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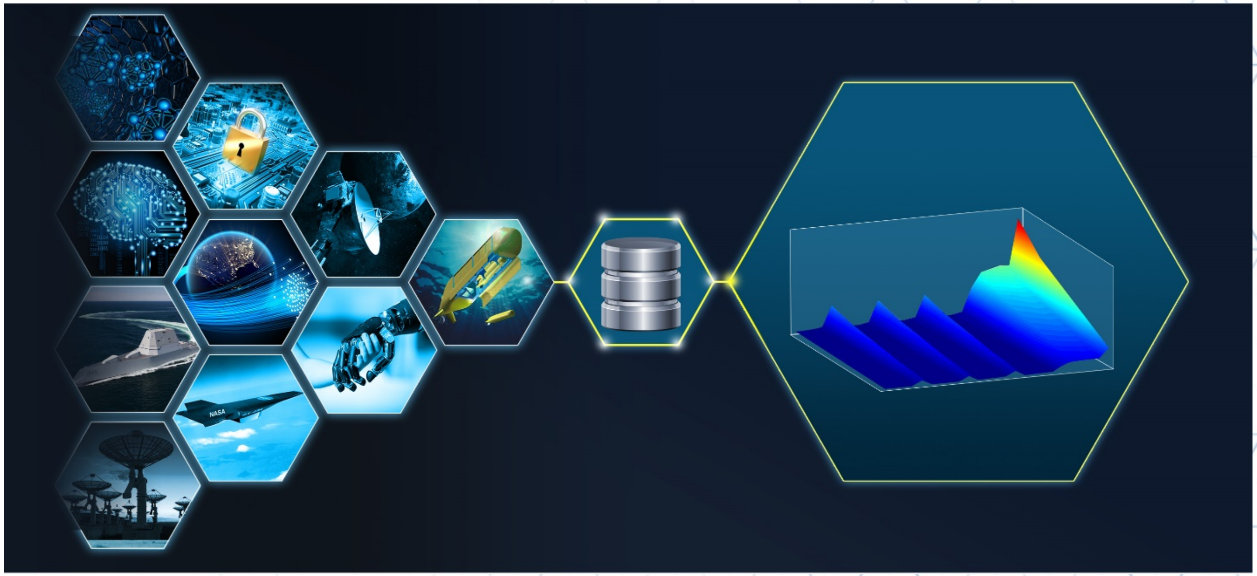
Advanced Estimating Methodologies FOR Conceptual Stage Development



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Outline

- Challenge : Early Technology Development Estimating
- Background: Technology Development Risk
- Goal / Objectives of Cost Research
- APL First Generation Technology Development Models
- Methodology:
  - Investigation of Complementary Independent Cost Predictor Variables: Research & Development Degree of Difficulty (RD^3) and Technology Area (TA)
  - Initial Results - Cost Estimate Central Values and Uncertainty PDF
  - Mean Cost Index (MCI) Method - RD^3 and TA
  - Standard Development Cost Framework and Benchmarking Research
  - Resulting Cost Benchmarking results by Milestones, Activities and TRL / MRL
- New Cost Model Sample output with SHL, TIL, RD^3 and TA Parameters
  - 3 Parameter Model results - Risk Adjusted PDFs
  - 4 Parameter Model results - Risk Adjusted PDFs
- Summary: Improved Technology and System Development Cost Estimating Capabilities

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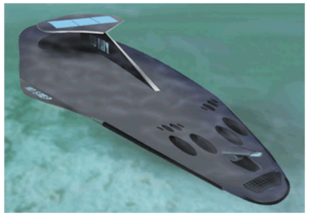
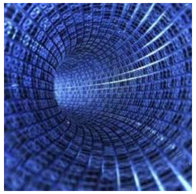
APL Conceptual & Early Life Cycle Technology Development Technologies and Systems

- Numerous applications across DoD, Intel, Space and Civil sectors
- Range of Technologies and Applications
  - Sea – Ships / Submarines / Unmanned
  - Air – Aircraft / Airships / Unmanned
  - Space – Satellites / Spacecraft / Probes
  - Weapon Systems – Strategic / Tactical
  - Networks – Ground, Space and Marine Data / Communications / Sensors
  - Robotics / Automation / Nanotechnology
  - Information Technology / Electronics / Cyber
  - Military Strategy and Force Structure
  - Energy and Infrastructure
  - Warrior Armament
  - Healthcare

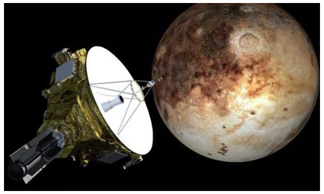








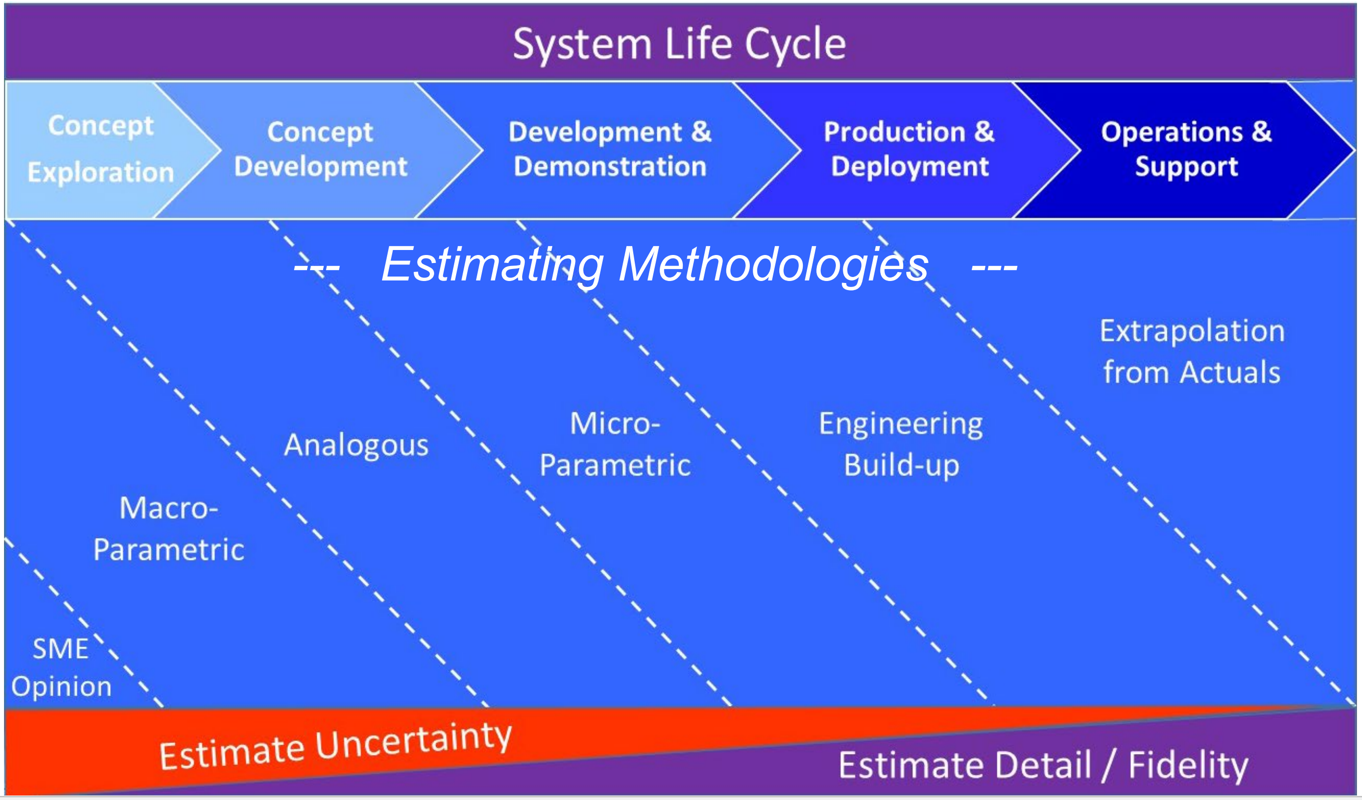




Challenge: Early Technology & System Dvlp Estimating

Most difficult phase for cost estimating in life cycle (LC)

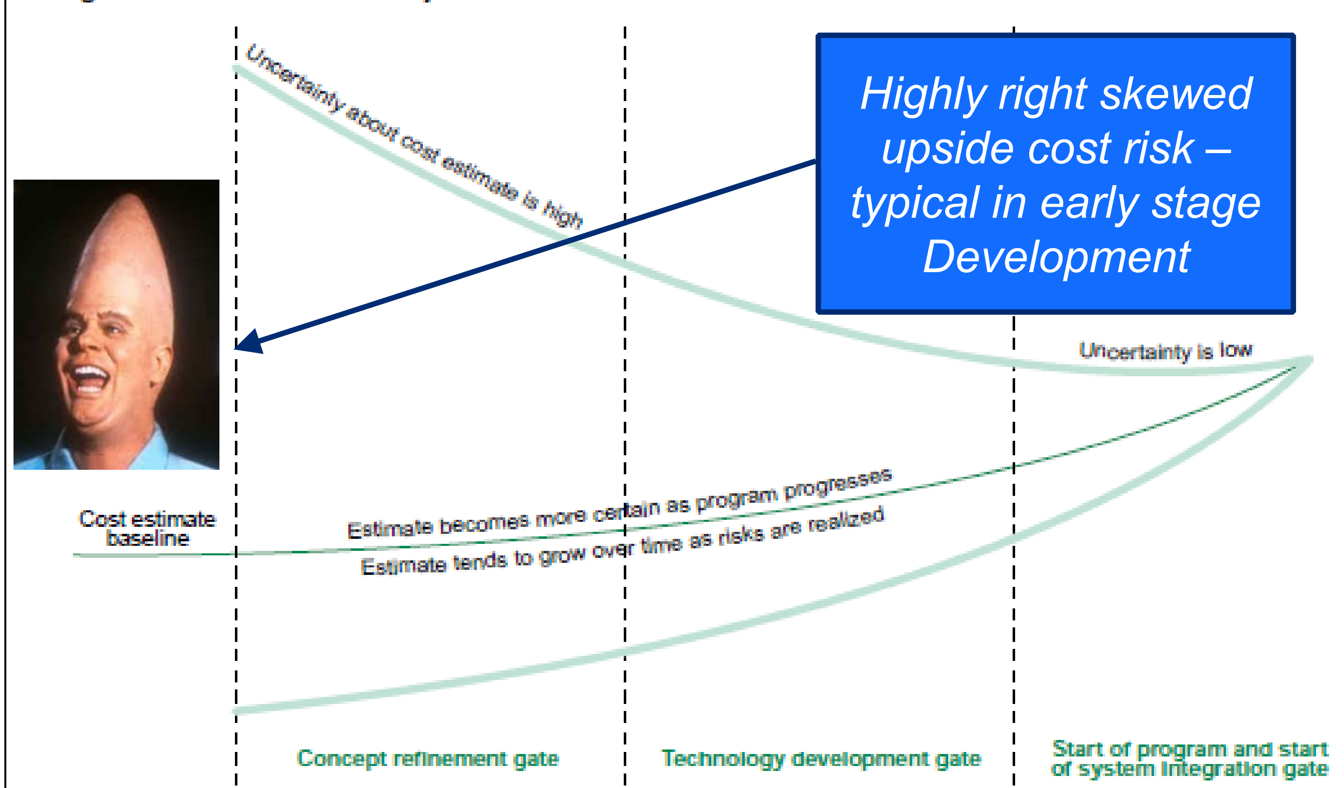
- New or low TRL technologies - little or no analogous / comparable systems
- Conceptual stages - Highest level of uncertainty and unknowns in LC
- Lack of technical, engineering, design or performance parameters available to drive traditional micro-parametric models



Background: Technology Development Risk

- Uncertainty (both known and unknown risks) during concept exploration and technology development is the highest in system LC
- Technology Development is inherently the highest risk activity in Acquisition and the toughest challenge to cost estimating discipline

Figure 4: Cone of Uncertainty



Source: GAO.

