Air Force Reusable Booster System A Quick-look, Design Focused Modeling and Cost Analysis Study

Edgar Zapata
NASA Kennedy Space Center
12/05/11

2011 Joint Army Navy NASA Air Force -"JANNAF"- Conference
Huntsville, AL

Acknowledgements

- The author gratefully acknowledges the support and feedback of:
  - Jason Mossman, Senior Aerospace Engineer, Applications and Assessments Branch, Propulsion Directorate, Air Force Research Lab, Edwards Air Force Base, California.
  - Greg Moster, Aerospace Engineer, Air Force Research Lab, Wright-Patterson Air Force Base, Ohio.
  - Carey McCleskey, NASA Kennedy Space Center, Engineering & Technology Directorate.

About the Author

- 1988-2000 NASA Kennedy Space Center Shuttle Operations
  - Engineer, ET flight hardware fluids/propulsion, LOX facilities incl. mobile launcher, shuttle load & launch.
- 1995-2000 Advanced Projects, Modeling & Simulation, and Program Analysis
  - Providing a KSC ground operations perspective to future space transportation programs.
- Support to numerous future space transportation system studies and projects since the mid-90’s. Most recently-
  - 2005 NASA Exploration Systems Architecture Study.
  - 2006-2010 Constellation Standing Review Boards.
  - 2009 NASA Programmatic Risk Assessment team in support of the 2009 Presidentially Appointed Review of Human Space Flight Plans Committee.
  - 2011 Human-spaceflight Architecture Team (HAT), Propellant Depot Study Team, cost analysis lead.

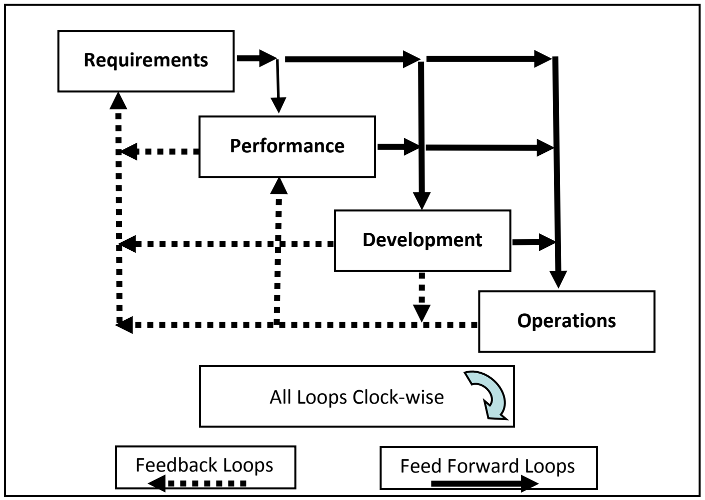
Cost Study Goals

- Support US launch systems decision makers, esp. in regards to the research, technology and demonstration investments required for reusable systems to succeed.
- Encourage operable directions in Reusable Booster / Launch Vehicle Systems technology choices, system design and product and process developments.
- Perform a quick-look cost study, while developing a cost model for more refined future analysis.
  - Better understand the relationships and drivers between design choices, costs, and between elements.
  - Comprehensiveness. Consistency. Explore drivers & sensitivities.
  - Identify cross-over points for useful comparisons between RBS systems and existing expendable launch systems.

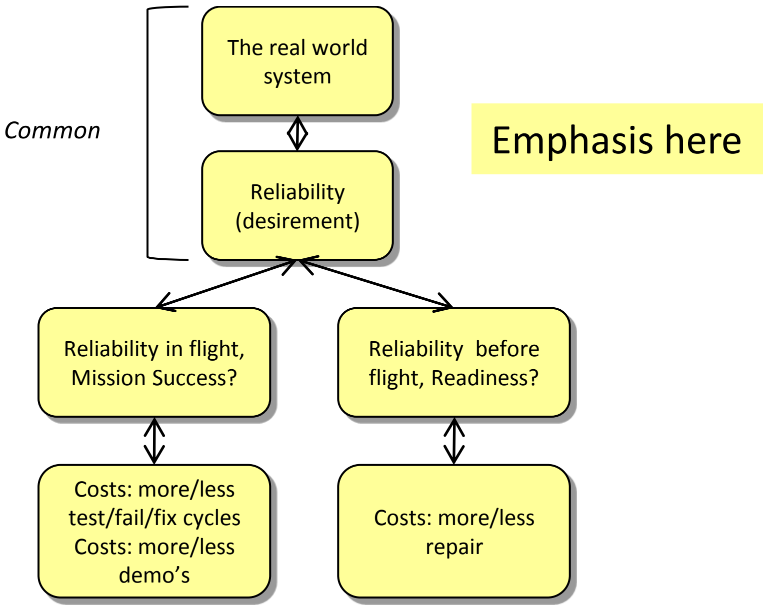
Cost Study Approach

- Focus on methodology.
- Examine RBS in a range of potential cost scenarios, across a range of potential design choices.
- Akin to a sensitivity analysis on the dials and knobs of a model, with the model representing the choices and tangible actions that exist in the real world.

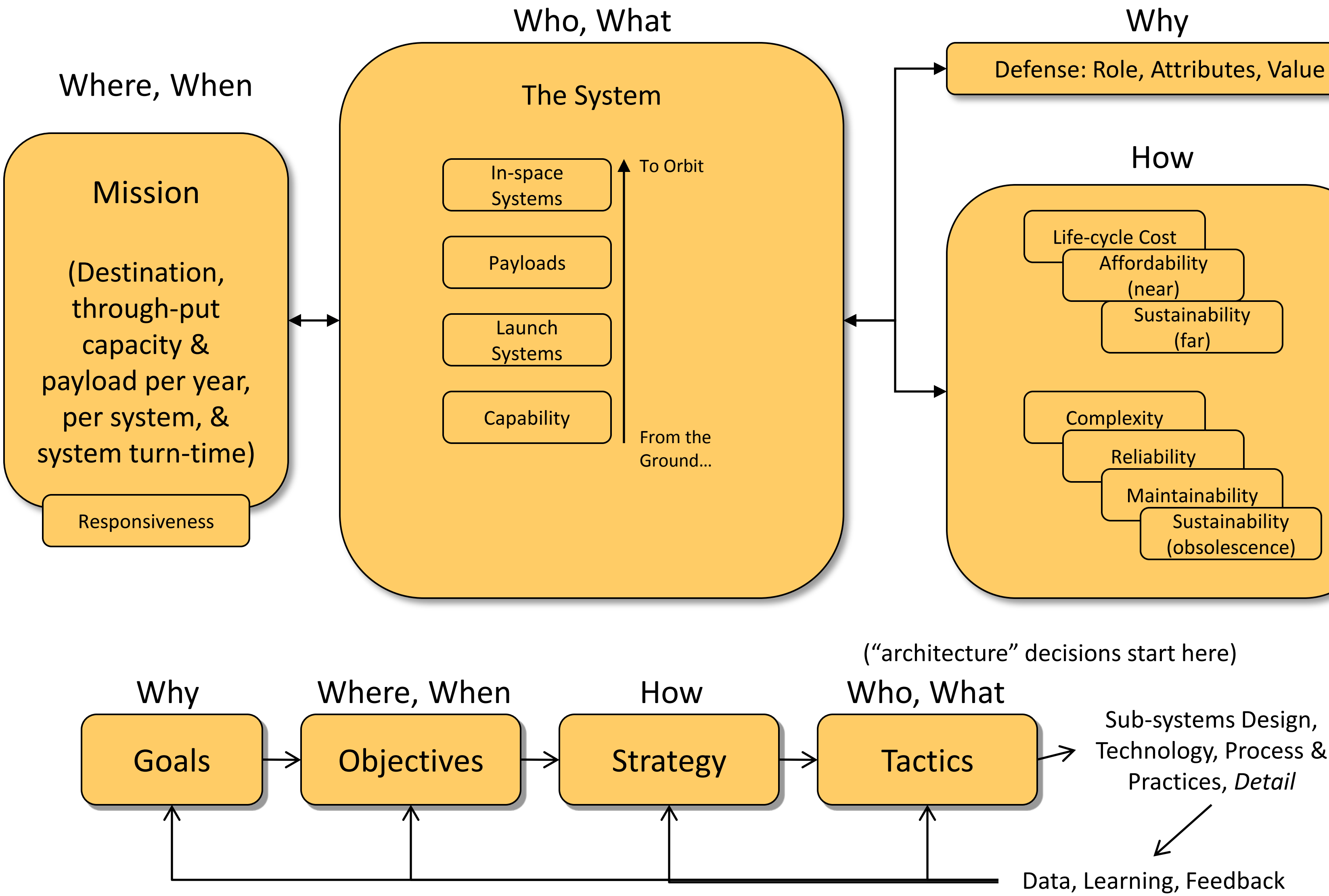
Example, traditional design structure matrix (DSM), dog-in-sled vantage point



Alternate view, analysts see the system from a common vantage point



Information Structure



Scope of the System

Legend:
- Estimate or Other
- Sensitivity or Off-line Estimate
- Analysis Output
- Not Included in this Phase of Analysis

Performing Organizations: †"Blue-Suitors" & *Contractor & Other Support Personnel

Non-recurring Costs
(Design, Development, Test & Engineering (DDT&E) thru 1st unit; establish production capability, "develop the capability")

- †*R&D and Demonstrations
- †*Ground Operations - Capability Development
- In-space Operations - Capability Development

Design, develop, acquire & activate
-Facilities
-Ground Support Equipment
-Organizational processes and practices
-Training, procedures, etc

- RBS Flight System +Engine

Includes initial fleet, parts, etc

- Payloads
- Upper Stage Flight System

Could be existing, with one-time modifications

- •Cost per Year across a Flight Rate
- •Fixed Costs to Keep
- •Variable Costs to Use
- •Responsiveness (TBD metric)
- •Sustainability (TBD metric)
- •Flight Rate "required" (TBD definition)
- •Others?

