesian modeling tools to consider iterations
- Facilitates *architecture optimization* for minimum cost and time
- Eventually gives estimates of integration and test process cost and time (*project level estimates*) for a fixed architecture.
- We first consider integration
  and then
  test architecture optimization.

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PART I

Integration modeling

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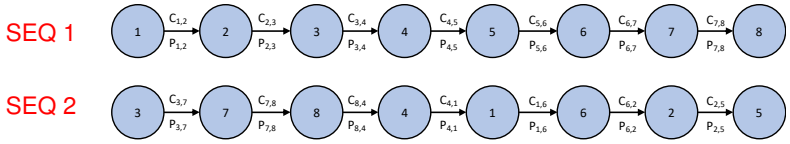
Integration process specification

- Process cost
- Process success probability
- Sequence of integration tasks (execution)
- Process complexity (with regards to iteration)



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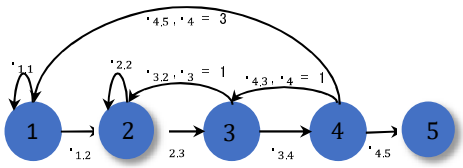
Integration complexity

Process complexity characterizes the amount of iteration the process requires in case of failure for any task to proceed to the next stage.



$$C_{Int} = \sum_{i=1}^{n-1} k_i \, (max)$$

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Shoval, S. & Efatmaneshnik, M. Int J Adv Manuf Technol (2019). https://doi.org/10.1007/s00170-019-03802-2

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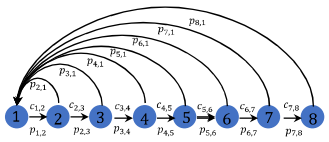
Integration cost: Bayesian formulation

For maximum process complexity

the cost is:

$$\hat{\mathrm{C}}(\mathrm{n}) = \sum_{i=1}^{n-1} \frac{c_{i,i+1}}{\prod_{j=i}^{n} p_{j,j+1}}$$ ← Heterogenous process

$$\hat{C}_n = \sum_{i=1}^{n} \frac{C}{P^i} = \frac{C}{1-P}\left(\frac{1}{P^n} - 1\right)$$ ← Uniform process



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Simple task sequencing heuristics

1) Given equal costs for all assembly tasks, when less reliable tasks (lower probabilities of success) are executed earlier in the process, the expected cost of the whole assembly would be lower.

2) the *minimum expected cost of a complex assembly process in which all assembly tasks are mutually dependent and have the same reliabilities for success is given by a sequence that sorts the costs in ascending order.*

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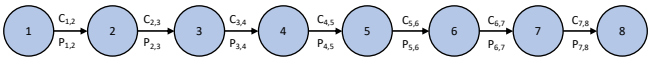
Management Question: Optimal integration investment

If integration task cost and success probability are *correlated* what is the optimum amount of investment in each task?



$$\hat{C}(n) = \sum_{i=1}^{n-1} \frac{c_{i,i+1}}{\prod_{j=i}^{n} p_{j,j+1}}$$

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Remedies to manage integration iteration

1. Increase the probability of task success
2. Decrease the tasks cost
3. Decouple design (reduce integration complexity)
4. Sequence optimization
5. Modularization

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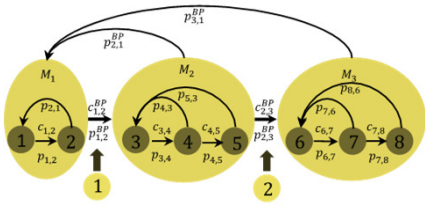
Modularization

Reduces iteration

$$\hat{C}^M = \sum_{i=1}^{m-1} \frac{c^{BP}_{M_i,M_{i+1}}}{\prod_{j=i}^{m-1} p^{BP}_{M_j,M_{j+1}}} + \sum_{i=1}^{m} \sum_{j=1}^{n_i-1} \frac{c^{M_i}_{j,j+1}}{\prod_{k=j}^{n_i-1} p^{M_i}_{k,k+1}}$$