Source: GAO Cost Est and Assessment Guide - Best Practices Mar 2009

Goal / Objectives of Cost Research

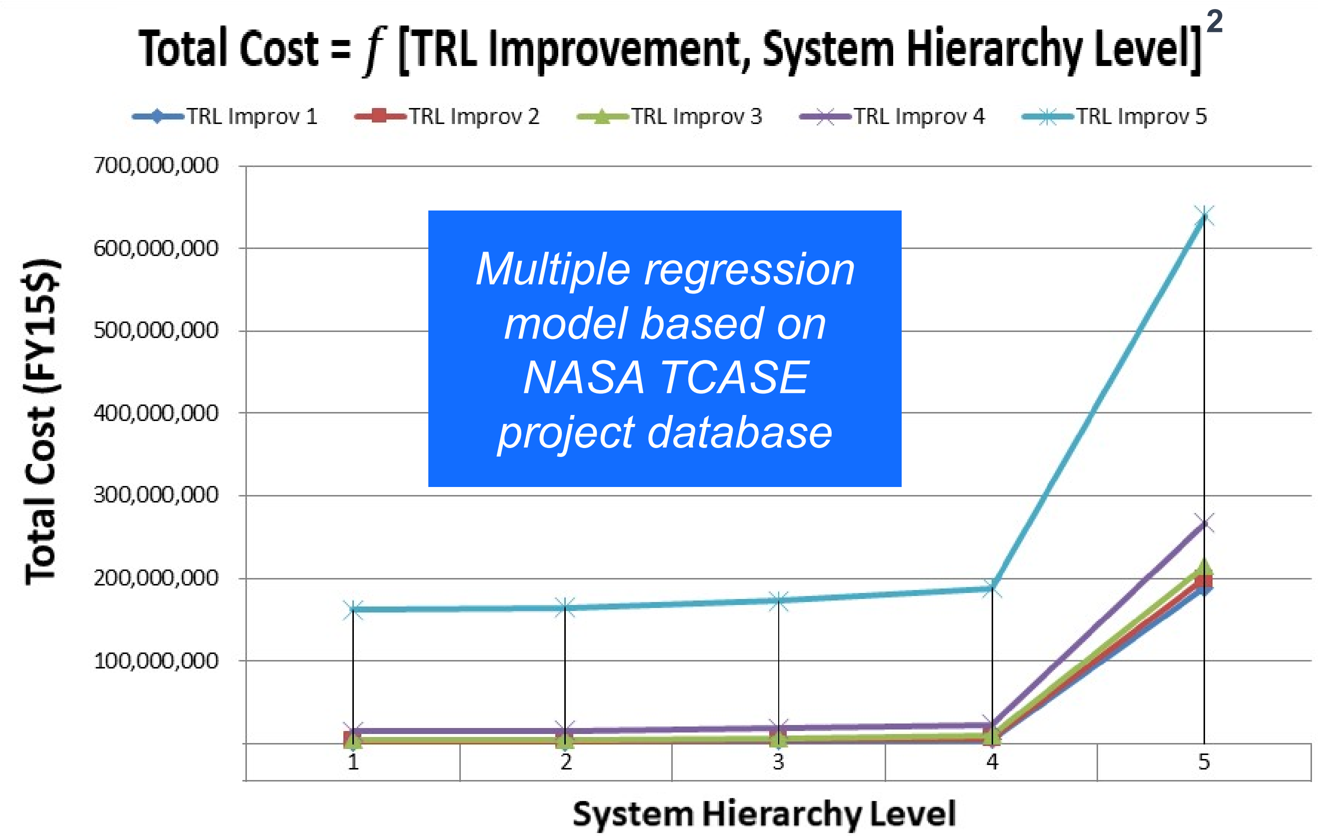
Goal: Improve Capabilities of Conceptual Phase Technology and Systems Development Cost Estimating

- Expand forecasting power and precision of first generation development phase macro-parameter cost models (2017)
  - Research and implement independent parameters to complement System Hierarchy Level (SHL) / TRL Improvement Level (TIL) legacy models
  - Capture a substantially broader perspective of essential cost & risk driver attributes: technology and system scale; maturity; complexity; form / function, development difficulty, and level of integration
- Produce higher fidelity cost uncertainty models: probability density functions (PDF) tailored to multiple macro-parameter categories/levels
- Develop a Standard Development Phase Cost Framework with integral Cost Benchmarks to better:
  - Plan & allocate budget resources and investments by key Development milestones, activities and technology maturity levels
  - Refine monolithic TIL costs to discrete TRL start and end states

Background: APL First Generation Technology Development Models

Sample Macro-Parametric Cost Model for Early Technology Development

System Hierarchy Level	
1	HW/ SW / Mat'l. End Item
2	Component / Part
3	Assembly
4	Subsystem
5	System



	1	2	3	4	5
TRL Improv 1	1,367,536	1,558,023	2,489,428	4,555,093	188,465,019
TRL Improv 2	2,510,944	2,766,855	3,971,933	6,499,672	200,036,759
TRL Improv 3	4,421,020	4,758,563	6,305,107	9,409,382	214,958,453
TRL Improv 4	14,366,101	14,969,585	17,628,570	22,611,104	267,293,178
TRL Improv 5	162,260,270	164,273,773	172,830,919	187,771,983	639,937,276

TRL Improvement Level = increase in number of std. TRL levels achieved from start to end of development

Reference: Research Paper "Parametric Cost and Schedule Modeling for Early Technology Development", Figure 11, Alexander, JHU-APL 2017

Methodology: Investigation of Complementary Independent Cost Predictor Variables

- Search of NASA TCASE Database[1] for other macro-parameters resulted in two primary candidates
  - Research and Development (R&D) Degree of Difficulty (RD^3)
  - Technology Area (TA)
  - Several others evaluated include Advanced Degree of Difficulty (AD^2) Key Performance Parameters (KPPs) and key system characteristics
- Large # project records for each parameter
  - RD^3 – approximately 426 project records
  - TA – approximately 1730 project records
- Insufficient # of projects containing all 4 indep parameters so alternate methods identified to include add'l. attributes
  - Mean Cost Index (MCI) method
  - Composite Geometric Mean method

1. *NASA Technology Cost and Schedule Estimating (TCASE) tool contains ~ 3,000 project technology Development database with 164 fields of programmatic & technical parameters, cost & schedule data*

Research & Development Degree of Difficulty (RD^3)

Level	Definition
5	The degree of difficultry anticipated in achieving R&D objectives for this technology is so high that a fundamental breakthrough is required [$P_{success}$ = 0.2]
4	A very high degree of difficulty anticipated in achieving R&D objectives for this technology [$P_{success}$ = 0.5]
3	A high degree of difficulty anticipated in achieving R&D objectives for this technology [$P_{success}$ = 0.8]
2	A moderate degree of difficulty should be anticipated in achieving R&D objectives for this technology [$P_{success}$ = 0.9]
1	A very low degree of difficulty is anticipated in achieving R&D objectives for this technology [$P_{success}$ = 0.99]

Source: “RESEARCH & DEVELOPMENT DEGREE OF DIFFICULTY (RD^3) - A White Paper” by John C. Mankins, NASA Headquarters. Office of Space Flight, Advanced Projects Office, March 10, 1998

Technology Areas (TA)

No.	Description
TA01	Launch propulsion systems
TA02	In-space propulsion technologies
TA03	Space power and energy storage
TA04	Robotics, telerobotics, autonomous systems
TA05	Communication and navigation
TA06	Human health, life support, habitation systems
TA07	Human exploration destination systems
TA08	Science instruments, observatories, sensor systems
TA09	Entry, descent, and landing systems
TA10	Nanotechnology
TA11	Modeling, simulation, information tech
TA12	Materials, structures, mechanical systems, manufacturing
TA13	Ground and launch systems processing
TA14	Thermal management systems
(+) 1	Aeronautics

Technology areas and supporting roadmaps developed by NASA, validated by the National Research Council (NRC). (Reference: Technology Estimating Research Project - Introduction and Definitions, June, 2013)

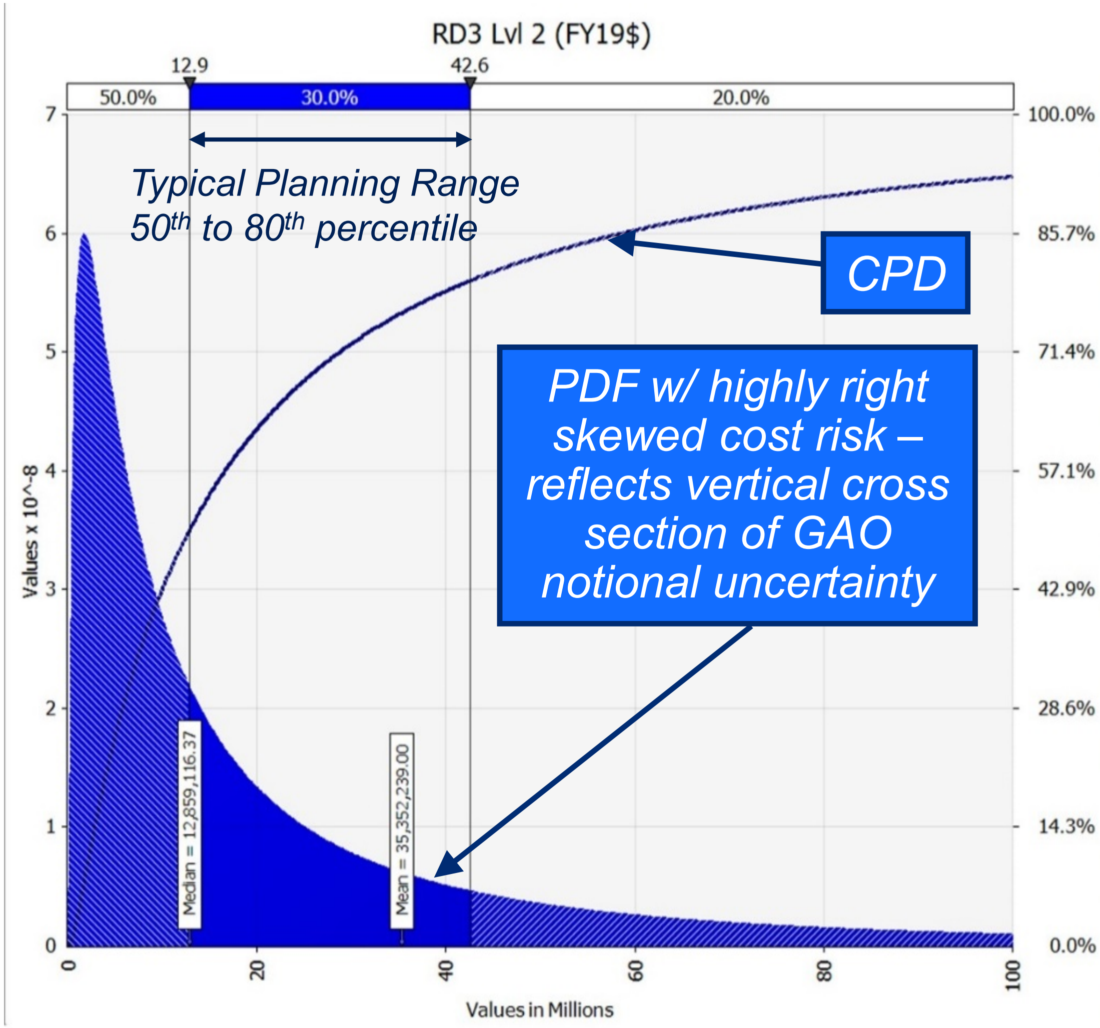
Cost Metrics for Project RD^3 Levels

- First segregated project costs by RD^3 producing favorable results with steady progressive incremental costs across levels
- Large uncertainty ranges are typical and appropriate for conceptual phase developments due to risks (known and unknown) and greatest cost growth potential in early stages
- Cost uncertainty is driven by factors including: requirements creep; technology & design changes; operational & threat environment deviations; research organization, staffing or management changeover; supply chain disruptions; budget or resource priority realignments; legal / regulatory / political environment changes