Recurring Costs
(Production, operations, launches, missions, "use the capability")

- †Ground Operations (the "logistics" of it)

All labor & material for
-End-to-end (hands-on thru support functions)
-Facilities
-Ground Support Equipment
-Vehicle (incl. spares, parts)

- In-space Operations
- RBS Flight System +Engine

Replacement production (losses, end of design life, obsolescence, etc)

- Payloads - Preparation & Integration
- Upper Stage Flight System

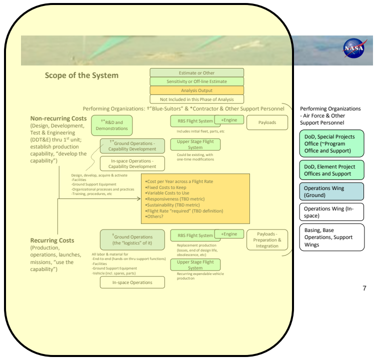
Recurring expendable vehicle production

Performing Organizations - Air Force & Other Support Personnel

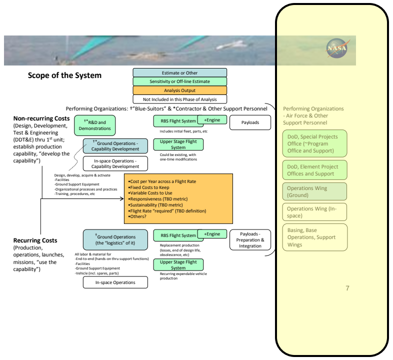
- DoD, Special Projects Office (~Program Office and Support)
- DoD, Element Project Offices and Support
- Operations Wing (Ground)
- Operations Wing (In-space)
- Basing, Base Operations, Support Wings

Functional Definition – Performing Organizations

- Contractor & Other Support Personnel
  - Includes “Fee” & “Contingency”
  - Excludes “Program Support” & “Vehicle Level Integration” (or equivalent, as applicable)
    - Will be book-kept instead under Air Force & Other Support Personnel, within DoD, Element Project Offices & Support

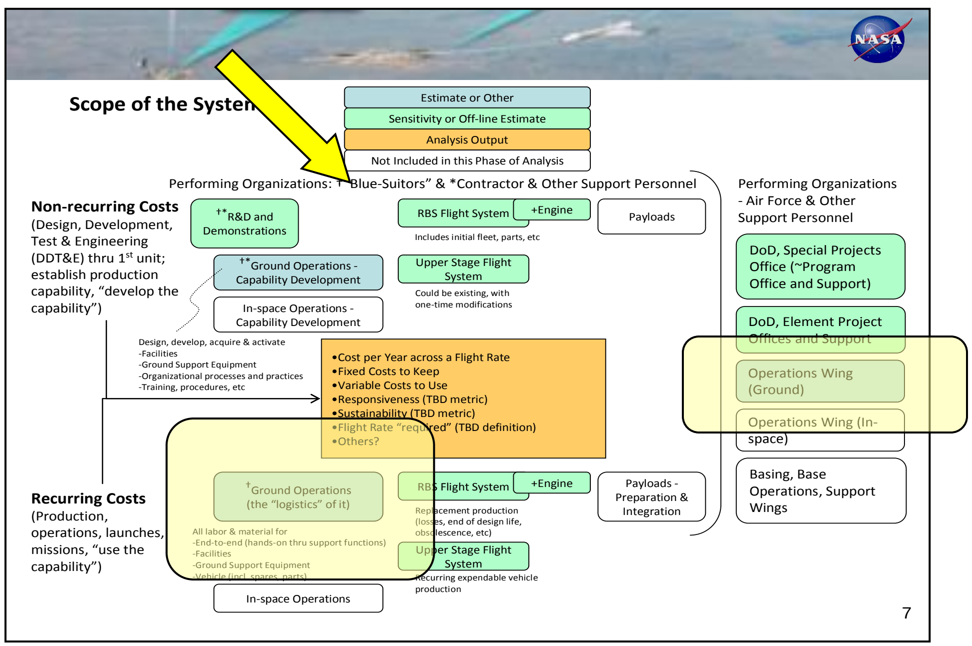


- Air Force & Other Support Personnel
  - The levels of management responsible for the development through acquisition of the system.
    - Integration across elements, across phases, development through operation.
    - Management of each element.
    - Managing the operation of the system.



Functional Definition – Performing Organizations

- "Blue-Suiters"
  - Concept of Operations would use Air force personnel in both the recurring operations, as well as in the project and program functions.
  - Initial labor estimation is agnostic to the organizational designation.



Modeling

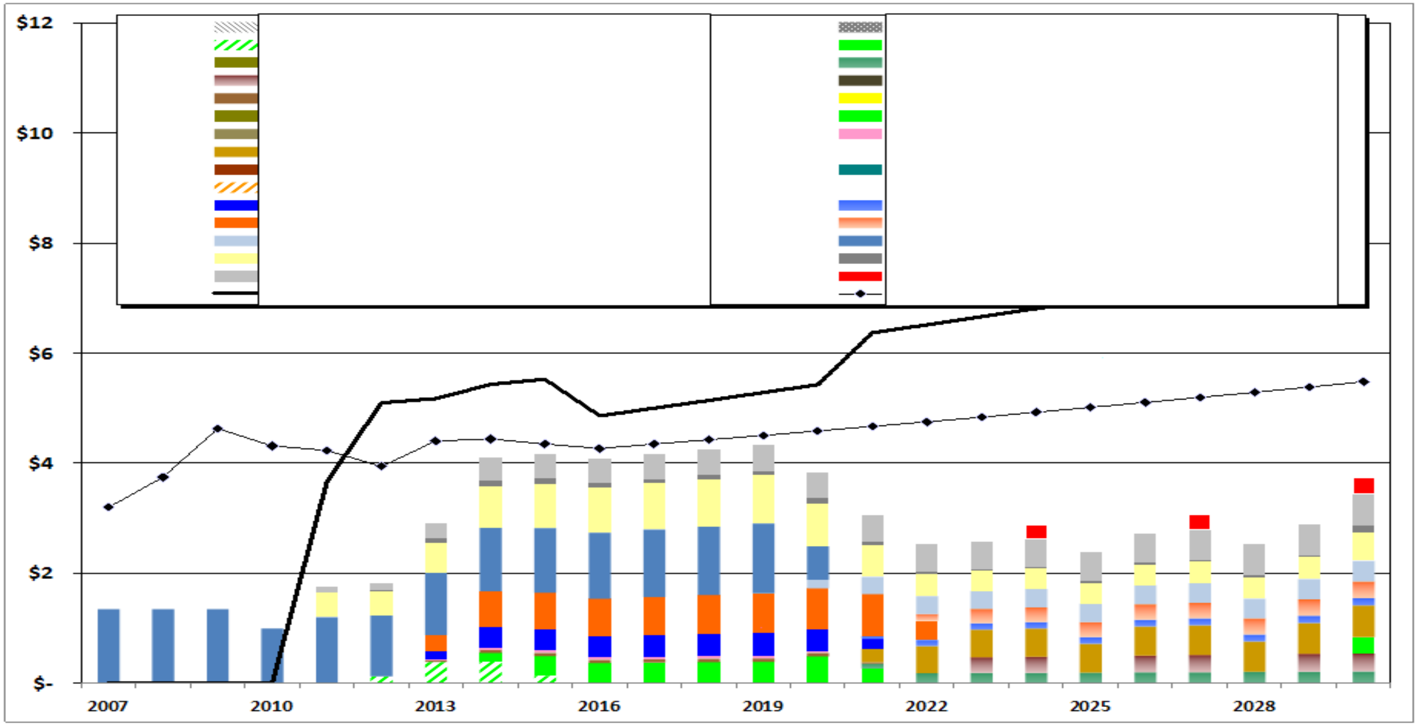
- Why Models?
  - Have developed and used numerous space transportation system cost models since the late 1990’s.
  - NASA now has a standard for models and simulations (Ref, Ref).
  - The DoD has it’s High Level Architecture with a focus on simulation interoperability
    - Emphasis on playing well with others, once your simulation is working.

Modeling

- Why Models?
  - A model is a *very elaborate* thought experiment.
  - The experiment should be informed and made more “real” by having some basis in real world experience.
    - Either real data, as part of the models basis of calculations, or outputs that stand up to sanity checks.
  - The goal is usually to be more informative than just a series of guesses.
  - Getting real world data into a model, and getting outputs that “make sense”, all without excessive forcing, calibration, or assumptions (those guesses again) leads to a model that’s useful in figuring out how the real world thing of interest might behave when acted upon.

Model Candidates - Life-Cycle Cost / Budget Models

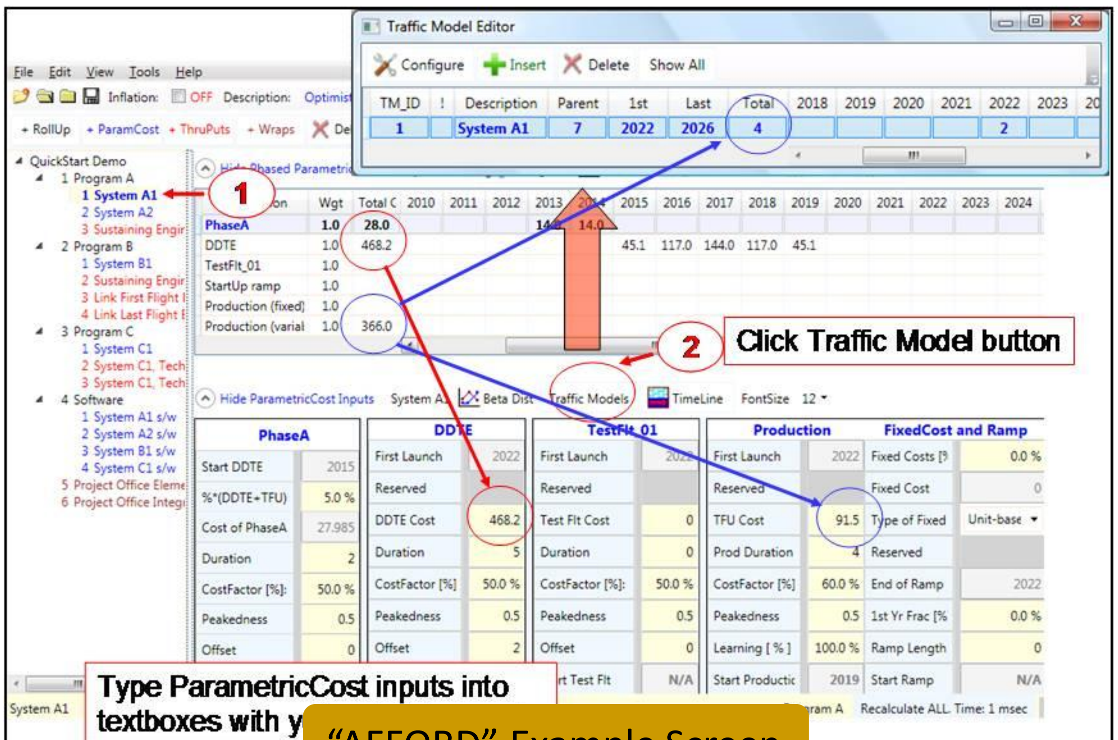
- Architectural, comprehensive, long term.
- Scalable, flexible, nimble, MS-Excel; adept in “what-if” phase.
- Methods easily ported and modified to new applications.