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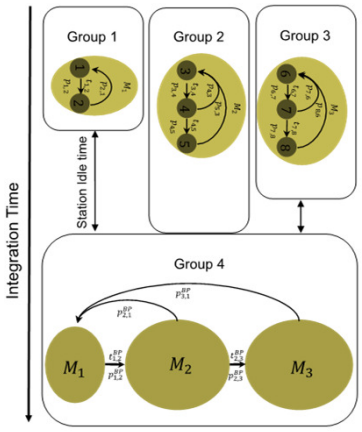
Modularization

Increase chance of parallel integration of units (subsystems) leading to reduction of *minimum integration time.*

$$\hat{T}^M = \sum_{i=1}^{m-1} \frac{t^{BP}_{M_i,M_{i+1}}}{\prod_{j=i}^{m-1} p^{BP}_{M_j,M_{j+1}}} + \max_{i=1\ldots m} \sum_{j=1}^{n_i-1} \frac{t^{M_i}_{j,j+1}}{\prod_{k=j}^{n_i-1} p^{M_i}_{k,k+1}}$$



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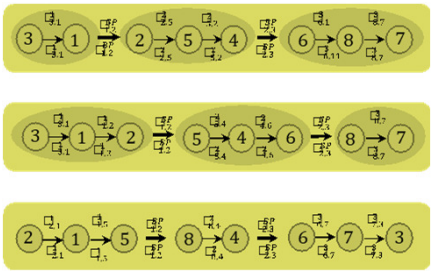
Optimum integration architecture

For a fixed set of configuration items the optimum architecture (sequence and modular architecture) is determined by:

$$N = \sum_{m=1}^{n} S(n,m) \prod_{i=1}^{m} k_i! = S(n,m) * n!$$

$$S(n,m) = \frac{1}{m!} \sum_{i=0}^{m} (-1)^i \frac{m!}{i!\,(m-i)!} (m-i)^n$$

Stirling number of the Second Kind



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PART II

Test modeling

Testability

- The degree to which a component or a system can be tested in isolation from other components or systems.
- Effort required for testing a system.
- The degree of effectiveness and efficiency with which test criteria can be established for a system.
- Testability can be a property of a requirement, a system, or any structural constituent of the system, i.e. subsystem, component.

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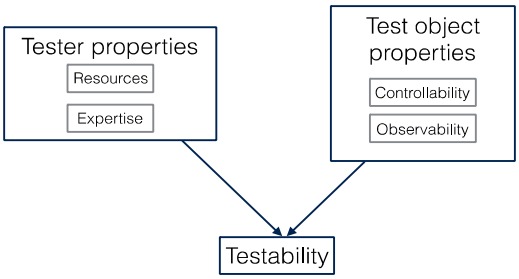
Design for Testability



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Measures of Testability

- Test Quality (TQ)
  - The average capacity of a test to identify any type of defect. $\mathrm{TQ} = Pr(Fault = Detected \mid Unit = Faulty)$
- Test Cost (TC)
  - is determined by the size of the tested system, TQ and the topology/architecture of the testing. A low-cost test implies high testability—that is, the high probability of test accuracy facilitates quick identification of faults.
- System Quality after the Test (SQaT)
  - Depends on TQ and System Quality before the Test

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Testing Architecture

- The way various tests are assigned to components, modules, subsystems and systems.
- Affects both SQaT and TC.
- *We define* a Test Setting (TS) as a quadruple $T_S = \{N_S, Q_S, A_S, T_A\}$
- N_S is the number of system components, with Unit Qualities (UQs) identified in $Q_S = \{Q_i\}$, $Q_i = 1 - Pr(Unit_i = Faulty)$,
- A_S is a test architecture for system S, that needs m tests with TQs in $T_A = \{\tau_1 \ldots \tau_m\}$,