RD^3 Project Sample Cost Data Statistics (FY19$)					Uncertainty
RD3 Lvl	Records	Mean	Median	Std Dev	PDF Function
1	17	$ 18,072,037	$ 9,799,623	$ 18,436,153	Gamma
2	153	$ 32,399,635	$ 13,242,734	$ 52,082,945	Lognorm
3	174	$ 44,543,794	$ 19,864,101	$ 111,674,939	Burr12
4	76	$ 56,739,467	$ 26,485,469	$ 85,282,868	Weibull
5	6	$ 79,677,118	$ 57,605,894	$ 73,348,093	Erlang

Example RD^3 Cost Curve Fit Uncertainty PDF

Cost Curve Fit PDF and cumulative probability distribution (CPD) for RD^3 = 2 (Lognormal FY19$M)



	Lognorm(35352239,90532673.2)
Minimum	0.00
Maximum	+∞
Mean	35,352,239.00
Mode	1,701,372.98
Median	12,859,116.37
Std Dev	90,532,673.20
Skewness	24.4771
Kurtosis	4,295.0989
Left X	12,859,116.37
Left P	50.0%
Right X	42,563,464.77
Right P	80.0%
Dif. X	29,704,348.40
Dif. P	30.0%
1%	470,269.19
5%	1,239,567.64
10%	2,078,084.00
15%	2,944,827.77
20%	3,884,948.62
25%	4,927,353.73
30%	6,099,806.94
35%	7,433,932.80
40%	8,968,746.36
45%	10,754,658.41
50%	12,859,116.37
55%	15,375,372.00
60%	18,437,010.83
65%	22,243,525.50
70%	27,108,542.21
75%	33,558,961.44
80%	42,563,464.77
85%	56,151,628.02
90%	79,571,794.92
95%	133,398,830.43
99%	351,621,743.13

Cost Metrics for Project TA Categories

- Mixed results: most categories falling within reasonable range with a few central value outliers (TA categories # 5, 8, 9, 10,15) due to:
  - Limited sample sizes and in some instances TA inter-categorical project size concentrations
- Large range of uncertainties again expected / normal for conceptual phase developments due to larger risks and cost growth potential in early stages
  - Very large ranges also due to TA not being an incremental measure but broad uniform categories spanning full range of project scale, complexity and maturity

TA Project Cost Data Statistics (FY19$)					
No.	Technology Area (TA)	Records	Mean	Median	Std Dev
1	Launch Propulsion Systems	159	$ 29,482,594	$ 896,999	$ 125,232,312
2	In-Space Propulsion Technologies	111	$ 22,420,479	$ 1,122,812	$ 68,386,702
3	Space Power and Energy Storage	229	$ 21,455,560	$ 800,408	$ 136,454,438
4	Robotics, Telerobotics, Autonomous Systems	73	$ 25,936,013	$ 13,246,144	$ 42,926,634
5	Communication and Navigation	182	$ 8,439,804	$ 972,011	$ 24,215,606
6	Human Health, Life Support, Habitation Systems	224	$ 53,192,277	$ 15,891,281	$ 87,320,195
7	Human Exploration Destination Systems	59	$ 48,878,481	$ 26,485,469	$ 62,394,548
8	Science Instruments, Observatories, Sensor Systems	123	$ 8,934,078	$ 926,115	$ 39,299,914
9	Entry, Descent, and Landing Systems	15	$ 356,640,735	$ 25,965,543	$ 668,318,491
10	Nanotechnology	24	$ 2,762,815	$ 401,754	$ 5,452,029
11	Modeling, Simulation, Information Tech	95	$ 39,777,986	$ 1,491,313	$ 176,746,995
12	Materials. Structures, Mechanical Systems, Mfg.	229	$ 11,845,815	$ 803,508	$ 33,782,225
13	Ground and Launch Systems Processing	23	$ 50,093,679	$ 13,529,154	$ 126,535,384
14	Thermal Management Systems	85	$ 19,242,667	$ 2,648,547	$ 37,251,256
15	Aeronautics	99	$ 5,904,203	$ 393,329	$ 16,990,139

Mean Cost Index (MCI) Method - RD^3 and TA

- Mean Cost Factors (MCF) = project level cost / SHL-TIL population mean
- MCI = aggregate or stratify MCFs by RD^3 level and TA
- Sample equivalence established by formal testing
  - 2 common equivalence tests: Two one-sided test (TOST) and Welches t-test (see backup slides & research paper for details) between three SHL-TIL, RD^3 and TA samples
- Results demonstrate equivalence so cost translations between samples can be applied using MCIs (project attribute cost factors of sample means)
- RD^3 & TA MCIs applied directly to legacy models produced a full range of 3 and 4 parameter project configurations using SHL, TIL, RD^3 and TA metrics

Note: Composite Geometric Mean Method produced poor results and was eliminated as a viable modeling option

Mean Cost Index (MCI) Results - RD^3 and TA

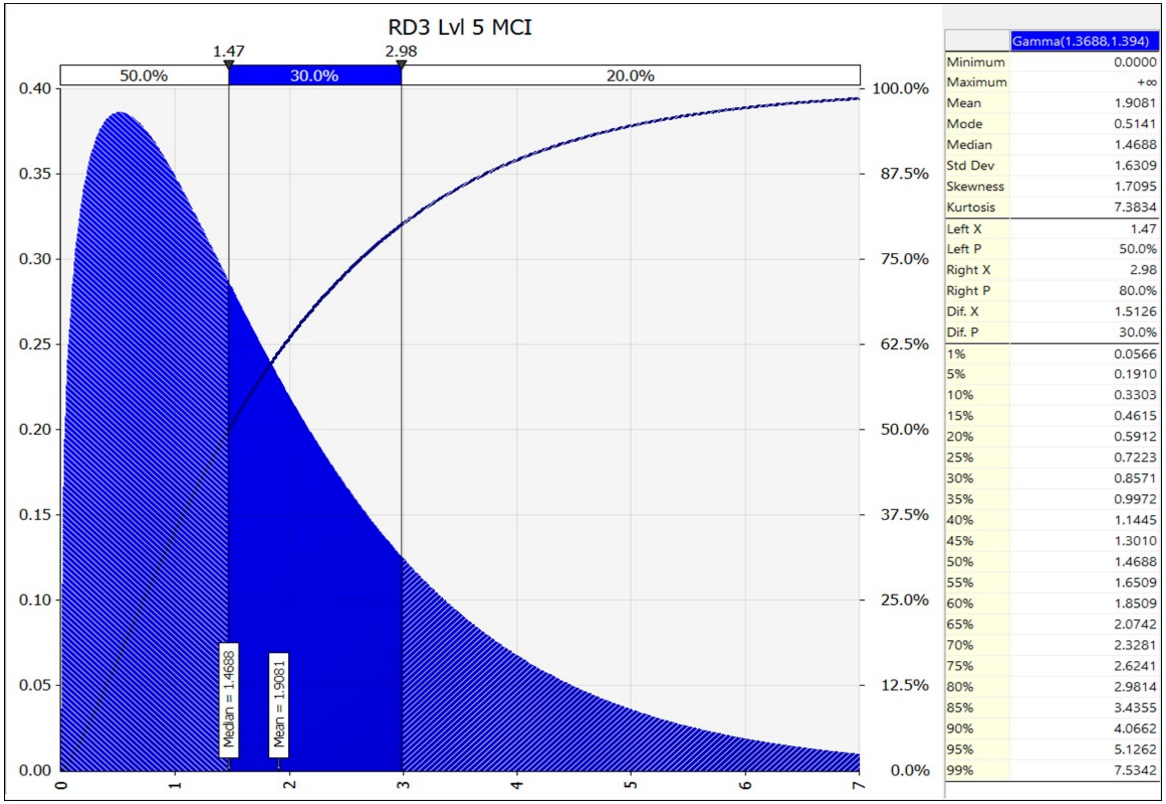
Mean, Median and Std Dev of Index values

RD^3 Mean Cost Index (MCI)			
RD3 Lvl	Mean	Median	Std Dev
1	0.4083	0.2352	0.4412
2	0.7759	0.3171	1.2473
3	1.0690	0.4770	2.6810
4	1.3620	0.6360	2.0470
5	1.9081	0.7929	1.7566

TA Mean Cost Index (MCI)				
No.	Technology Area (TA)	Mean	Median	Std Dev
1	Launch Propulsion Systems	1.0940	0.0333	4.6480
2	In-Space Propulsion Technologies	0.8300	0.0416	2.5320
3	Space Power and Energy Storage	0.7940	0.0296	5.0520
4	Robotics, Telerobotics, Autonomous Systems	0.9603	0.4905	1.5894
5	Communication and Navigation	0.3125	0.0360	0.8966
6	Human Health, Life Support, Habitation Systems	1.9740	0.5900	3.2410
7	Human Exploration Destination Systems	1.8098	0.9807	2.3102
8	Science Instruments, Observatories, Sensor System	0.3310	0.0344	1.4660
9	Entry, Descent, and Landing Systems	13.2360	0.9640	24.8020
10	Nanotechnology	0.1025	0.0149	0.2023
11	Modeling, Simulation, Information Tech	1.4730	0.0552	6.5440
12	Materials. Structures, Mechanical Systems, Mfg.	0.4390	0.0298	1.2510
13	Ground and Launch Systems Processing	1.8550	0.5010	4.6850
14	Thermal Management Systems	0.7125	0.0981	1.3793
15	Aeronautics	0.2186	0.0146	0.6291

RD³ MCI Uncertainty Probability Density Functions (PDFs) Curve Fits

RD³ Mean Cost Index (MCI)			
RD3 Lvl	**PDF Type**	**Function**	**@RISK PDF Formula**
1	Gamma	0.40831	=RiskGamma(0.59877,0.68192,RiskName("RD3 Lvl 1 MCI"))
2	Lognorm	0.84662	=RiskLognorm(0.84662,2.1681,RiskName("RD3 Lvl 2 MCI"))
3	Pearson6	1.06865	=RiskPearson6(1.1572,1.7721,0.71302,RiskName("RD3 Lvl 3 MCI"))
4	Gamma	1.36200	=RiskGamma(0.71451,1.9062,RiskName("RD3 Lvl 4 MCI"))
5	Gamma	1.90811	=RiskGamma(1.3688,1.394,RiskName("RD3 Lvl 5 MCI"))



RD³ uncertainty PDFs reflect Joint Agency Cost Schedule Risk and Uncertainty Handbook common cost uncertainty functions: lognormal, gamma, et.al.