Budget Modeling Life-Cycle Output vs. a Target Resource Goal

Model Candidates - “AFFORD”

- Cost Tool “AFFORD” developed by NASA Langley Research Center
  - Similar to prior – but <u>not</u> MS Excel.
  - More capable as regards building-up estimates and the treatment of details, but learning curve required; possibly less nimble.

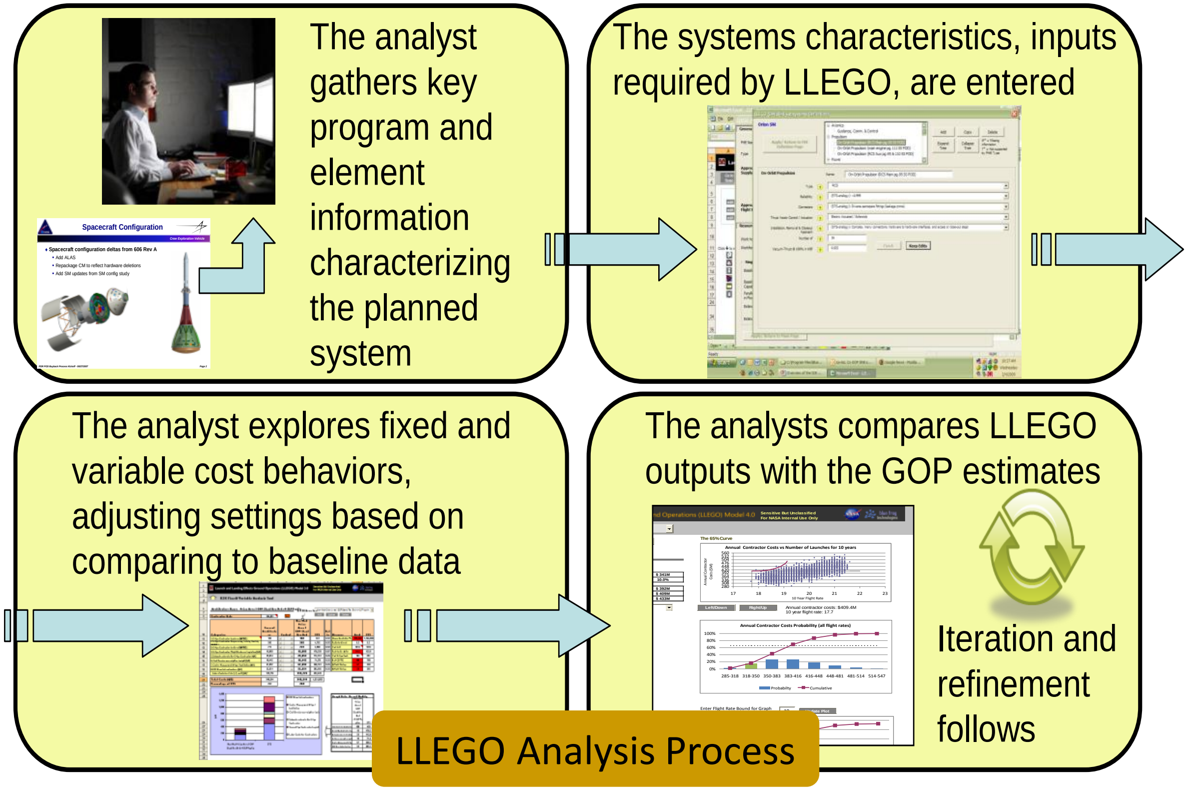


“AFFORD” Example Screen

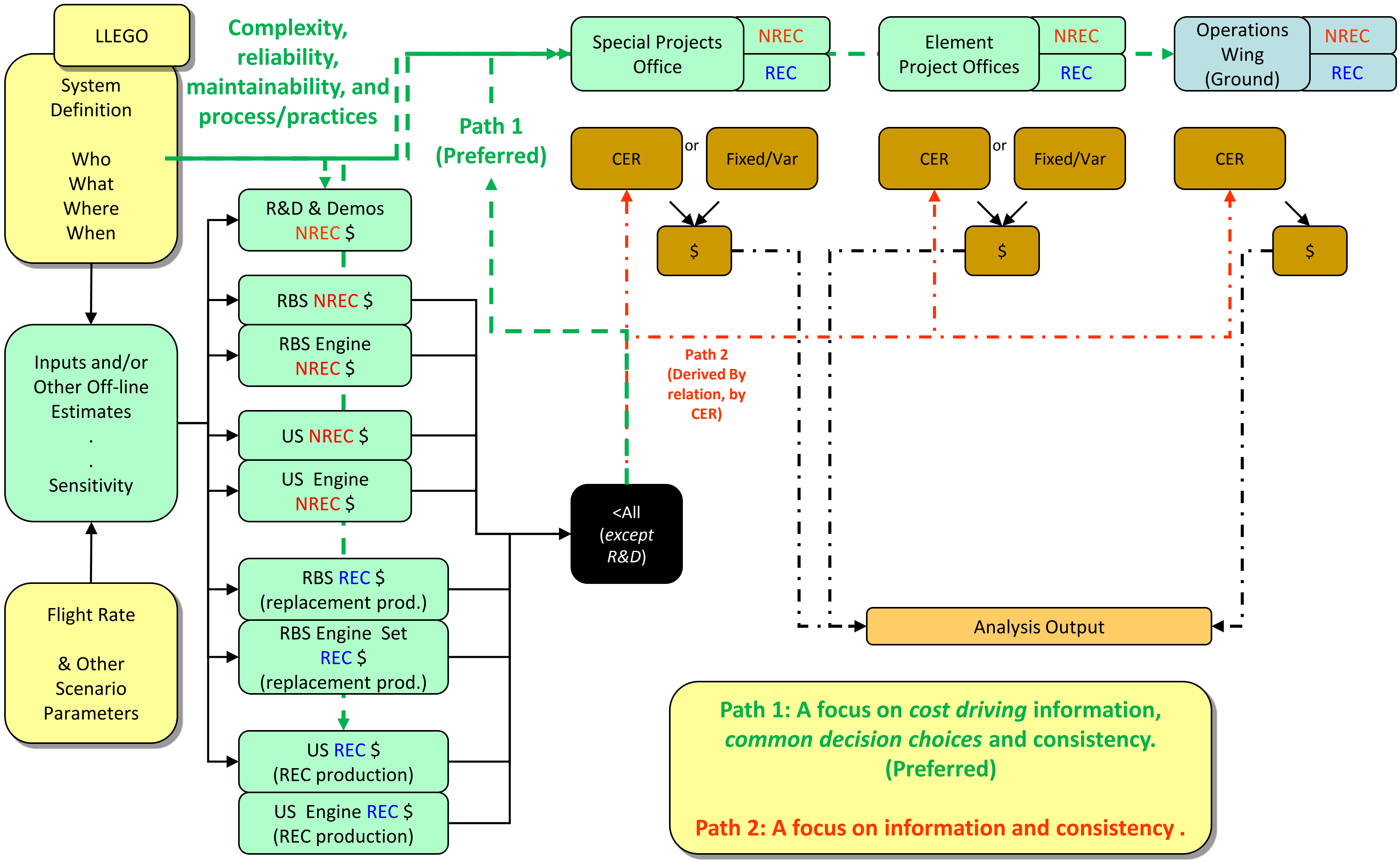
Fig jpg ok

Model Candidates - “LLEGO”

- The Launch & Landing Effects Ground Operations cost model
  - Ground Systems focused
  - Estimating from first causes (complexity, reliability, maintainability)
  - Useful in a design driven cost study



Mixed LLEGO/Life-Cycle Cost Model: Schematic



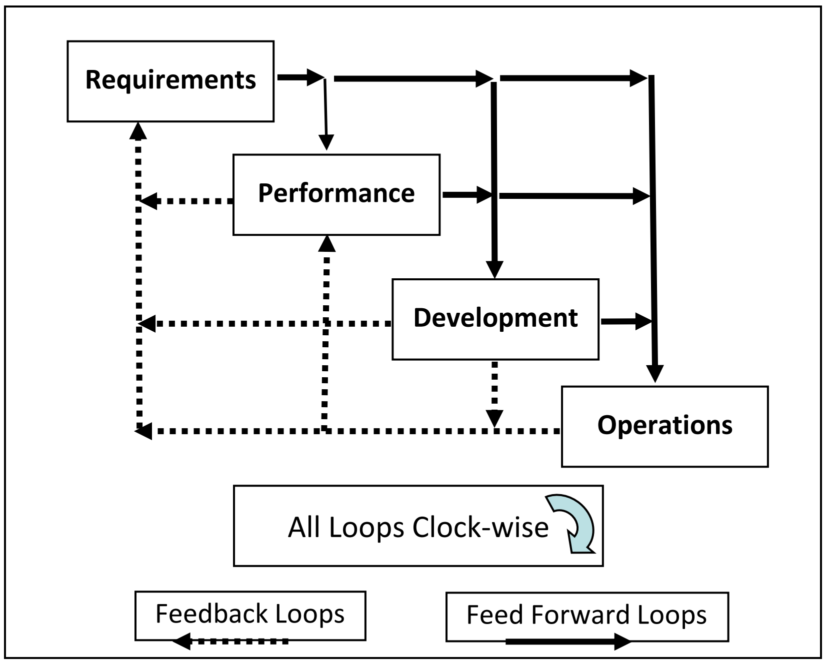
Path 1: A focus on *cost driving* information, *common decision choices* and consistency. (Preferred)

Path 2: A focus on information and consistency .