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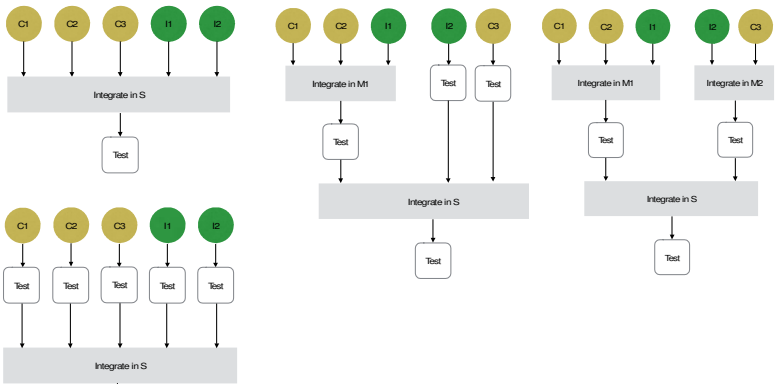
Testing Architecture (cont'd)

Different Examples of testing a system of five components



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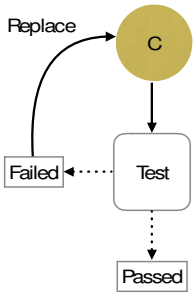
Test Cost

Deriving Issues:

- Number of required testbeds (stubs etc)
- Required test quality
- Number of test repetitions either planed or unplanned (due to tested unit fai



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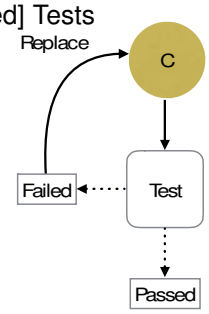
Problem Description

Determined SQaT and Expected Number of [unplanned] Tests (ENT) given TQ and UQ



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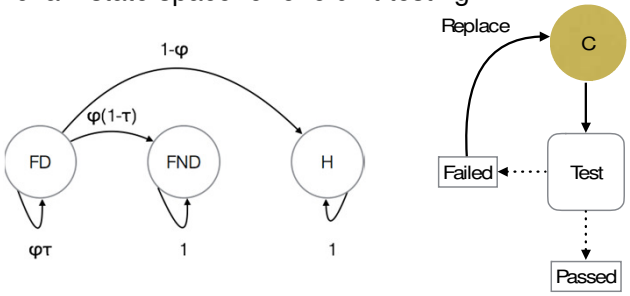
A Markovian Solution

Absorbing Markov chain state space for one unit testing



FD = Fault Detected, FND = Fault Not Detected
H = Healthy, $\varphi = Pr(Unit = Faulty), \tau = Pr(Fault = Detected \mid Unit = Faulty)$

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Markov Chain solutions

$[FND_\infty \quad H_\infty] = (1-T)^{-1}A = \left[\frac{\varphi(1-\tau)}{1-\varphi\tau} \quad \frac{1-\varphi}{1-\varphi\tau}\right]$

FND_∞ and H_∞ are the *FND* and *H* states probabilities after absorption.

$$SQaT = Q_{UT} = \frac{1-\varphi}{1-\varphi\tau} = \frac{Q_U}{Q_U\tau-\tau+1}$$

Latent defect probability: $P_{LD} = 1 - Q_{UT} = \frac{\varphi(1-\tau)}{1-\varphi\tau}$

Expected number of steps (tests) to absorption:

$$\text{ENT} = n_T = \frac{1}{1-\varphi\tau} = \frac{1}{Q_S\tau-\tau+1}$$

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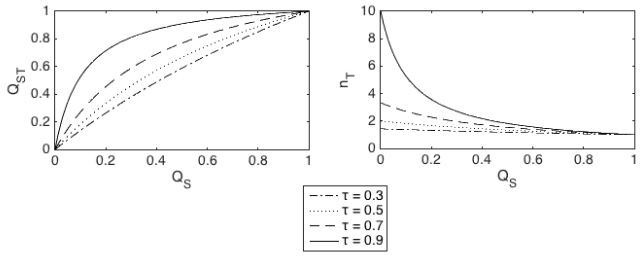
Unit Testing

There is a tradeoff between acquiring quality components and setting up quality tests: *a management decision*