Example Plot of MCI uncertainty curve fit for RD³ = 5 (gamma PDF). Substantially higher fidelity uncertainty models were produced by curve fits using larger datasets tailored to individual RD³ levels.

SHL-TIL-RD^3 Composite Model Mean Project Point Estimate Costs (FY19$)

Model No. (SHL / TIL / RD^3)	Mean Project Pt Estimate Cost (FY19$)	Model No. (SHL / TIL / RD^3)	Mean Project Pt Estimate Cost (FY19$)	Model No. (SHL / TIL / RD^3)	Mean Project Pt Estimate Cost (FY19$)
1/1/1	$ 598,201	1/3/1	$ 1,933,886	1/5/1	$ 70,977,471
1/1/2	$ 1,132,084	1/3/2	$ 3,659,842	1/5/2	$ 134,323,516
1/1/3	$ 1,566,194	1/3/3	$ 5,063,248	1/5/3	$ 185,831,291
1/1/4	$ 1,995,468	1/3/4	$ 6,451,023	1/5/4	$ 236,765,406
1/1/5	$ 2,795,560	1/3/5	$ 9,037,589	1/5/5	$ 331,697,555
2/1/1	$ 681,525	2/3/1	$ 2,081,537	2/5/1	$ 71,858,237
2/1/2	$ 1,289,774	2/3/2	$ 3,939,269	2/5/2	$ 135,990,350
2/1/3	$ 1,784,351	2/3/3	$ 5,449,824	2/5/3	$ 188,137,290
2/1/4	$ 2,273,421	2/3/4	$ 6,943,554	2/5/4	$ 239,703,451
2/1/5	$ 3,184,959	2/3/5	$ 9,727,604	2/5/5	$ 335,813,623
3/1/1	$ 1,088,950	3/3/1	$ 2,758,042	3/5/1	$ 75,601,387
3/1/2	$ 2,060,817	3/3/2	$ 5,219,541	3/5/2	$ 143,074,190
3/1/3	$ 2,851,059	3/3/3	$ 7,221,030	3/5/3	$ 197,937,504
3/1/4	$ 3,632,499	3/3/4	$ 9,200,227	3/5/4	$ 252,189,785
3/1/5	$ 5,088,966	3/3/5	$ 12,889,099	3/5/5	$ 353,306,409
4/1/1	$ 1,992,533	4/3/1	$ 4,115,944	4/5/1	$ 82,137,053
4/1/2	$ 3,770,831	4/3/2	$ 7,789,346	4/5/2	$ 155,442,814
4/1/3	$ 5,216,797	4/3/3	$ 10,776,253	4/5/3	$ 215,049,008
4/1/4	$ 6,646,658	4/3/4	$ 13,729,894	4/5/4	$ 273,991,345
4/1/5	$ 9,311,665	4/3/5	$ 19,234,956	4/5/5	$ 383,849,403
5/1/1	$ 82,440,208	5/3/1	$ 94,029,224	5/5/1	$ 279,927,608
5/1/2	$ 156,016,528	5/3/2	$ 177,948,522	5/5/2	$ 529,757,685
5/1/3	$ 215,842,718	5/3/3	$ 246,184,767	5/5/3	$ 732,898,881
5/1/4	$ 275,002,603	5/3/4	$ 313,661,041	5/5/4	$ 933,777,620
5/1/5	$ 385,266,128	5/3/5	$ 439,424,841	5/5/5	$ 1,308,179,939
1/2/1	$ 1,098,362	1/4/1	$ 6,284,160		
1/2/2	$ 2,078,629	1/4/2	$ 11,892,654		
1/2/3	$ 2,875,701	1/4/3	$ 16,453,018		

Partial table of 125 total SHL-TIL-RD^3 project configuration values available from research paper Appendix J Table J-1

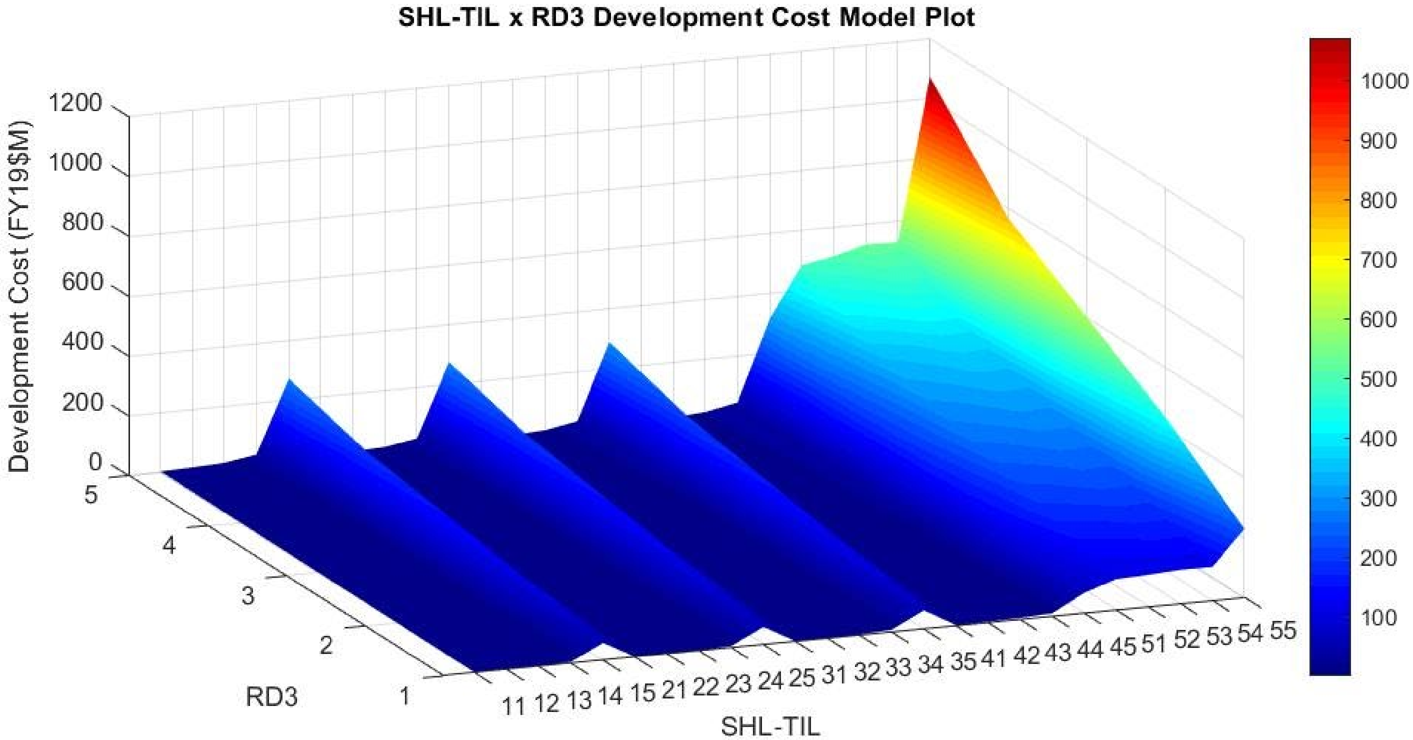
Estimating Methodology:

Three Parameter Models: *Table at left represents the expected mean point estimate costs (FY19$) for the 125 possible SHL-TIL-RD^3 three parameter models (250 possible SHL-TIL-TA model combinations were also produced). Cost uncertainty PDF output for each model were also generated by running* ***Monte Carlo simulation*** *of the product of SHL-TIL regression model output x the applicable RD^3 MCI PDF functions.*

Four Parameter Model: *To produce models including all four parameters, simply add another factor for the applicable TA MCI mean value of the product (e.g., SHL-TIL mean x RD^3 MCI x TA MCI). This results in 1,250 possible four parameter model variants (25 SHL-TIL x 5 RD^{3}s x 10 TAs). Similarly full output PDFs can be generated for each configuration using Monte Carlo simulation.*

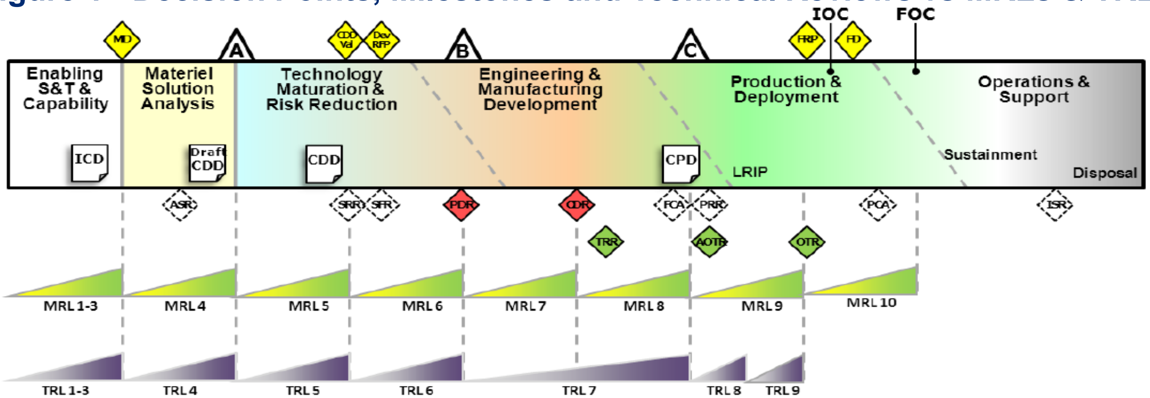
3D Plot of Development Cost vs SHL-TIL & RD^3

- Plot of the 125, 3-Parameter Project Pt. Estimates: SHL-TIL x RD^3
- SHL-TIL axis are the discrete 5 x 5 SHL-TIL combinations
- Functions produce a mesh grid but continuous contour topography is generated to show relative level of parameters across cost scale
- Similar plot can be produced for each viable TA



Standard Development Framework: Key Milestones, Activities and TRL / MRL Mapping

Figure 1 - Decision Points, Milestones and Technical Reviews vs MRLs & TRLs



References:

1. *Figure 1: Manufacturing Readiness Level (MRL) Deskbook, OSD 2016*
2. *Figures 2&3: The Effects of System Prototype Demonstrations on Weapon Systems-DAU Defense Acquisition Research Journal (ARJ)-Jan 2015*