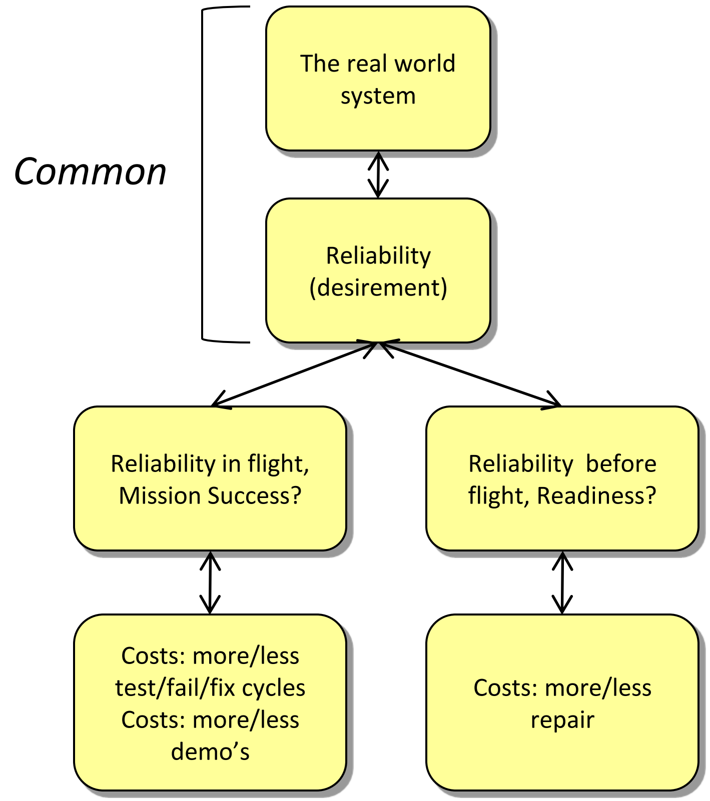
Mixed LLEGO/Life-Cycle Cost Model: Contrasts

- The model used here is exploring the alternate vantage point.

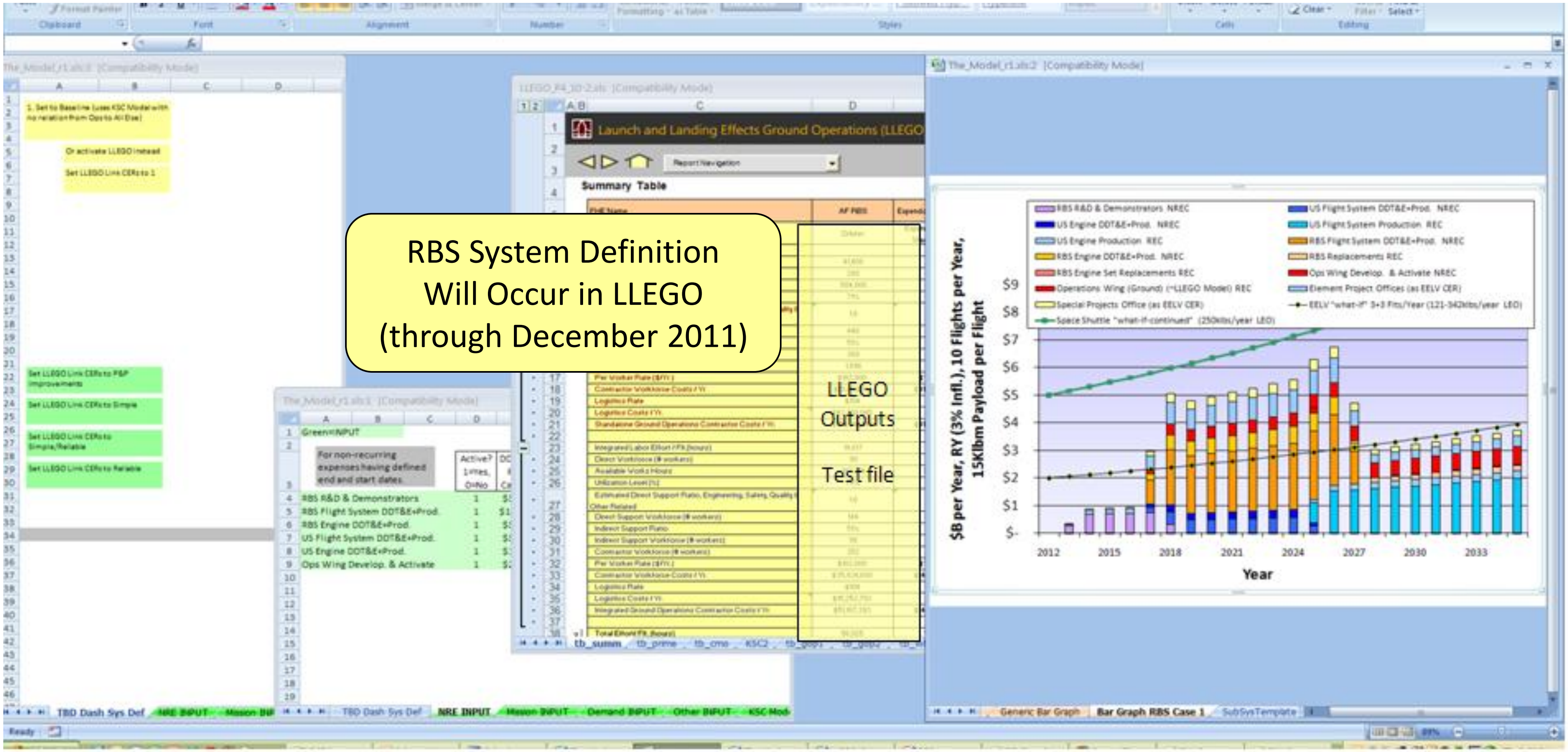
Example, traditional design structure matrix (DSM), dog-in-sled vantage point



Alternate view, analysts see the system from a common vantage point

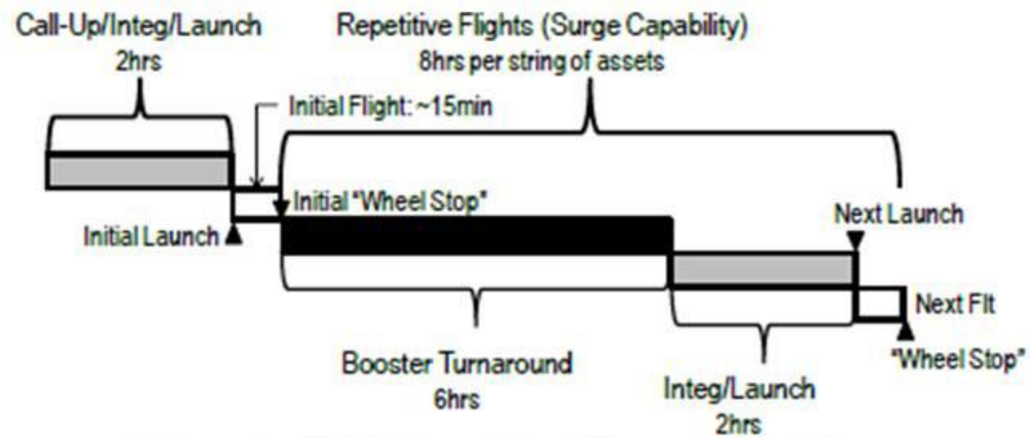


Mixed LLEGO/Life-Cycle Cost Model: Screen Shot



The Reusable Booster System – A Configuration

- Reusable Booster System configuration information useful for cost modeling and analysis is lacking.
  - Architecture information lacks sub-system and process design detail.
  - Where sub-system insight is available (i.e., "KSC/AFRL RBS CONOPS" (Ref, Ref) it is for guidance, defining design and technology expectations consistent with an efficient turnaround operations.
    - Not closed with performance or risk/reliability analysis.



RBS Operational Segment Definition

From the NASA KSC / AFRL RBS CONOPS

(NASA Technical Reports Server http://ntrs.nasa.gov)

Fig jpg ok

The Reusable Booster System – A Configuration

- Reusable Booster System configuration information useful for cost modeling and analysis is lacking.

  - Ideal is a single team, single source, integrating performance, cost, and risk/reliability.
    - *Addressed in Forward Work.*

  - This *methodology development*, modeling and quick-look analysis collates inputs and information from multiple sources, filling in gaps in the data from experience, yeilding a quick-look, preliminary cost analysis.

The Reusable Booster System – A Configuration

- “Reusable Booster System, Concept of Operations, A Ground Systems and Ground Operations Analysis for Rapid Response Orbital Space Delivery”
  - NASA KSC and AFRL Collaboration, A Conceptual Operational Flow

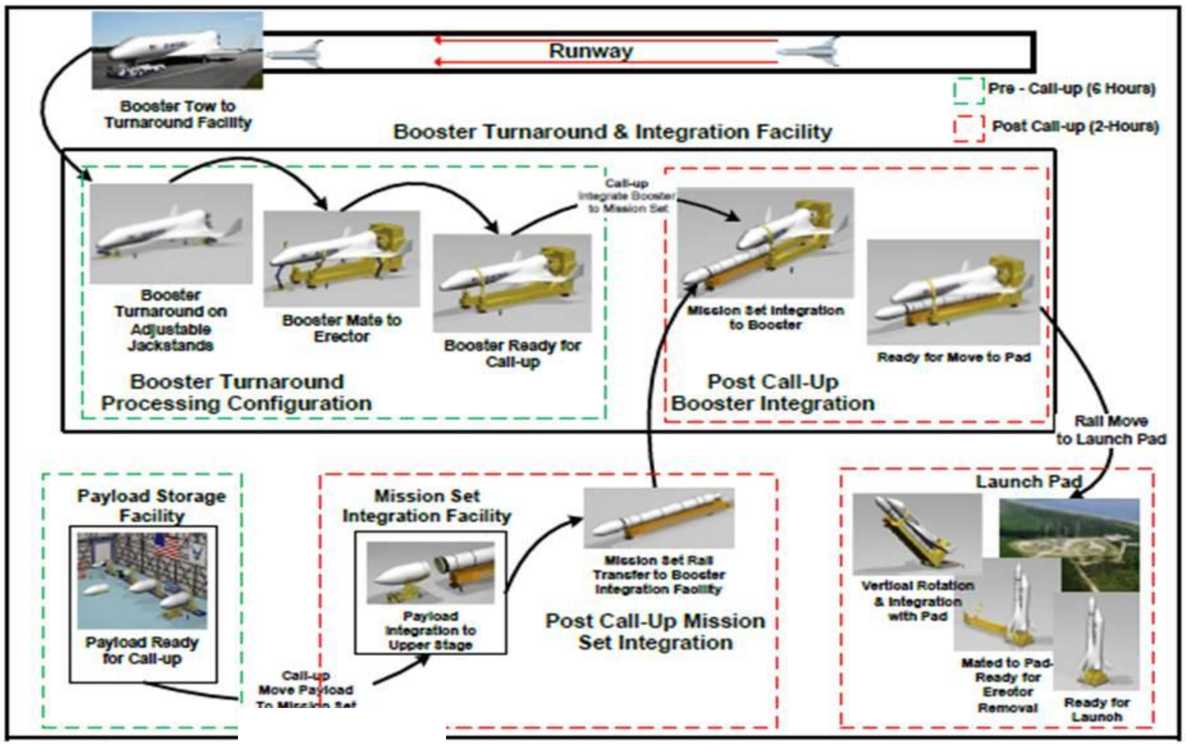


Figure 7—Conceptual Operational Flow

Fig jpg ok

The Reusable Booster System – A Configuration

- "Reusable Booster System, Concept of Operations, A Ground Systems and Ground Operations Analysis for Rapid Response Orbital Space Delivery"
  - NASA KSC and AFRL Collaboration, A Conceptual Operational Flow