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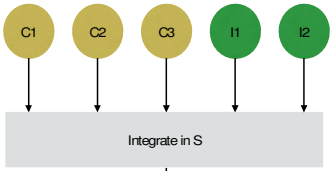
System Quality

A *S* system is considered as collection n components

$$Q_S = \prod_{i=1}^{n} Q_i = \prod_{i=1}^{n} (1 - \varphi_i)$$



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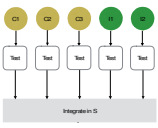
Single level System Testing

- N-test

$$n_{T|n} = \sum_{i=1}^{n} \frac{1}{Q_i \tau - \tau + 1}$$

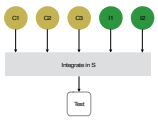
$$Q_{ST|n} = \left(\frac{Q_i}{Q_i \tau - \tau + 1} \right)^n$$



- 1-test

$$Q_{ST|1} = \frac{Q_i^n}{Q_i^n \tau - \tau + 1}$$

$$n_{T|1} = \frac{1}{Q_i^n \tau - \tau + 1}$$



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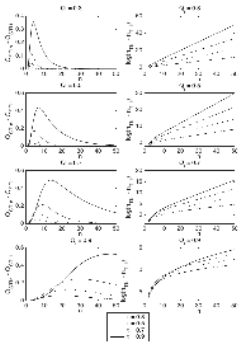
Heuristics for Single level Test

- For low quality tests, regardless of the number and quality of components before test, perform *1*-test. This is very good for test time/cost, while leading to not much difference in quality.
- With high quality tests and low quality components:
  - When number of components is low-medium (*n<30*) choose n-test over *1*-test because of large difference in SQaT.
  - When number of components is high (*n>30*) choose *1*-test which makes little difference in SQaT relative to *n*-test, but leads to relatively large savings in ENT.
- With high quality test and high quality components, regardless of the number of components, choose *n*-test. This leads to relatively superior results in SQaT and not much difference in test cost/time.



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Two Level Testing

No	M Vector
1	[5] 1 level
2	[1],[1],[1],[1],[1] 1level
3	[[5]]
4	[[1],[4]]
5	[[2],[3]]
6	[[1],[1],[3]]
7	[[1],[2],[2]]
8	[[1],[1],[1],[2]]
9	[[1],[1],[1],[1],[1]]

- $Q_{ST} = \frac{\prod_{i=1}^{n_M} Q_{MT_i}}{1-\tau_s(1-\prod_{i=1}^{N_M} Q_{MT_i})}$
- $n_{ST} = \sum_{i=1}^{N_M} \frac{n_{T|M_i}}{1-\tau_s(1-Q_{MT_i})} + \frac{1}{1-\tau_s(1-\prod_{i=1}^{n_M} Q_{MT_i})}$
- Q_{MT_i} quality of modules which depend on unit qualities within modules and TQs of module tests
- τ_s TQ at system level

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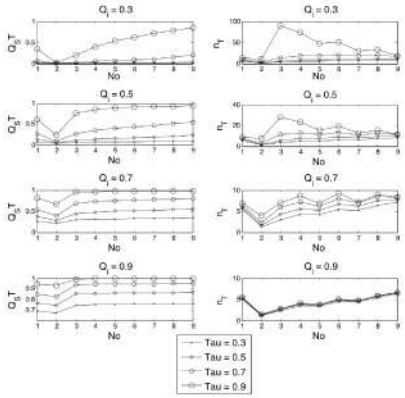
Test Architecture Evaluation

- Architecture 9 is most effective and efficient given all TQs are same, **however this does not hold when system size is large.**

No	M Vector
1	[5] 1 level
2	[1],[1],[1],[1],[1] 1level
3	[[5]]
4	[[1],[4]]
5	[[2],[3]]
6	[[1],[1],[3]]
7	[[1],[2],[2]]
8	[[1],[1],[1],[2]]
9	[[1],[1],[1],[1],[1]]