FIGURE 2. LEVEL OF PROTOTYPE DEMONSTRATIONS, VENUE, AND TECHNOLOGY MATURITY

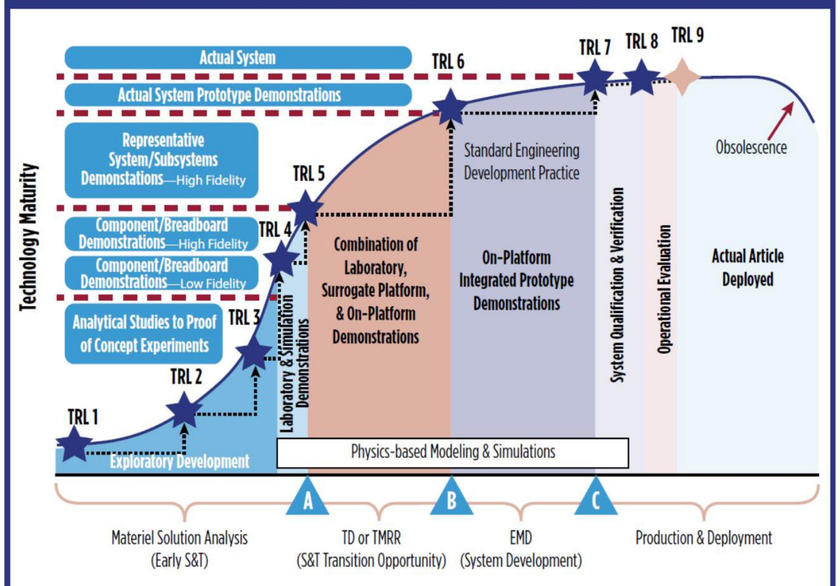


FIGURE 3. TECHNOLOGY READINESS LEVEL MAPPING TO PROTOTYPE DEMONSTRATION ATTRIBUTES

Demonstration Environment/Venue	TRL	State of Technology
Completed Operational Evaluation (Ready for Full-Rate P&D)	9	Actual System
Compliant, Qualified, & Test/Demo Complete (Ready for Operational Evaluation, OPEVAL)	8	Actual System
Demonstrated in Operational Environment (Ready for Limited Production Decision, MSC)	7	Actual System Prototype (Integrated, Fully Representative)
Demonstrated in Relevant Environment (Ready to Enter System Development, MSB)	6	System/Subsystem Model or Prototype (High-Fidelity Laboratory or Simulated Environment)
Validated in Relevant Environment (Ready to Enter Technology Development, TMRR)	5	Component and/or Breadboard (High-Fidelity Laboratory Integration)
Validation in Laboratory Environment (Ready to Begin Bridge for Technology Transition)	4	Component and/or Breadboard (Ad Hoc Laboratory Integration)
Analytical Validation & Proof of Concept (Start Active Research & Development, R&D)	3	Analytical & Experimental
Early Studies for Application Formulation (Invention & Practical Application Begins)	2	Conceptual Studies
Technology Research (Pure Science Begins Translation to R&D)	1	Basic Principles

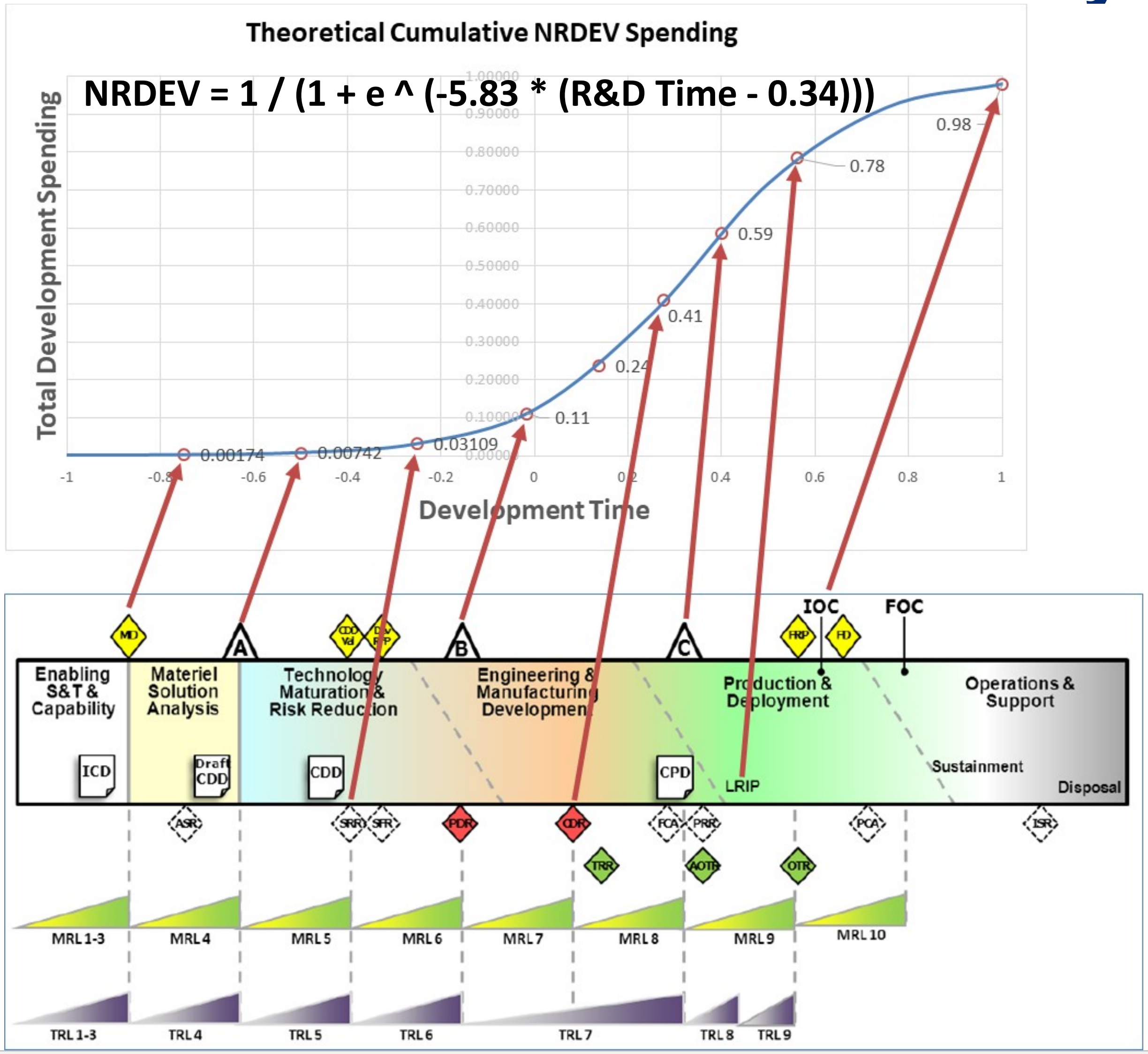
(DoD, 2009; DoD, 2011)

Standard Development Framework: General WBS vs Acquisition Milestones & TRLs / MRLs

Development WBS		Acquisition Phase	DoD Acq'n. Milestone	TRL	MRL
No.	Name				
1.1	Technology Development	Various			
1.1.1	Basic Research	Enabling S&T Capability	N/A	1	1
1.1.2	Technology Research	Enabling S&T Capability	CBA / ICD	2	2
1.1.3	Analytical Proof of Concept (PoC) Validation	Enabling S&T Capability	MDD	3	3
1.1.4	Validation in a Laboratory Environment (VLE)	Materiel Solution Analysis (MSA)	A	4	4
1.1.5	Validation in a Relevant Environment (VRE)	TMRR	VRE / SRR	5	5
1.1.6	Prototype Demo in Relevant Environment (DRE)	TMRR	B (PDR)	6	6
1.2	Systems Development	Various			
1.2.1	Systems Prototype Demo in Oper'l Environment (DOE)	Engineering and MFG Dvlp (EMD)	C	7	8
1.2.2	Full Scale Systems Dvlp. & Demonstration (SDD)	Prod'n & Deployment (P&D)	LRIP	8	8+
1.2.3	Operational Systems Evaluation (OPEval)	Prod'n & Deployment (P&D)	IOC (FRP)	9	9
1.2.4	Operational Systems Development	Operations & Support (O&S)	FOC	9+	10

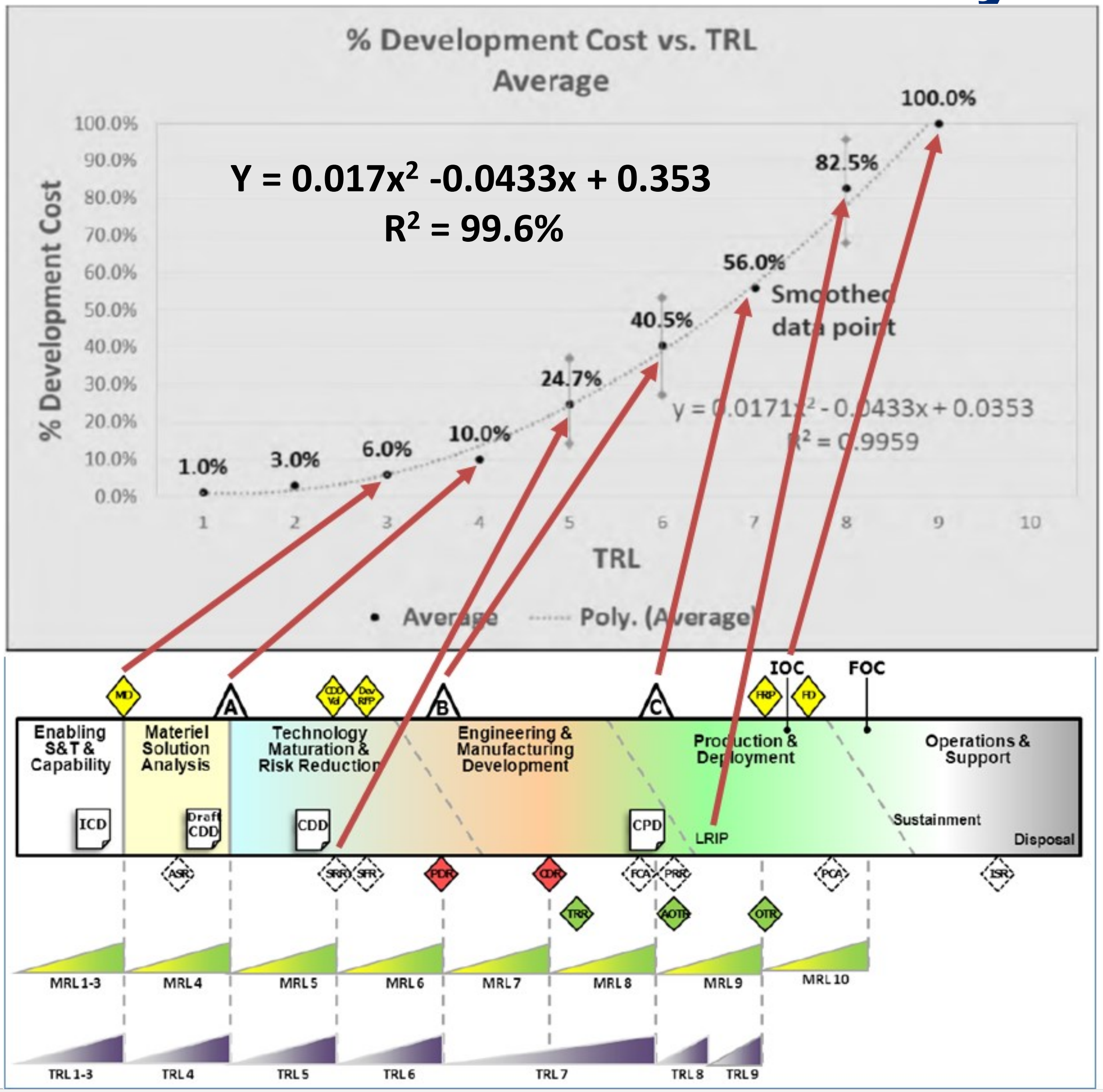
- Consensus of framework references from authoritative sources
  - Manufacturing Readiness Level (MRL) Deskbook – OSD
  - Defense ARJ - Defense Acquisition University (DAU)
  - RDT&E Budget Activity (BA) category definitions and outputs - DoD Comptroller
- Detailed 4 level WBS with data dictionary also developed (see backup slides and research paper)