Figure 9—Upper Stage Bottom Mount Configuration

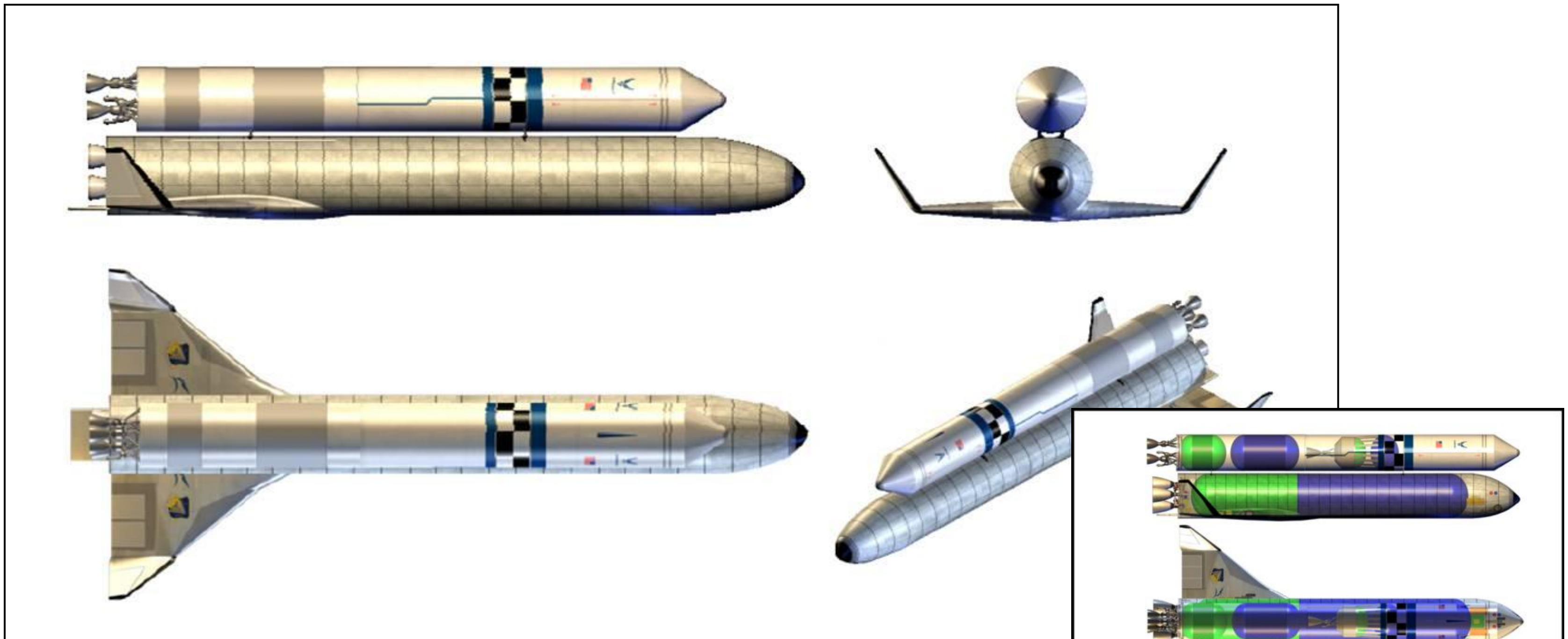
CONCEPTUAL ONLY

Connecting the upper stage to the bottom of the booster provides the lowest possible height for personnel access and least elevation change for the upper stage. There are no wing clearance constraints in this configuration and it provides better load control with the booster erector and upper stage transporter on a common side during transport. The upper stage is more rapidly positioned for mate after call-up and may be simply rolled under the booster for integration.

Fig jpg ok

The Reusable Booster System – A Configuration

- The merged information set reflects the following internal configuration.
  - Naturally, mixes information with an Upper Stage atop, with information where the Upper Stage is below.



Representative RBS Hybrid Launch Vehicle Configuration.

From Charania AIAA 2009

Fig jpg ok

The Reusable Booster System – A Configuration

- The merged information set will naturally suffer, being from diverse sources.
  - Inconsistencies on-
    - Placement of the 2nd stage / upper stage
    - Staging number
    - Sizing
      - Sub-systems feasibility and compatibility.

  - “Ranges” - around a given 15,000 lbm payload to LEO RBS being analyzed.

- Mixing and matching diverse configuration information is less than ideal, akin to “rubberizing an engine” or scaling.
  - Since the emphasis here is the method of analysis-the mix of configuration data available is adequate (for now).

Preliminary Model & Analysis: Results

- Step 1 – Choose the starting point cost inputs or baselines, *excluding the wing operations (ground operations through launch).*
  - Values taken from the literature, or where lacking as ROMs.
    - *Re. Gstattenbauer, Franke, Livingston.*
  - Initial inputs taken in complete isolation.
    - No inter-relationships to LLEGO / Ops wing effort, operability, improvements, etc.
  - Start with a small fleet of 10 Reusable Boosters, segueing from DDT&E and production setup, into actual production and missions in the mid-2020's.
    - A fleet of 15 by 2035.

Preliminary Model & Analysis: Results

- Step 2 - Complete the picture with an estimate from the model & analysis (LLEGO) for the wing operations of a basic, simplified reusable booster.

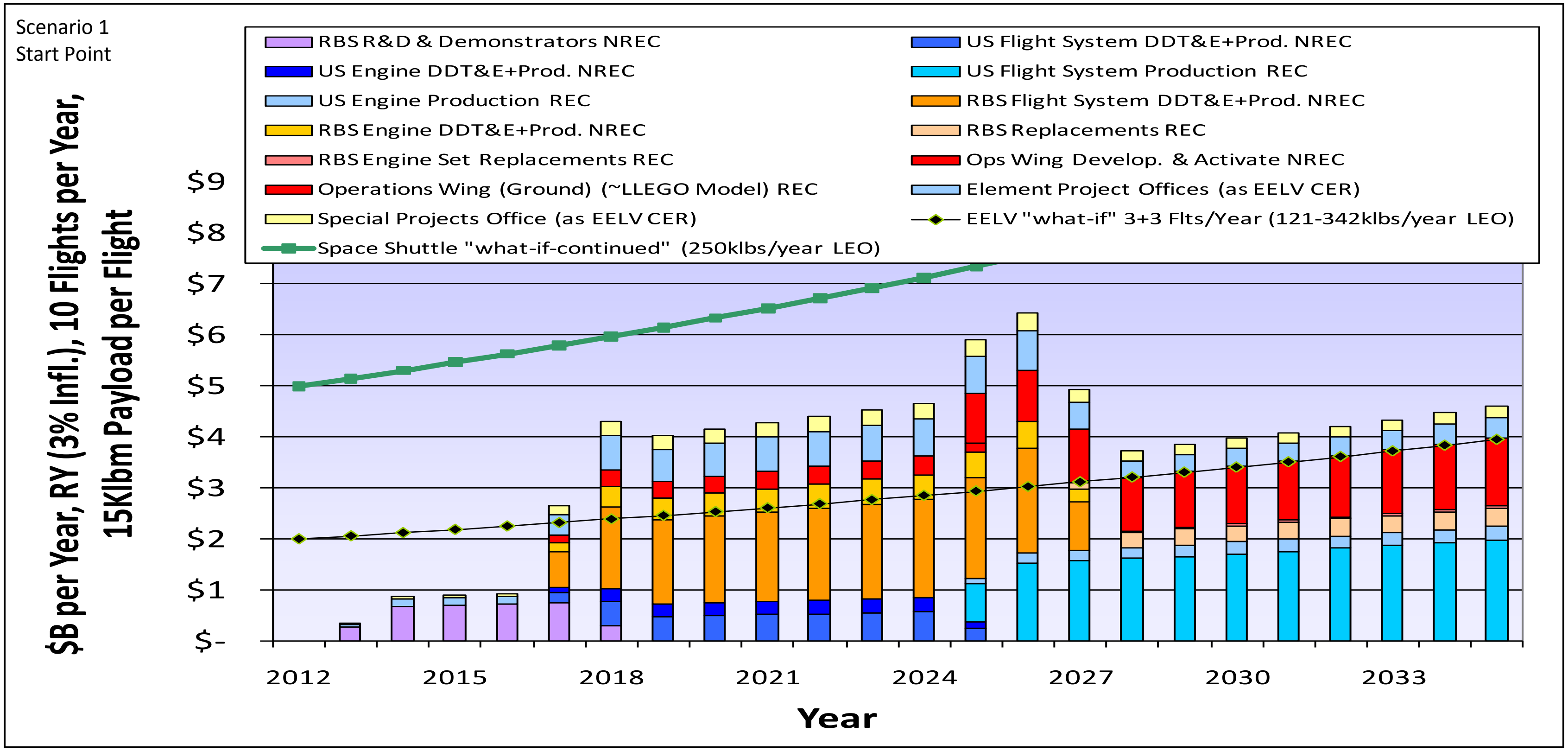
  - Taking a Shuttle Orbiter baseline-
    - Change dimensions (nominal)
    - Delete *numerou*s sub-systems
      - Payload, Crew, Windows, RCC, HRSI, Fuel Cells, Water Spray Boilers, Active Thermal Control Heat Exchangers, OMS.
      - All the fluids, tanks and engines of these systems (waters, FC Grade LOX, FC Grade LH2, assorted GN2 & GHe for pressurization, NH3, Freons, OMS Bi-prop Hypergolic fluids, etc).
    - Keep other basic systems (RCS, Landing Gear, Hydraulics, Avionics, etc).
    - Add/adjust for internal LOX/RP tanks, batteries (not APUs), etc.

