Descartes-Origins: A Simulation-Based Approach to Costs and Schedules of Future Spaceplace Development Programs

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- History of predicting costs for Reusable Launch Vehicles shows room for improvement
- Theoretical cost advantage of RLVs lies in the elimination of additional production while adding recurring ground operations costs
- To effectively compare RLV to ELV solutions, a full Life Cycle Cost estimate is needed, including:
  - DDT&E (design, development, test and evaluation)
  - TFU (theoretical first unit production)
  - Facilities, additional production, and any other non-recurring costs
  - Maintenance, ground operations, and other recurring costs

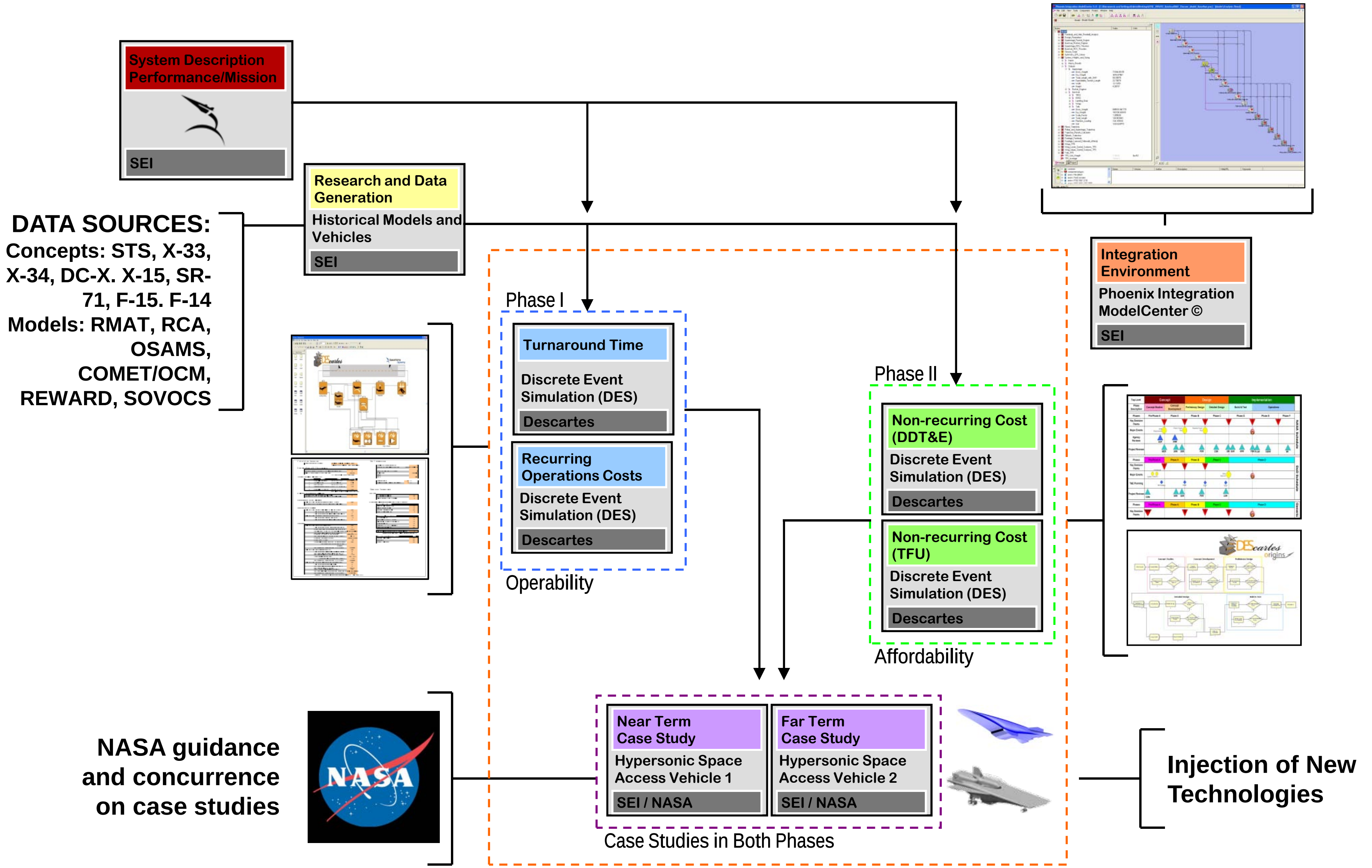
STS turnaround projected to be 2 weeks

Actual turnaround takes over 3 months

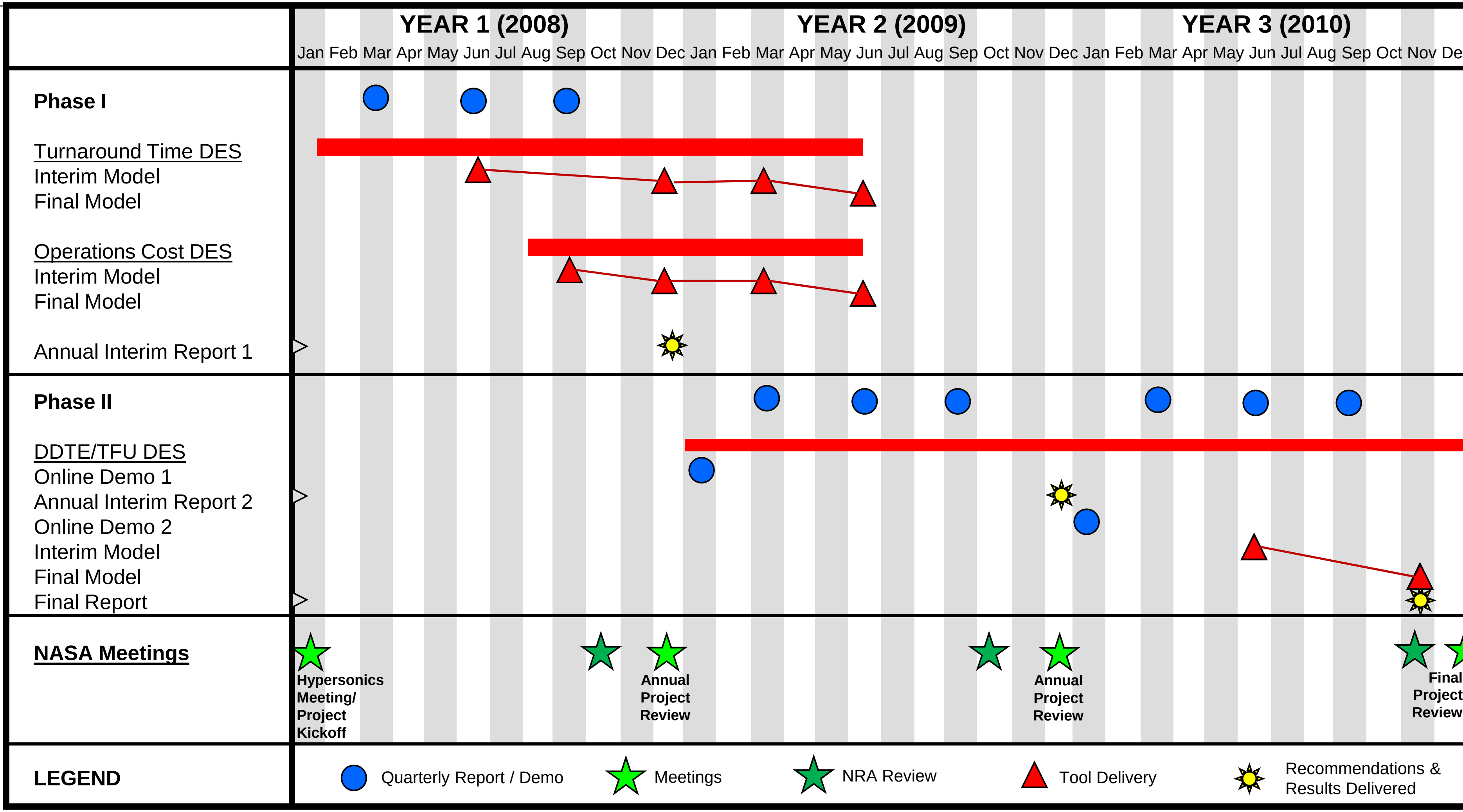
Life Cycle Economics Analysis

- In Discrete Event Simulation (DES), the operation of a system is represented as a chronological sequence of events
  - DES models use entities, resources, and various flow-chart-like processing blocks to represent complex systems
  - DES models can account for interaction of resources, complicated logical flows, and track numerous processes occurring in parallel and/or in series
- Rockwell Automation's Arena is among the industry-leading DES software packages
  - Arena provides graphical user interface and ability to animate entity flows over a base of the SIMAN DES language
  - Complex modeling possible with just create, dispose, process, decide, batch, separate, assign, and record blocks, along with entities, resources, variables, and Visual Basic manipulation
  - SEI uses Arena Basic Edition version 13.5 for DES modeling