Development Framework Cost Benchmarks vs Milestones & TRL / MRL - Study 1



Reference: Adapted from "Methodology to assess cost and schedule impact using System and Technology Readiness Level (SRL/TRL), Dr. Nate Sirirojvisuth, PRICE Systems, ICEAA SoCal Workshop, 2019 (Source Data: selected acquisition report (SAR) data from over 140 Major Defense Acquisition Programs (MDAP) programs)

Development Framework Cost Benchmarks vs Milestones & TRL / MRL - Study 2



Reference: Adapted from "Technology Development Level (TRL) vs. Percent Development Cost", Linick, James, BCF Solutions Inc., ICEAA Professional Development & Training Workshop, 2017 (Source data included cost information for programs in NASA's Resource Data Storage and Retrieval (REDSTAR) database)

Study 1 vs Study 2 Cost Benchmarks by Milestone and TRL / MRL

Milestone	Macro-parameter		Sirirojvisuth Study		Linick Analysis	
@ end	MRL	TRL	% Total Dvlp	Cum % Ttl Dvlp	% Total Dvlp	Cum % Ttl Dvlp
N/A	1	1	Negl.	Negl.	1.0%	1.0%
CBA / ICD	2	2	Negl.	Negl.	2.0%	3.0%
MDD	3	3	0.17%	0.17%	3.0%	6.0%
A	4	4	0.57%	0.74%	4.0%	10.0%
VRE / SRR	5	5	2.36%	3.10%	14.7%	24.7%
B (PDR)	6	6	8.0%	11.1%	15.8%	40.5%
Interm.	6+	6+	12.4%	23.5%	N/A	N/A
CDR	7	6++	17.2%	40.7%	N/A	N/A
C	8	7	17.7%	58.5%	15.5%	56.0%
LRIP	8+	8	20.0%	78.4%	26.5%	82.5%
IOC (FRP)	9	9	19.6%	97.9%	17.5%	100.0%

Study 1 vs Study 2 vs RDT&E BA Category Cost Benchmarks by Milestone and TRL / MRL

Tertiary Source: *DoD RDT&E expenditures by Budget Activity (BA): Twenty-three (23) years (FY1996 through FY2018) of actual OUSD - Comptroller / CFO RDT&E R-1 Budget Exhibit by BA from representing hundreds on programs normalized to CY$ and analyzed to create historical BA cost profiles)*

RDT&E Budget Activity (BA)		Milestone	TRL	Average % Development		
Code	BA Category	@ end	Notional @ End	Average	StdDev	CV
6.1	Basic Research	N/A	1	2.9%	0.5%	17.6%
6.2	Applied Research	MDD	3	7.7%	1.0%	12.5%
6.3	Advanced Technology Development (ATD)	VRE / SRR	5	9.4%	1.2%	12.7%
6.4	Advanced Component Development & Prototypes	B (PDR)	6	20.5%	1.6%	7.8%
6.5	System Development & Demonstration (SDD)	C	7	23.0%	3.0%	13.0%
6.7	Operational Systems Development	IOC (FRP)	9	36.5%	3.8%	10.5%
	Total Development			100.0%		

RDT&E Budget Activity (BA)		Milestone	TRL	RDT&E R-1 Exhibit BA Budgets	ICEAA / Linick Analysis	ICEAA / Sirirojvisuth Paper
Code	BA Category	@ end	Notional @ End	Cum % Dvlp Phase Cost	Cum % Dvlp Phase Cost	Cum % Dvlp Phase Cost
6.1	Basic Research	N/A	1	2.9%	1.0%	Negl.
6.2	Applied Research	MDD	3	10.6%	6.0%	0.2%
6.3	Advanced Technology Development (ATD)	VRE / SRR	5	20.0%	24.7%	3.1%
6.4	Advanced Component Development & Prototypes	B (PDR)	6	40.5%	40.5%	11.1%
6.5	System Development & Demonstration (SDD)	C	7	63.5%	56.0%	58.5%
6.7	Operational Systems Development	IOC (FRP)	9	100.0%	100.0%	97.9%

Analysis of Development Benchmark Cost Data

- RDT&E BA Cost data based on expansive, diverse sample of 23 yrs of DoD RDT&E projects (range of project size, complexity, difficulty)
- BCF / Linick Analysis produced similar results across Development milestones and TRLs / MRLs - data based on earlier Conrow and Lee research using augmented NASA REDSTAR[1] project data
- PRICE / Sirirojvisuth study diverged for TRLs 1-6: Project data based on MDAP ACAT 1 program SAR data
  - Smaller relative expenditures in early development may reflect economies of scale and greater risk sharing / aversion of large programs
  - Larger MDAP program SARs may not capture costs for broader use of government laboratory & testing operations w/ own funding available
  - Following TRL 6 cumulative development costs catchup and converge as technology development transitions into overall systems development
- Based on this assessment and general agreement with RDT&E BA benchmark costs, Linick analysis data applied for cost modeling

1. NASA's Resource Data Storage and Retrieval database (REDSTAR)

Adjust Monolithic TILs to Discrete TRL Start-End Transition Costs using % Weighting Factors

ICEAA Linick Cost benchmark transition data in upper table used to calculate the cost adjustment factors in the lower table (highlighted in green). Cost factors provide a method to adjust TIL costs for discrete TRL start to end transitions. This augments cost models to produce a project landscape of 9,000 potential project configurations: 36 TRL start-end states x 5 SHLs x 5 RD³s x 10 TA categories.

TRL_{End}	Cum % Dev. Cost	Percent Total Development Cost between TRL_{Start} and TRL_{End}							
	TIL =	1	2	3	4	5	6	7	8
1	1.0%								
2	3.0%	2.0%							
3	6.0%	3.0%	5.0%						
4	10.0%	4.0%	7.0%	9.0%					
5	24.7%	14.7%	18.7%	21.7%	23.7%				
6	40.5%	15.8%	30.5%	34.5%	37.5%	39.5%			
7	56.0%	15.5%	31.3%	46.0%	50.0%	53.0%	55.0%		
8	82.5%	26.5%	42.0%	57.8%	72.5%	76.5%	79.5%	81.5%	
9	100.0%	17.5%	44.0%	59.5%	75.3%	90.0%	94.0%	97.0%	99.0%
	TIL Average % =	**12.4%**	**25.5%**	**38.1%**	**51.8%**	**64.8%**	**76.2%**	**89.3%**	**99.0%**
	TIL =	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
TRL_{End}		**Relative Cost Adjustment Weighting to TI Level Average**							
1									
2		0.16			$TRL_{Start} = TRL_{End} - TIL$				
3		0.24	0.20						
4		0.32	0.27	0.24					
5		1.19	0.73	0.57	0.46				
6		1.28	1.20	0.91	0.72	0.61			
7		1.25	1.23	1.21	0.97	0.82	0.72		
8		2.14	1.65	1.52	1.40	1.18	1.04	0.91	
9		1.41	1.73	1.56	1.45	1.39	1.23	1.09	1.00
	TIL =	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**

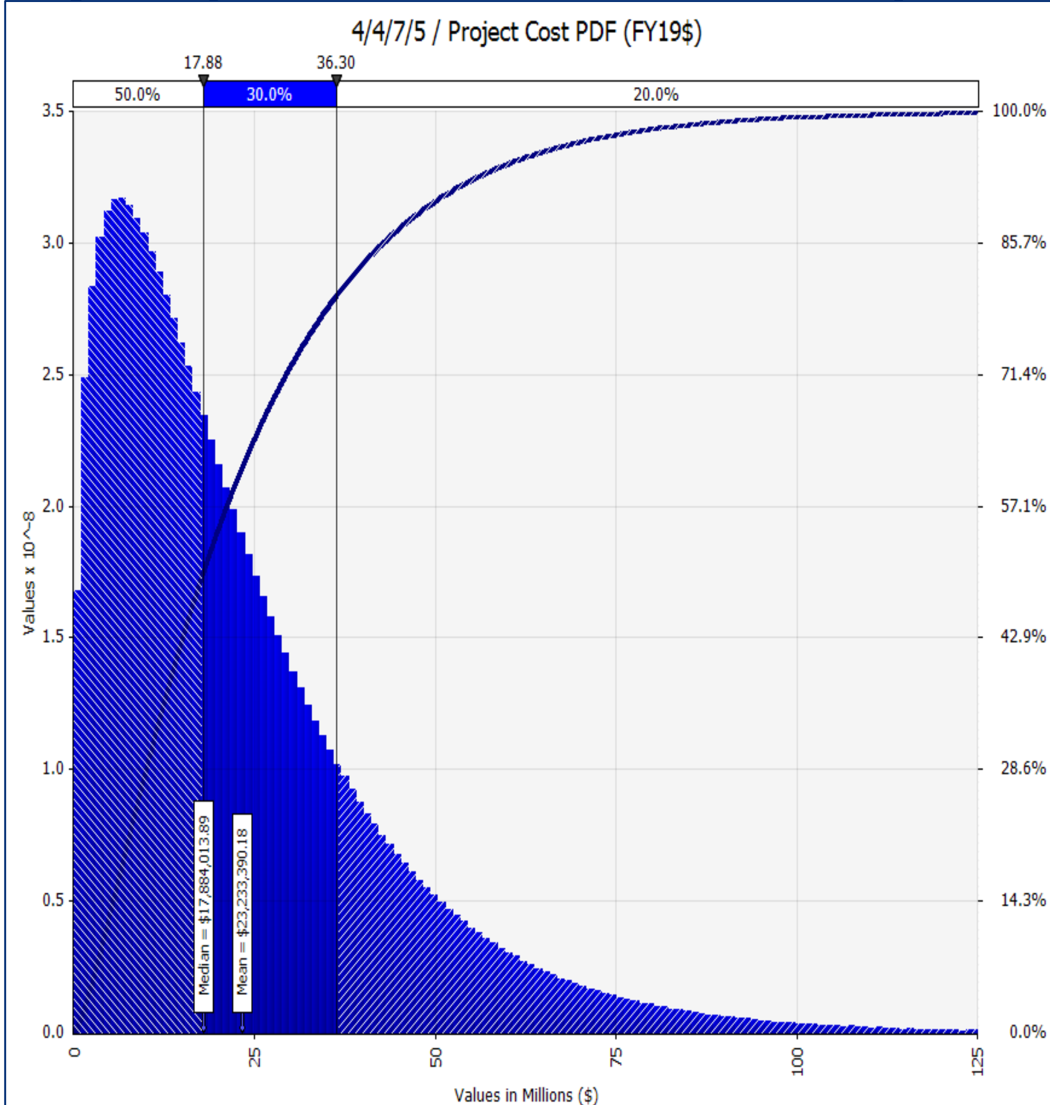
New Model Configurations and Fidelity

- Original First Generation Model Configurations:
  - 5 SHL x 5 TIL = 25
- New Second Generation Model Configurations:
  - 5 SHL x 36 $TRL_{S\text{-}E}$ transitions x 5 RD^3 x 10 TA = 9,000
- 360x Increase in Model Landscape Density = 9,000 / 25
  - 5 RD^3 MCI Range – 0.41 to 1.91
  - 10 TA MCI Range – 0.44 to 1.97
  - 36 $TRL_{S\text{-}E}$ transitions range – 0.16 to 2.14 of TIL transition costs
  - Combined refinement of max range = ~ 3% (product of lows) to ~ 800% (8x) (product of highs) the original SHL-TIL model results providing much greater estimate focus / tailoring