Preliminary Model & Analysis: Results

- Step 3 – Co-relate the design aspects from the LLEGO sub-systems centric view across the cost phases.
    - *Strengthening the relationship between near term, non-recurring costs, and far term recurring costs and flights.*
- Step 4 – Review results. Refine. Return. (*See Forward Work*).

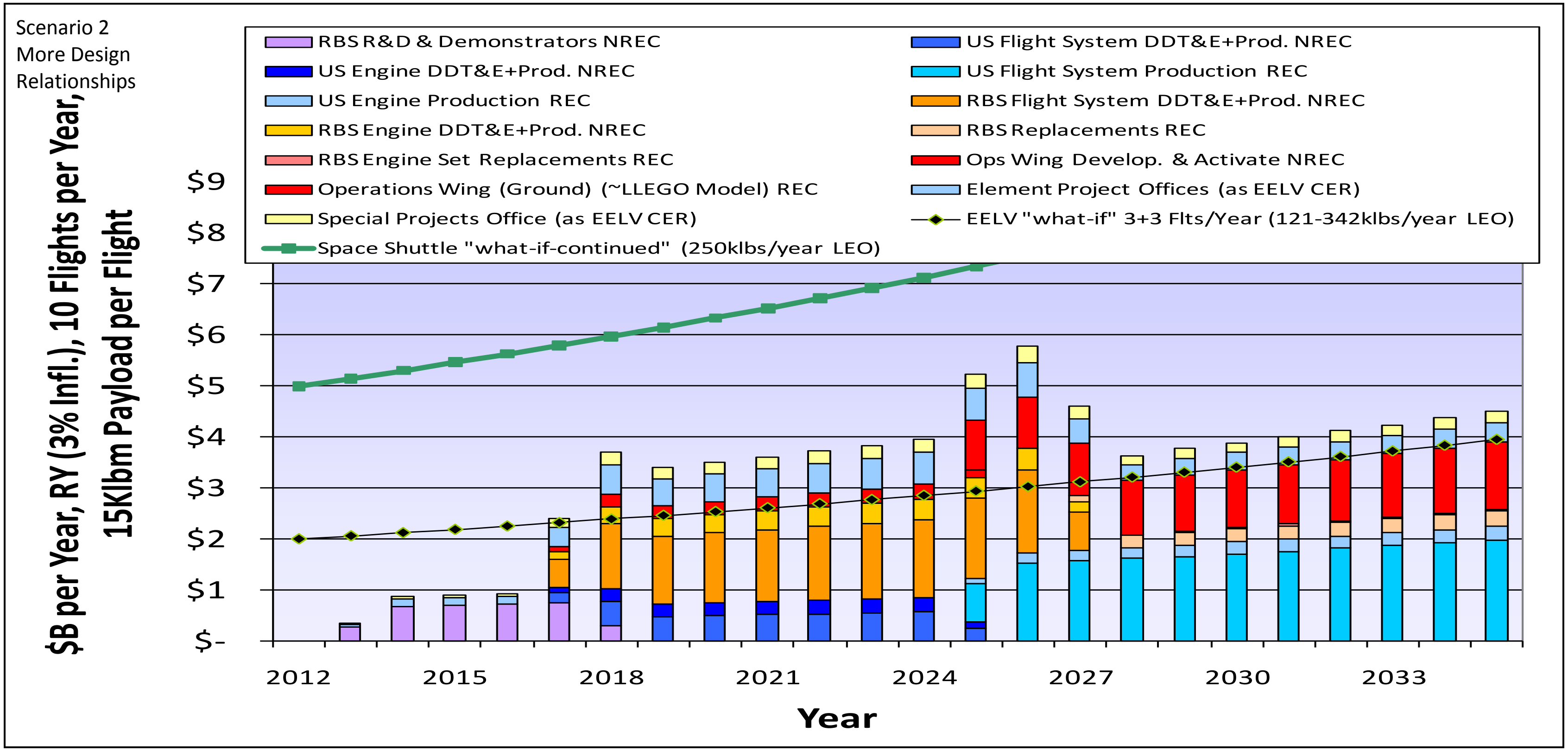
Preliminary Model & Analysis: Results

- The previous sets up Scenario 1 - the "Starting point definition".
  - May be ~same to much less payload/year compared to EELVs.
  - Traditional process/practices.
  - Actual payloads not really divisible.



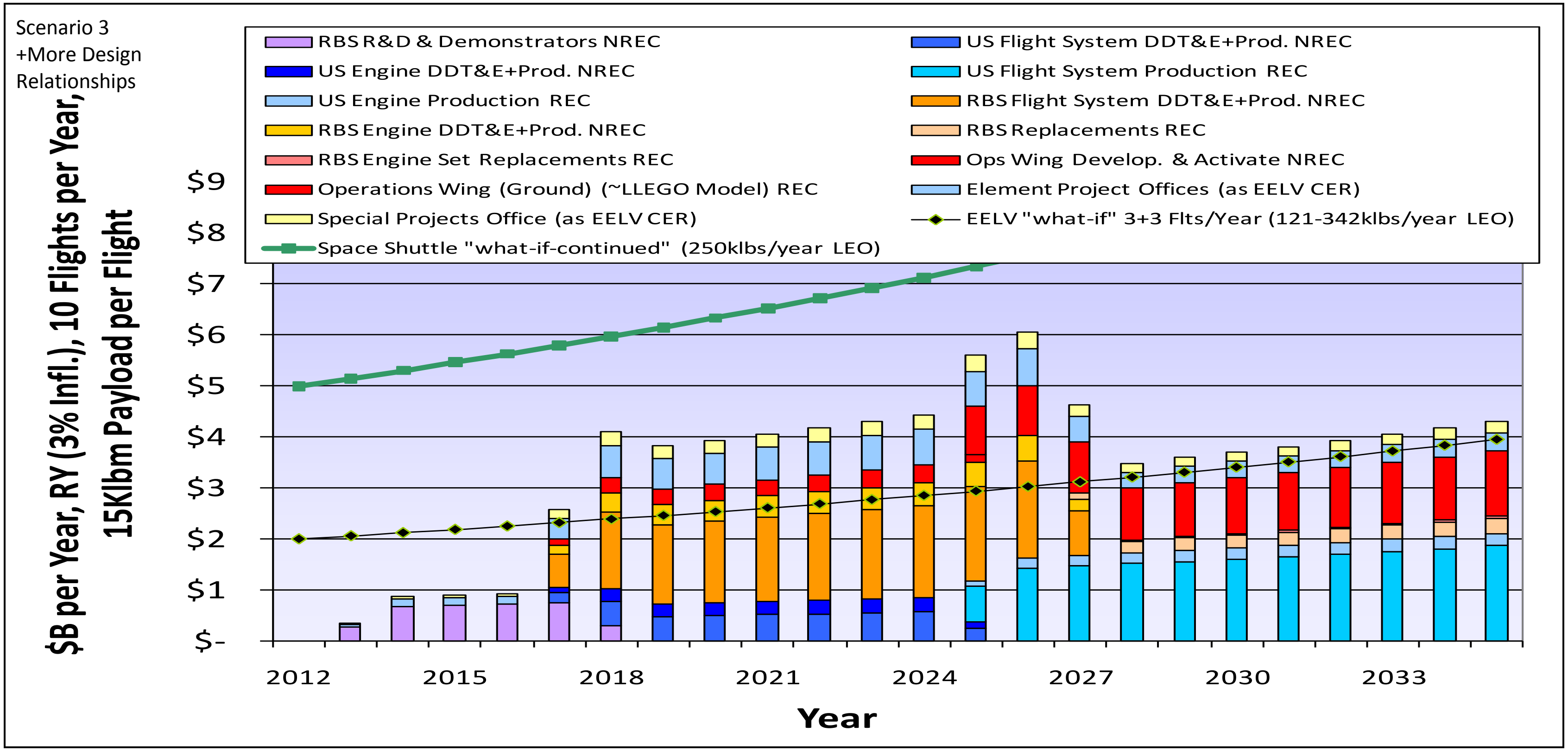
Preliminary Model & Analysis: Results

- Scenario 2: The simplifications in the reusable booster design are further co-related as up-front simplifications benefitting DDT&E, and later production.
    - Early RBS R&D, and the Upper Stage are un-affected.