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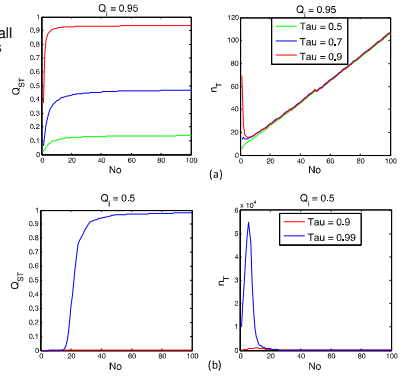
Effect of System Size

- SQaT and ENT of an n-component test with n = 100, and with (a) all Q_is equal to 0.95 and (b) all Q_is equal to 0.5. The horizontal axis is the balanced modularization no which also corresponds to the number of modules used in the test.
- Number corresponds to balanced modularization e.g.
- Number 1 corresponds to two consecutive 1-tests
- Number 100 corresponds to a n-test followed by 1-test
- Number 2 corresponds to [[50],[50]]
- Number 3 corresponds to [[33],[33],[34]] and so on



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Pareto Optimal Test Architecture (for SQaT and ENT)

Optimal M No		Test Quality															
		0.3	0.4	0.5	0.6	0.7	0.8	0.9	0.91	0.92	0.93	0.94	0.95	0.96	0.97	0.98	0.99
Unit Quality	0.5	100	100	100	100	100	100	100	100	100	100	100	100	100	100	51	51
	0.6	100	100	100	100	100	100	100	100	100	100	100	100	51	51	51	51
	0.7	100	100	100	100	100	100	100	100	51	51	51	51	51	51	34	34
	0.8	51	51	51	100	51	51	51	51	34	34	34	34	26	26	26	26
	0.9	13	17	21	26	26	17	13	13	13	13	13	13	13	13	13	13
	0.91	10	15	17	17	17	17	13	13	13	13	13	13	13	8	8	8
	0.92	8	13	15	17	17	13	13	8	8	8	8	8	8	8	8	8
	0.93	1	9	13	13	13	13	8	8	8	8	8	8	8	8	8	8
	0.94	1	7	8	9	9	8	6	6	6	6	6	6	6	6	6	6
	0.95	1	5	6	7	8	6	6	6	6	6	6	6	6	6	6	6
	0.96	1	3	4	5	6	5	4	4	4	4	4	4	4	4	4	4
	0.97	1	1	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	0.98	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2
	0.99	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

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Conclusion

- The selection of modular architecture is a delicate act and can be highly sensitive to both test parameters such as (TQs and unit qualities), as well as integration process parameters (integration task costs, and success probabilities).
- The model presented here is a useful starting point for architecture selection and analysis, and linking each architecture option to project level cost and time.

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Refereces

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Any questions?

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abstract

- **A modelling approach for integration of systems**
- **engineering and program management**
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- to publish and use.
- **Abstract**. Defence systems acquisition is fraught with all sorts of financial, technical and political risks. The most effective way of mitigating risks associated with acquisition of complex systems is through identification of these risks as early as concept examination phase. One possible avenue to de-risk complex acquisition projects is through the integration of program management and systems engineering views. In General terms, project/program management is concerned with timely and on the budget execution of projects where as Systems Engineering is concerned with complexity management and successful systems integration. While the two domains are not the same, it is obvious that good systems engineering practices lead to better execution of acquisition projects. This paper will outline an approach for risk and complexity evaluation and mitigation of capability concepts to be used, in risk mitigation planning, systems engineering planning and project control activities. The approach will be based on a Bayesian and Probabilistic Systems Engineering Model that will utilize probabilistic success or failure in execution of systems engineering tasks and the early estimation of the resulting reworks. This work applies probabilistic analysis to a network view of the physical system (software and hardware) where the projected building blocks of the system are considered to obtain an estimation of the final system assured and unassured quality, reliability and utility. The resulting test and integration processes will be characterized in terms of their expected rework, time and budget. The network of the inter-related tasks will be solved as a Bayesian Network for expected time and cost of execution and variances of those, that can together be used to evaluate project level risk.

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