Project Cost Estimate PDF – 3 Parameter Model Example (SHL / TILs-e / RD3)

Project Cost Output Uncertainty PDF for Project Configuration # 4/4/7/5:

- SHL = 4
- TRL $_{Start}$ = 4
- TRL $_{End}$ = 7 (TIL = 7 - 4 = 3)
- RD ^{3} = 5

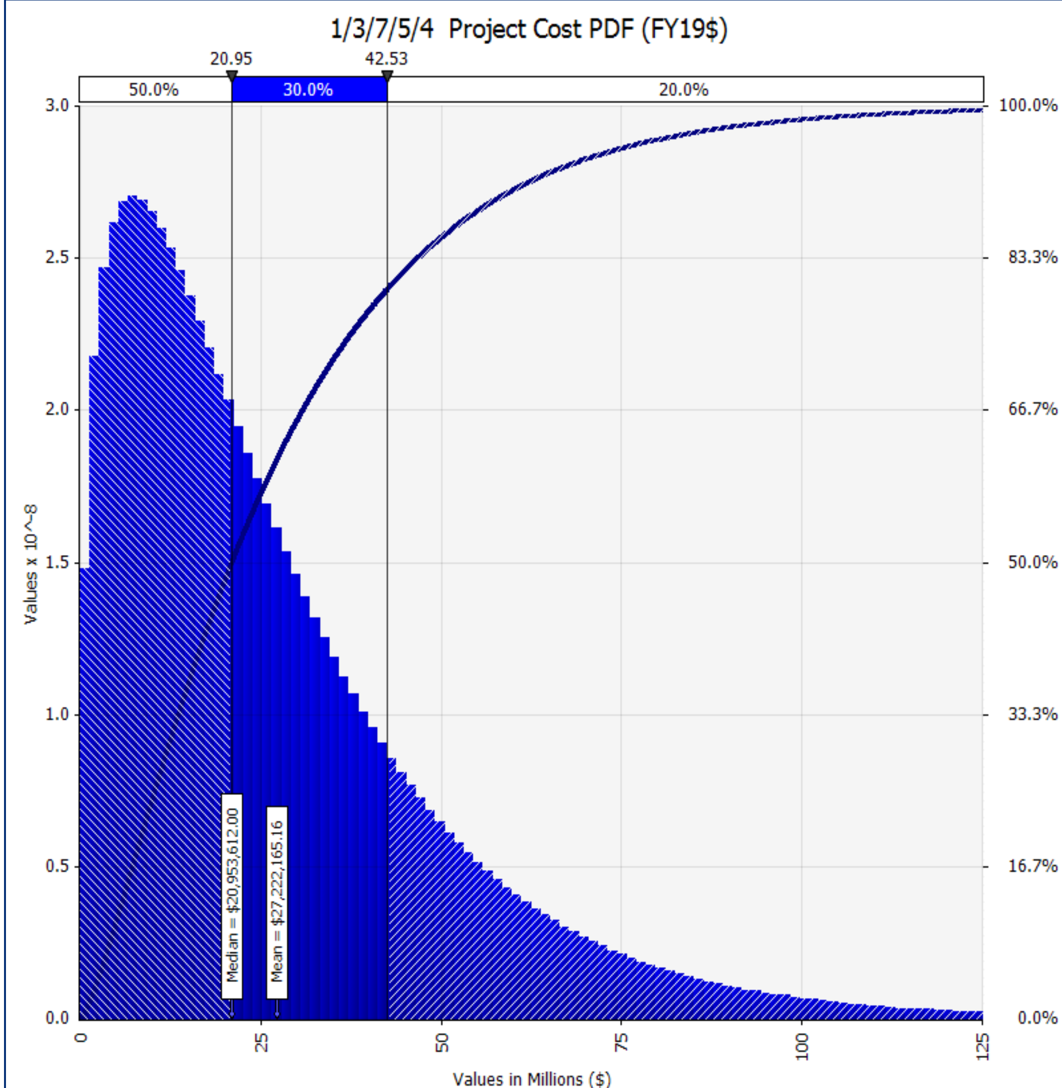


	16584016.401
Cell	RD3 Cost Models!N71
Minimum	$6,739.42
Maximum	$205,860,084.42
Mean	$23,233,390.18
90% CI	± $146,068.56
Mode	$6,408,521.02
Median	$17,884,013.89
Std Dev	$19,856,671.43
Skewness	1.7067
Kurtosis	7.3381
Values	50000
Errors	0
Filtered	0
Left X	$17,884,013.89
Left P	50.0%
Right X	$36,301,281.59
Right P	80.0%
Dif. X	$18,417,267.70
Dif. P	30.0%
1%	$689,071.21
5%	$2,325,994.32
10%	$4,021,760.96
15%	$5,619,308.47
20%	$7,198,086.71
25%	$8,794,420.27
30%	$10,435,319.29
35%	$12,142,284.40
40%	$13,935,734.58
45%	$15,840,402.05
50%	$17,884,013.89
55%	$20,101,073.50
60%	$22,536,900.51
65%	$25,255,584.01
70%	$28,347,565.98
75%	$31,951,060.77
80%	$36,301,281.59
85%	$41,829,692.30
90%	$49,508,556.20
95%	$62,417,222.44
99%	$91,707,898.79

Project Cost Estimate PDF – 4 Parameter Model Example (SHL / TILs-e / RD3 / TA)

Project Cost Output Uncertainty PDF for Project Configuration # 1/3/7/5/4:

- SHL = 1
- TRL $_{Start}$ = 3
- TRL $_{End}$ = 7 (TIL = 7 - 3 = 4)
- RD^3 = 5 and
- TA = 4 (Robotics & Autonomous Systems)



	1/3/7/5/4 Project Cost PDF (FY19$)
Cell	RD3 Cost Models!Q81
Minimum	$7,412.56
Maximum	$265,944,812.20
Mean	$27,222,165.16
90% CI	± $171,180.74
Mode	$7,508,584.92
Median	$20,953,612.00
Std Dev	$23,270,440.58
Skewness	1.7121
Kurtosis	7.4186
Values	50000
Errors	0
Filtered	0
Left X	$20,953,612.00
Left P	50.0%
Right X	$42,532,402.68
Right P	80.0%
Dif. X	$21,578,790.67
Dif. P	30.0%
1%	$807,383.73
5%	$2,724,636.57
10%	$4,711,686.60
15%	$6,584,173.67
20%	$8,433,727.76
25%	$10,304,289.80
30%	$12,226,864.20
35%	$14,226,605.84
40%	$16,327,817.04
45%	$18,560,038.96
50%	$20,953,612.00
55%	$23,551,190.23
60%	$26,405,612.39
65%	$29,591,299.44
70%	$33,212,452.12
75%	$37,435,584.41
80%	$42,532,402.68
85%	$49,011,825.21
90%	$58,005,891.29
95%	$73,127,540.29
99%	$107,460,563.28

Summary: Vastly Improved Technology and System Development Cost Estimating Capabilities

- Methodologies produce more robust cost estimating capability for conceptual phase Development
  - Refines cost models reflecting more comprehensive set of key cost drivers: scale; maturity; system complexity; technology form / function, development difficulty, and level of integration
  - Expands parametric project landscape from limited 25 point 2D grid to 9,000 point 4D high-resolution topography (5 SHLs x 36 TRL start-end states x 5 RD^{3}s x 10 TAs)
  - Improved Development cost uncertainty models tailored to much larger project populations
- Standard Development Framework with integral Cost Benchmarks provides further capabilities:
  - Forecast / track investment Development phase costs across integrated milestones, activities and readiness levels (TRL / MRL / SRL)
  - Cost factors generated fine-tune unitary TIL costs to discrete TRL start and end states

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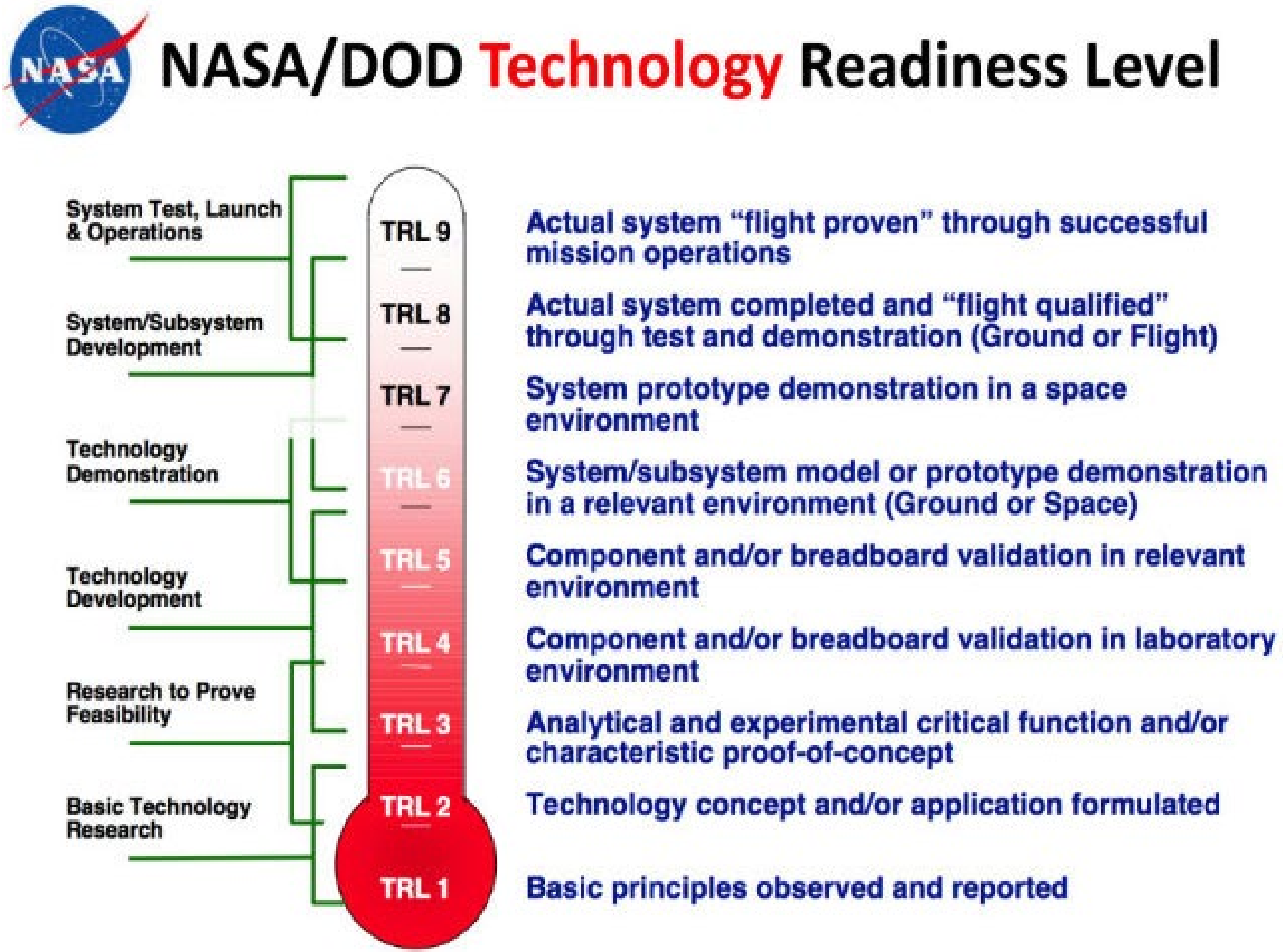
chuck.alexander@jhuapl.edu

System Hierarchy Level (SHL)

System Hierarchy Table		
No.	**Tier**	**Definition**
5	System	An integrated set of constituent elements that are combined in an operational or support environment to accomplish a defined objective
4	Subsystem	A portion of a system
3	Assembly	A set of components (as a unit) before they are installed to make a final product
2	Component / Part	A portion of an assembly
1	Hardware / Material	An item or substance used to form a component

Source: Note: Adapted from NASA TCASE Training Guide and User Manual. - numbers in the first column are inverted from the original table to correspond to the progressive ordinal numbers necessary to perform the analysis.