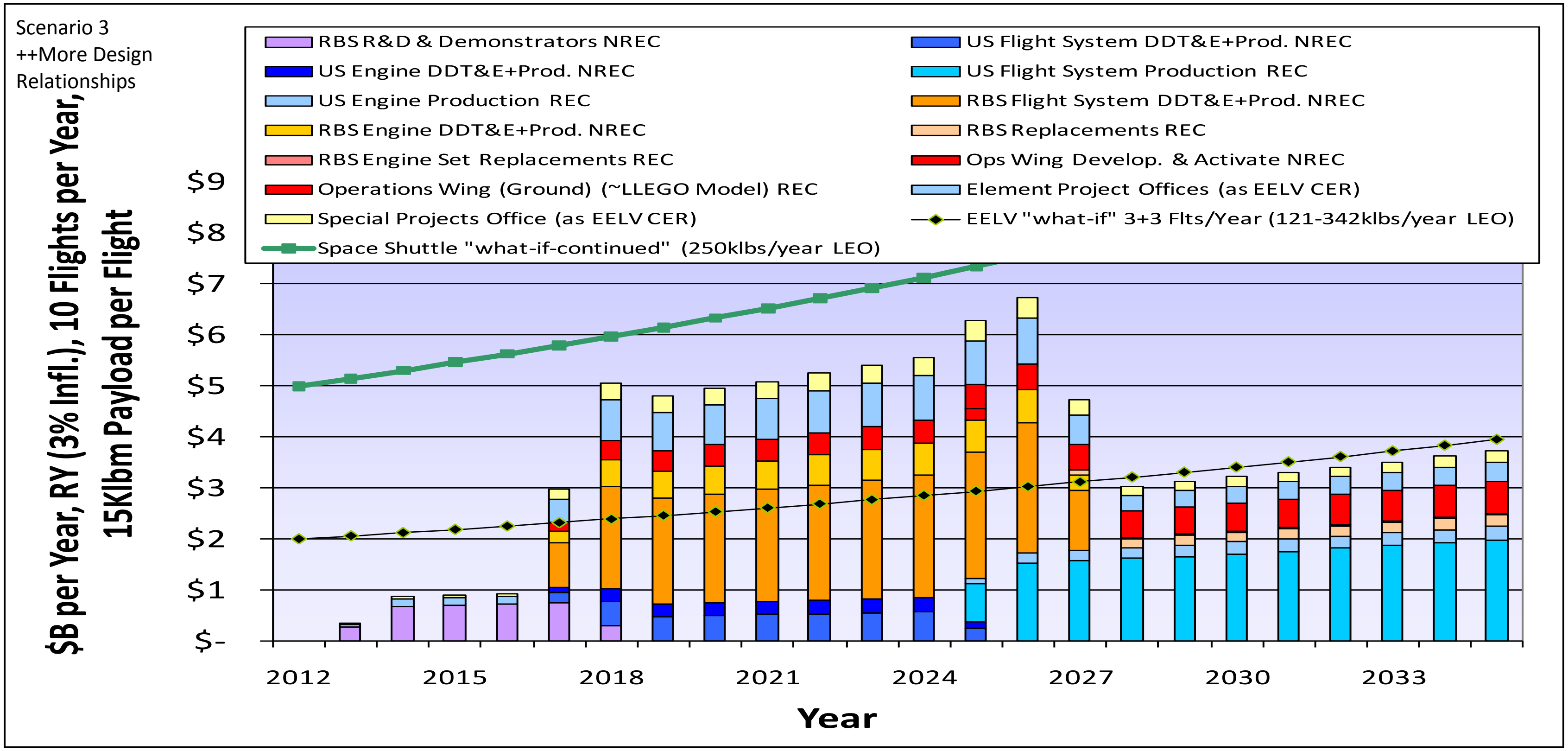
Preliminary Model & Analysis: Results

- <u>Scenario 3</u>: The reliability of the reusable booster is increased.
  - Increases in up-front costs.
  - More test/fail/fix/fly/re-design/learning cycles. *US learned too…*
  - Benefits later, in production & wing ops & missions.



Preliminary Model & Analysis: Results

- Scenario 4: Process & Practice improvements in the operations wing. Significant process reinventions, new ways of doing business.
  - Per functional definitions, includes both contractor & blue-suiters.
  - These require up-front investment.



Preliminary Model & Analysis: Observations

- *Methodology* promising: Shows a means to take tangible design or process decisions that are part of any decision-making early on and explore their cost effects across phases of the life-cycle.
    - No “magic happens here”.

- Preliminary indications are consistent with a previous AoA, where “improvements in systems engineering” were identified as a major cost driver.
    - The analysis here goes further – into many indirect process/practice functions, as well as the systems engineering, simplifications, and reliability needs.

Potential Forward Work

- Further research and model the connection between early, tangible design, process, or technology decisions and consequences (pro and con).
  - Do the models available in the community adequately connect an ops wings reliability posture (critical to turn-time, fast response) to the up-front costs of development and test/fail/fix/fly/re-designs?
  - How do design decisions interact?
    - Simplification also helps reliability (fewer parts to fail), but what balance of resources applied to each in a development gets the most value? (Simplification often deletes functional capability).
  - How can organizational processes and practices firmly reflect on a bid? On programmatic risk?
    - Realism. Risk. Credibility.
  - How might R&D better connect to lower early development costs?

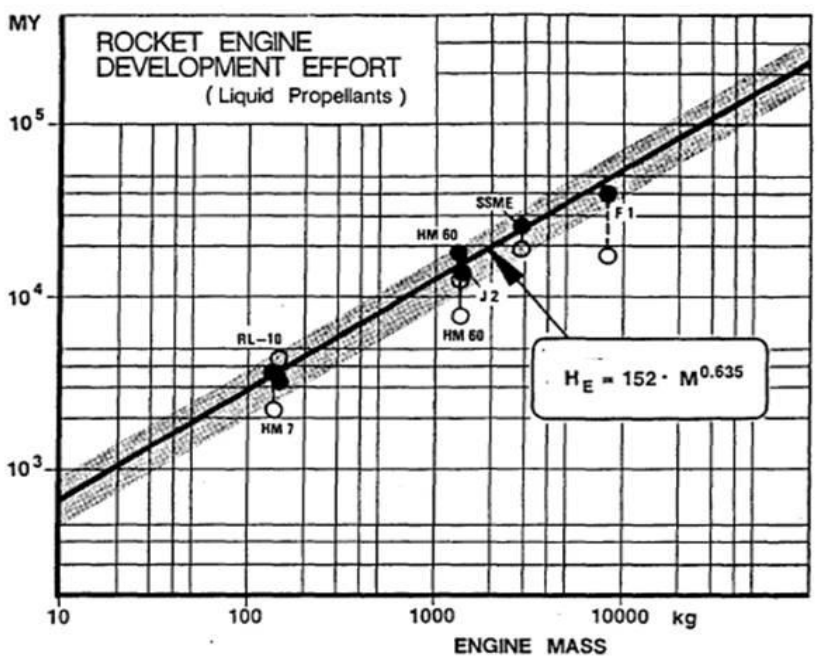
Potential Forward Work

- More formalized analysis-
  - Refine and improve the method, relationships and framework of this basic analysis.
  - More formal ground rules and assumptions, basis of estimates, documentation.
  - Refine RBS configuration details and documentation.
    - Move on to the larger configurations currently in technology roadmaps for consideration – 40 to 60k lbm to LEO payloads.
- Address "call-up time" implications, rolled into the methodology.
- Locate scenarios where up-front costs are less, while preserving the recurring costs and flight rate posture.

Backup

Modeling

- Why Models?
  - Interpreting X and Y regressions is not always simple.
  - Were costs book-kept properly? Are they “real” costs in the real world? Are system factors really comparable? Is there a co-relation that’s really causal, or hidden?



D. Koelle, “Transcost” Model circa 2000.

Modeling

- Why Models?
  - Bottoms-up efforts as an alternative?
    - Pros:
      - Technical experts know systems and processes.
      - Process experts know their practices.
    - Cons:
      - Technical experts rarely understand real costs, inter-relationships of systems to production rates, total fixed costs, total workforce, indirect costs, etc.
      - Process experts rarely know the relationship between information and material processes and the final product.
        - Also-why “invest” in configuration control and its I/T system to be cheaper and more productive when ample reasons exist not to?

Payloads, Sizing

Compiled from astronautix.com, UCS Database, spaceflightnow.com
Launches of satellites directly supporting U.S. military or intelligence customers
1/1/2000 through 12/31/2010

Year	Launch Attempts
2000	12
2001	8
2002	1
2003	11
2004	5
2005	7
2006	8
2007	8
2008	4
2009	10
2010	7

81 launches total
7.36 launches per year (average)

	CCAFS	VAFB	Kodiak	Kwaj	Wallops	Total
2000	7	5	0	0	0	12
2001	5	2	1	0	0	8
2002	1	0	0	0	0	1
2003	8	3	0	0	0	11
2004	5	0	0	0	0	5
2005	3	4	0	0	0	7
2006	3	3	0	1	1	8
2007	7	0	0	0	1	8
2008	1	1	0	2	0	4
2009	7	2	0	0	1	10
2010	4	2	1	0	0	7
Total	51	22	2	3	3	81

	Comm	Research	Early Warr	PNT	NRO	Weather	Total
2000	2	4	1	3	2	0	12
2001	1	2	1	1	3	0	8
2002	1	0	0	0	0	0	1
2003	4	1	0	3	2	1	11
2004	0	0	1	3	1	0	5
2005	0	3	0	1	3	0	7
2006	0	3	0	2	2	1	8
2007	1	2	1	2	2	0	8
2008	0	2	0	1	1	0	4
2009	2	3	0	2	2	1	10
2010	1	2	1	1	2	0	7
Total	12	22	5	19	20	3	81

Payloads, Sizing

	Pegasus X	Minotaur /Ta	Falcon I	Athena	Delta II	Titan II	Atlas II/III	Delta IV	Titan IV	Atlas V	Total
2000	1	3	0	0	3	0	3	0	2	0	12
2001	0	0	0	1	2	0	2	0	3	0	8
2002	0	0	0	0	0	0	0	0	1	0	1
2003	0	0	0	0	3	2	2	2	2	0	11
2004	0	0	0	0	3	0	1	0	1	0	5
2005	1	2	0	0	1	0	1	0	2	0	7
2006	0	1	1	0	4	0	0	2	0	0	8
2007	0	1	0	0	2	0	0	1	0	4	8
2008	1	0	1	0	1	0	0	0	0	1	4
2009	0	1	0	0	4	0	0	2	0	3	10
2010	0	2	0	0	0	0	0	2	0	3	7
Total	3	10	2	1	23	2	9	9	11	11	81

	GEO	GPS Orbit	LEO Polar	LEO ~60 deg	LEO < 50 deg	Highly Elliptical	Total
2000	3	3	3	2	0	1	12
2001	3	1	1	2	0	1	8
2002	1	0	0	0	0	0	1
2003	5	3	2	1	0	0	11
2004	1	3	0	0	0	1	5
2005	0	1	4	2	0	0	7
2006	1	2	1	1	2	1	8
2007	2	2	0	1	2	1	8
2008	0	1	0	0	2	1	4
2009	4	2	2	1	1	0	10
2010	2	1	3	0	1	0	7
	22	19	16	10	8	6	81