Technology Readiness Levels (TRL)

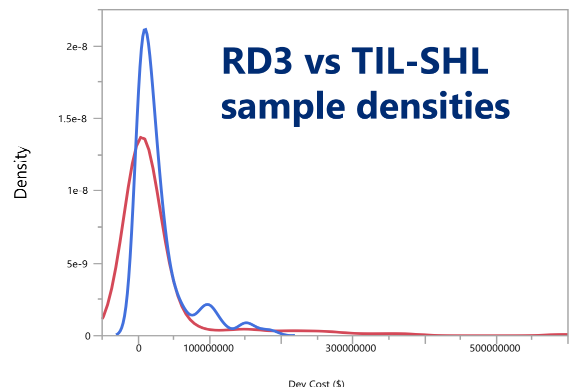


Reference: Technology Estimating: A Process to Determine the Cost and Schedule of Space Technology Research and Development - Dec 2013, Cole, Greenberg, Comstock, Schaffer

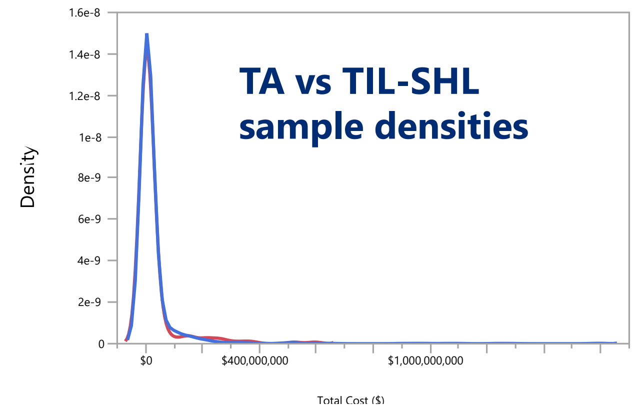
Mean Cost Index (MCI) Method Sample Equivalence Testing

Adjust SHL-TIL Model Results based on RD^3 and TA MCI Factors

- Perform equivalence tests to demonstrate and validate sample equivalence between RD3 and TA samples and the TIL-SHL sample project mean cost data
- Two common Equivalence tests were conducted to demonstrate sample equivalence: the two one-sided test (TOST) and the Aspin-Welch test[1]
- Results demonstrated equivalent project cost data can be established via means translations (i.e., factor of the sample means)



Sample means showed only a 0.25% variance between the TIL-SHL vs RD^3 trimmed samples and 1.4% for the TIL-SHL vs TA trimmed samples (w/o outliers)



1. *The TOST equivalence test can be used to validate the equivalence of the means of two groups by demonstrating they do not differ by more than a specified margin. When the sample sizes and variances of two groups are unequal (nonparametric), such as with the TIL-SHL, RD^3 and TA data samples being compared, Welch's t-test for unequal variance (also known as the Satterwaite's test, or Aspin-Welch test, or the unequal variances t-test) is commonly utilized to test sample equivalence (Equivalence Tests: A Practical Primer for t Tests, Correlations, and Meta-Analyses, Lakens D. 2017).*

Detailed Standard Development Framework WBS

WBS #	WBS Name	WBS Description *(Note: general WBS guidance only and not intended as prescriptive, tailor WBS to system architecture and project requirements)*
1.0	**DEVELOPMENT**	Technology and Systems Development advancing and transitioning technology from conceptual scientific investigation through full systems development and demonstration in an operational environment to Full Operational Capability (FOC).
1.1	**Technology Development**	Proof of concept (PoC) or feasibility demonstration in simulation and laboratory environment
1.1.1	**Basic Research**	Basic research is systematic study directed toward greater knowledge or understanding of the fundamental aspects of phenomena and of
1.1.2	**Technology Research**	Incubation stage scientific investigation with translation to basic principles & early exploratory development during pre-material solution analys
1.1.3	**Analytical Proof of Concept (PoC) Validation**	Analytical PoC or feasibility demonstrated in a simulated environment establishing initial practicality of proposed solutions to technological req
1.1.3.1	Development NRE	Development non-recurring Systems Engineering (NRE) including security considerations
1.1.3.2	Systems Hardware	Systems hardware development, modifications or purchases (COTS), needed for this phase of demonstration
1.1.3.3	Systems Software	Systems software development, modifications or purchases (COTS), needed for this phase of demonstration
1.1.3.4	Systems Integration	System integration activities including internal and external interfaces needed for this phase of demonstration
1.1.3.5	Testing	Testing including any applicable test labor, equip, labs/ranges, or platform costs and certification req'ts etc. needed for this phase of
1.1.3.6	Project Management (PM)	Project planning, management and oversight activities
1.1.3.7	Support Services	Other support services may include logistics support, configuration management, facilities, IT, security, etc.
1.1.3.8	Other Direct Costs (ODCs)	ODCs may include applicable subcontract services, network / communications costs, travel, etc.
1.1.4	**Validation in a Laboratory Environment (VLE)**	Component or breadboard validation or ad hoc demonstration testing in a laboratory environment (VLE)
1.1.4.1	Development NRE	Development non-recurring Systems Engineering (NRE) including security considerations
1.1.4.2	Systems Hardware	Systems hardware development, modifications or purchases (COTS), needed for this phase of demonstration
1.1.4.3	Systems Software	Systems software development, modifications or purchases (COTS), needed for this phase of demonstration
...	...	...
1.1.5	**Validation in a Relevant Environment (VRE)**	Component or breadboard high fidelity proof of concept validation or demonstration in a laboratory or relevant environment (VRE) (around SRR)
1.1.5.1	Development NRE	Development non-recurring Systems Engineering (NRE) including security considerations
1.1.5.2	Systems Hardware	Systems hardware development, modifications or purchases (COTS), needed for this phase of demonstration
1.1.5.3	Systems Software	Systems software development, modifications or purchases (COTS), needed for this phase of demonstration
...	...	...
1.1.6	**Prototype Demo in Relevant Environment (DRE)**	Prototype system/subsystem technology design, integration build, test and checkout for Demonstration a Relevant Environment (DRE)
1.1.6.1	Prototype System Design	Design of Prototype architecture functional product breakdown of primary HW, SW and all internal and external interfaces
1.1.6.2	Vendor NRE	Vendor non-recurring systems engineering (NRE)
1.1.6.3	Prototype System Build(s)	Build of Prototype architecture functional product breakdown of primary HW, SW and all internal and external interfaces
1.1.6.4	Support Platform(s) / Systems Modification Design	Platforms like sea/air/land/space assets and comms. systems that require modifications to support Conops
1.1.6.5	System Integration, Assembly, Test and Checkout (IA	Prototype Integration, Assembly, Test and Checkout (IAT&C)
1.1.6.6	Systems Data	Prototype data & doc'n including vendor system specs, drawings/diagrams and Opns manuals as well as gov't purchase of intellectual data proper
1.2	**Systems Development**	Advancing technology from Prototype to full scale system functional integration, test and demonstration with operational system through IOC
1.2.1	**Systems Prototype Demo in Oper'l Environment (DOE**	Systems Prototype Demo in Oper'l Environment
1.2.2	**Full Scale Systems Dvlp. & Demonstration (SDD)**	System Test and Evaluation (T&E) - functional or operational system test and demonstration
1.2.2.1	Full Scale System (FSS) Design	Design of full scale architecture functional product breakdown of primary HW, SW and all internal and external interfaces
1.2.2.2	FSS Vendor NRE	Vendor non-recurring systems engineering (NRE)
1.2.2.3	FSS LRIP Build(s)	Build of low rate initial production (LRIP) full scale systems including primary HW, SW and all internal and external interfaces
1.2.2.4	FSS Support Platform(s) / Systems Modification Desi	Platform modification and integration design and including sea/air/land/space assets and C3I systems to support Conops
1.2.2.5	FSS Integration, Assembly, Test and Checkout (IAT&	Full Scale System Integration, Assembly, Test and Checkout (IAT&C)
1.2.2.6	FSS Data	FSS data & doc'n including vendor system specs, drawings/diagrams and opns manuals as well as gov't purchase of intellectual data property righ
1.2.2.7	FSS Test Labor	Government (Military and Civilian) and Contractor personnel to plan and perform the operational system field tests
1.2.2.8	FSS Test Equipment	Procurement or lease of all necessary FSS test equipment
1.2.2.9	FSS Test Support Organizations and Ranges	Costs for use of all test facilities, labs, ranges and associated ODCs
1.2.2.10	FSS Test Platforms	Procurement, lease or usage fees for test support platforms including sea/air/land/space assets and C3I systems that are part of the operational
1.2.2.11	FSS Pre-Test Certification	Costs associated with certification / approval to integrate development systems with operational systems for testing
1.2.2.12	FSS Demonstration Test	System T&E / demonstration testing
1.2.2.13	Project Management	Project planning, management and oversight activities
1.2.3	**Operational Systems Evaluation (OPEval)**	Full system operational evaluation (OPEval) through full rate production (RFP) approval, concluding with initial operational capability (IOC)
1.2.4	**Operational Systems Development**	Development efforts such as engineering or design modifications to resolve manufacturing or production issues for fielded systems up to FOC

Acquisition Milestone and Development Process Acronyms

ACRONYMS	
CDR	Critical Design Review
DOE	Demonstrated in an Operational Environment
DRE	Demonstrated in a Relevant Environment
EMD	Engineering and Manufacturing Development
FOC	Full Operational Capability
FRP	Full Rate Production
IOC	Initial Operating Capability
LRIP	Low Rate Initial Production
MDD	Materiel Development Decision
MSA	Materiel Solution Analysis
OPEval	Operational Evaluation
OT&E	Operational Test and Evaluation
P&D	Production & Deployment
PDR	Preliminary Design Review
PoC	Proof of Concept
S&T	Science and Technology
SRR	System Requirements Review
T&E	Test and Evaluation
TMMR	Technology Maturation and Risk Reduction
VLE	Validation in a Laboratory Environment
VRE	Validation in a Relevant Environment