Payloads, Sizing

	Vehicle	Site	Payload	Mass (lb)	Orbit
1/21/2000	Atlas IIA	CCAFS	DSCS III B-8	2716	GEO
1/27/2000	Minotaur	VAFB	Multiple research	250	Polar LEO
3/12/2000	Taurus	VAFB	MTI (research)	1294	Polar LEO
5/8/2000	Titan IV	CCAFS	DSP F20	5240	GEO
5/11/2000	Delta II	CCAFS	GPS 2R-4	4470	GPS, 55 deg
6/7/2000	Pegasus XL	VAFB	P95-2 (research)	544	LEO, 69 deg
7/16/2000	Delta II	CCAFS	GPS 2R-5	4479	GPS, 55 deg
7/19/2000	Minotaur	VAFB	Mightysat 2.1 (research)	260	Polar LEO
8/17/2000	Titan IV	VAFB	NRO	Unknown	LEO 68 deg
10/20/2000	Atlas IIA	CCAFS	DSCS III B-11	2722	GEO
11/10/2000	Delta II	CCAFS	GPS 2R-6	4479	GPS, 55 deg
12/6/2000	Atlas IIAS	CCAFS	NRO	Unknown	Highly elliptical, 63 deg
1/30/2001	Delta II	CCAFS	GPS 2R-7	4479	GPS, 55 deg
2/27/2001	Titan IV	CCAFS	Milstar-2 DFS 4	10290	GEO
5/18/2001	Delta II	CCAFS	GeoLITE (research)	205	GEO
8/6/2001	Titan IV	CCAFS	DSP F21	5000	GEO
9/8/2001	Atlas IIAS	VAFB	NRO	Unknown	LEO, 63 deg
9/30/2001	Athena I	Kodiak	Multiple research	300	LEO, 67 deg
10/5/2001	Titan IV	VAFB	NRO	Unknown	Polar LEO
10/11/2001	Atlas IIAS	CCAFS	NRO	Unknown	Highly elliptical, 63 deg
1/16/2002	Titan IV	CCAFS	Milstar-2 DFS 5	10030	GEO
1/6/2003	Titan II	VAFB	Coriolis (research)	1825	Polar LEO
1/29/2003	Delta II	CCAFS	GPS 2R-8	4479	GPS, 55 deg
3/11/2003	Delta IV M	CCAFS	DSCS III A-3	2722	GEO
3/31/2003	Delta II	CCAFS	GPS 2R-9	4479	GPS, 55 deg
4/8/2003	Titan IV	CCAFS	Milstar-2	9900	GEO
8/29/2003	Delta IV M	CCAFS	DSCS III B-6	2722	GEO
9/9/2003	Titan IV	CCAFS	NRO	Unknown	GEO
10/18/2003	Titan II	VAFB	DMSP 5D-3	2544	Polar LEO
12/2/2003	Atlas IIAS	VAFB	NRO	Unknown	LEO, 63 deg
12/18/2003	Atlas IIIB	CCAFS	UFO F/O F11	6646	GEO
12/21/2003	Delta II	CCAFS	GPS 2R-10	4479	GPS, 55 deg
2/14/2004	Titan IV	CCAFS	DSP F22	5240	GEO
3/20/2004	Delta II	CCAFS	GPS 2R-11	4479	GPS, 55 deg
6/23/2004	Delta II	CCAFS	GPS 2R-12	4479	GPS, 55 deg
8/31/2004	Atlas IIAS	CCAFS	NRO	Unknown	Highly elliptical, 63 deg
11/6/2004	Delta II	CCAFS	GPS 2R-13	4479	GPS, 55 deg
2/3/2005	Atlas IIIB	CCAFS	NRO	Unknown	LEO, 63 deg
4/11/2005	Minotaur	VAFB	XSS-11 (research)	319	Polar LEO
4/15/2005	Pegasus XL	VAFB	DART (research)	790	Polar LEO
4/30/2005	Titan IV	CCAFS	NRO	Unknown	LEO 57 deg
9/23/2005	Minotaur	VAFB	Streak (research)	919	Polar LEO
9/26/2005	Delta II	CCAFS	GPS 2R-14	4479	GPS, 55 deg
10/19/2005	Titan IV	VAFB	NRO	Unknown	Polar LEO

Payloads, Sizing

3/24/2006	Falcon I	Kwaj	Falconsat 2 (research)	44	LEO?
6/21/2006	Delta II	CCAFS	MiTEx (research)	992	GEO
6/25/2006	Delta IV M+	VAFB	NRO	Unknown	Highly elliptical, 63 deg
9/25/2006	Delta II	CCAFS	GPS 2R-15	4479	GPS, 55 deg
11/4/2006	Delta IV M	VAFB	DMSP 5D-3	2544	Polar LEO
11/17/2006	Delta II	CCAFS	GPS 2R-16	4479	GPS, 55 deg
12/14/2006	Delta II	VAFB	NRO	Unknown	LEO, 69 deg
12/16/2006	Minotaur	Wallops	Tacsat 2 (research)	810	LEO, 40 deg
End 2006					
3/6/2007	Atlas V	CCAFS	Multiple research	3694	LEO 35-46 deg
4/24/2007	Minotaur	Wallops	NFIRE (research)	1089	LEO 48 deg
6/15/2007	Atlas V	CCAFS	NRO	Unknown	LEO, 63 deg
10/11/2007	Atlas V	CCAFS	WGS SV-1	11400	GEO
10/17/2007	Delta II	CCAFS	GPS 2R-17	4479	GPS, 55 deg
11/11/2007	Delta IV	CCAFS	DSP 23	5248	GEO
12/10/2007	Atlas V	CCAFS	NRO	Unknown	Highly elliptical, 60 deg
12/20/2007	Delta II	CCAFS	GPS 2R-18	4479	GPS, 55 deg
End 2007					
3/13/2008	Atlas V	VAFB	NRO	Unknown	Highly Elliptical, 64 degrees
3/15/2008	Delta II	CCAFS	GPS 2R-19	4479	GPS, 55 deg
4/16/2008	Pegasus XL	Kwaj	C/NOFS (research)	850	LEO 13 deg
8/3/2008	Falcon I	Kwaj	Jumpstart (research)	184	LEO 9 deg
End 2008					
1/18/2009	Delta IV	CCAFS	NRO	Unknown	GEO
3/24/2009	Delta II	CCAFS	GPS 2R-20	4479	GPS, 55 deg
4/4/2009	Atlas V	CCAFS	WGS-2	13200	GEO
5/5/2009	Delta II	VAFB	STSS-ATRR (research)	4400	Polar LEO
5/18/2009	Minotaur	Wallops	Tacsat 3 (research)	880	LEO 41 deg
8/17/2009	Delta II	CCAFS	GPS 2R-21	4479	GPS, 55 deg
9/8/2009	Atlas V	CCAFS	PAN (mission unknown)	Unknown	GEO
9/25/2009	Delta II	CCAFS	STSS 1 & 2 (research)	2473 (each)	LEO, 58 deg
10/18/2009	Atlas V	VAFB	DMSP 5D-3	2600	Polar LEO
12/6/2009	Delta IV	CCAFS	WGS 3 (comm)	13200	GEO
End 2009					
4/22/2010	Atlas V	CCAFS	X-37 (research)	11000	LEO
5/28/2010	Delta IV	CCAFS	GPS 2F-1	3500	GPS, 55 deg
8/14/2010	Atlas V	CCAFS	AEHF SV-1	13600	GEO
9/21/2010	Atlas V	VAFB	NRO	Unknown	LEO, 123 deg
9/30/2010	Minotaur IV	VAFB	SBSS (space tracking)	2275	Polar LEO
11/20/2010	Minotaur IV	Kodiak	Multiple research	> 810	Polar LEO
11/21/2010	Delta IV H	CCAFS	NRO	Unknown	GEO

Payloads, Sizing

DoD Missions			
	Launch Site	Destination	Payload Mass (lb)
1	CCAFS	GEO	13500
2	CCAFS	GEO	11500
3	CCAFS	Molniya 63 deg	8000
4	CCAFS	GPS, 55 deg	4500
5	CCAFS	GPS, 55 deg	4500
6	VAFB	Polar	35000
7	VAFB	LEO, 65 deg	2500
Civil Missions			
	Launch Site	Destination	Payload Mass (lb)
1	CCAFS	GEO	12500
2	CCAFS	GEO	7500
3	CCAFS	GEO	5000
4	CCAFS	LEO, 60 deg	1500
5	CCAFS	Mars	2500
6	VAFB	Polar	5500
7	VAFB	Polar	2500

The Generalized Form of the LLEGO Equations

**FHE Score $_{(sub\text{-}system)}$ = ƒ (reliability/dependability, complexity/quantity, operability/maintainability)

Predicted Total *Work Content (in Hours) "touch"/launch (PWCt/L) =
$\Sigma_{(sub\text{-}systems)}$ [FHE Score / Baseline Score] × Baseline Work Content (Labor-Hours)/launch

Labor Costs$_j$ = ƒ (PWCt/L, launch rate, ratios of *direct support, *indirect, subs & CS)
j = 1 … n : representing n types of the ratios of support to WC (with variability)

∑For all FHEs in the Architecture
And *(optional)*
New-Ways-of-Doing Business Modifiers for numerous CER ratios

Alters baseline ratios

***Ground Ops Contractor, akin to a "USA" contractor**
****FHE=Flight Hardware Element**

Note: Other functions such as flight hardware logistics do not follow the form of the above cost estimating relationship (CER), but are also not in the GOP PMR. Still other CERs, such as for institutional "CMO" type costs are not covered in the above CER for both similar and other reasons.

The LLEGO Model

LLEGO co-relates a systems design characteristics to Shuttle cost data by means of cost estimating relationships driven by these semi-independent variables:

Characterizes "Who, What"

- Reliability – Will it fail? Will it work right when needed? Will it pass all tests? Does it need tests? (a high flight rate is enabled by high reliability).
  - Examples-Poor reliability of a Shuttle-like pedigree will co-relate to needing tests, for lack of confidence, not passing tests, causing trouble-shooting, low confidence even after standalone checkout, requiring further last-minute or integrated tests, and occasionally failing to a level that leaves no options but to remove and replace.
- Complexity – How many parts? Electronics? Tanks? Thrusters? Actuators?
  - Examples-High parts count, or by relation poor modularity, means more work than if there were fewer parts or more modularity, meaning more planned work; complexity also offers more work opportunities as inter-actions during checkout and processing to get into a ready state or for servicing for launch.
- Operability – How easy is it to check out? Connect GSE or on-board? Is a broken part easy to get at or buried? Toxic to handle or benign if it leaks? (Maintainability).
  - Examples-A toxic fluid is a less operable choice than a benign one. A high number of different fluids, regardless of type, is worse than fewer and common, all else being equal. Fewer tanks mean less leak paths. Fewer black boxes or controllers mean fewer interfaces via software or cables.

Characterizes "How"

- Processes & Practices – "how" does everything lead up to the product? These are the indirect processes and their costs. Commercial? Mature? Not?
  - Examples: Scheduling, requirements management, configuration control, information flow, the design/change process, verification processes, acquisition. In Supply chain terms "plan, source, make, deliver, return". These can drive cost results across a broad range of outcomes semi-independent of the 3 prior factors.