Descartes NRA Project

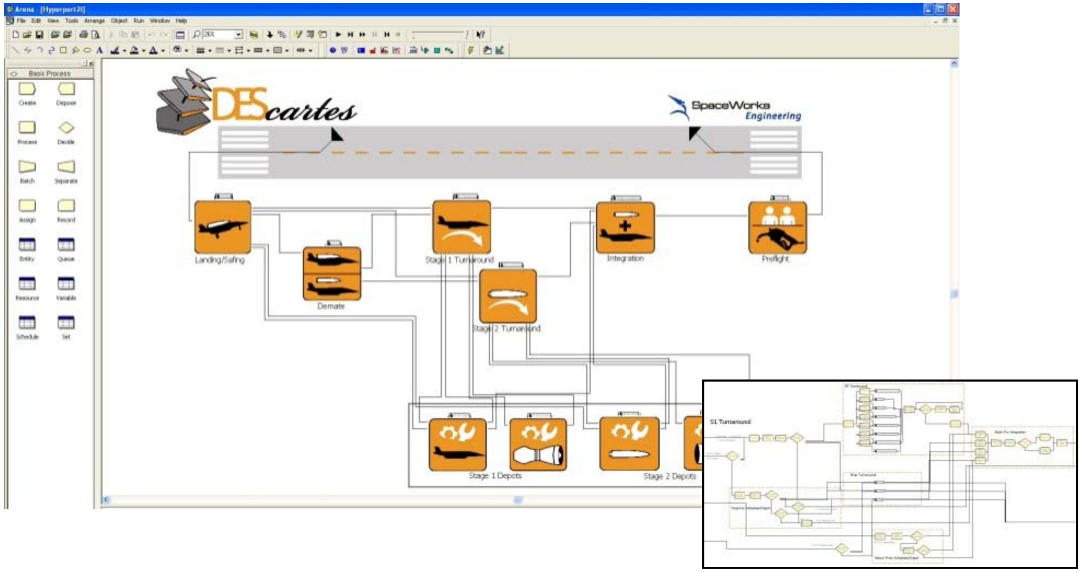


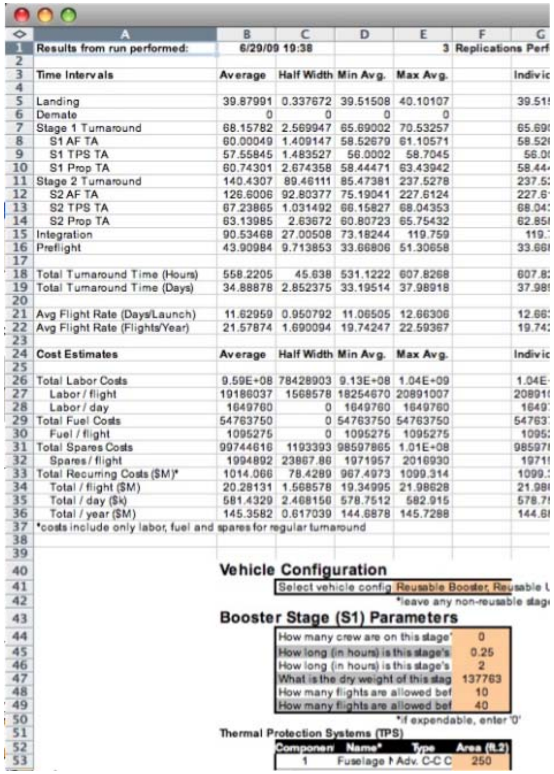
Descartes NRA Project Overview



Descartes NRA Contract begins January 2008, lasts through December 2010.
Phase I (Hyperport) was completed June 2009.
Phase II (Origins) is currently underway.

Descartes NRA Project Timeline





	A	B	C	D	E	F	G
1	Results from run performed:	6/29/09 19:38			3	Replications Perf	
2							
3	Time Intervals	Average	Half Width	Min Avg.	Max Avg.		Indivic
4							
5	Landing	39.87991	0.337672	39.51508	40.10107		39.51
6	Demate	0	0	0	0		
7	Stage 1 Turnaround	68.15782	2.569947	65.69002	70.53257		65.69
8	S1 AF TA	60.00049	1.409147	58.52679	61.10571		58.52
9	S1 TPS TA	57.55845	1.483527	56.0002	58.7045		56.0
10	S1 Prop TA	60.74301	2.674358	58.44471	63.43942		58.44
11	Stage 2 Turnaround	140.4307	89.46111	85.47381	237.5278		237.5
12	S2 AF TA	126.6006	92.80377	75.19041	227.6124		227.6
13	S2 TPS TA	67.23865	1.031492	66.15827	68.04353		68.04
14	S2 Prop TA	63.13985	2.63672	60.80723	65.75432		62.85
15	Integration	90.53468	27.00508	73.18244	119.759		119.
16	Preflight	43.90984	9.713853	33.66806	51.30658		33.66
17							
18	Total Turnaround Time (Hours)	558.2205	45.638	531.1222	607.8268		607.8
19	Total Turnaround Time (Days)	34.88878	2.852375	33.19514	37.98918		37.98
20							
21	Avg Flight Rate (Days/Launch)	11.62959	0.950792	11.06505	12.66306		12.66
22	Avg Flight Rate (Flights/Year)	21.57874	1.690094	19.74247	22.59367		19.74
23							
24	Cost Estimates	Average	Half Width	Min Avg.	Max Avg.		Indivic
25							
26	Total Labor Costs	9.59E+08	78428903	9.13E+08	1.04E+09		1.04E
27	Labor / flight	19186037	1568578	18254670	20891007		20891
28	Labor / day	1649760	0	1649760	1649760		1649
29	Total Fuel Costs	54763750	0	54763750	54763750		54763
30	Fuel / flight	1095275	0	1095275	1095275		1095
31	Total Spares Costs	99744616	1193393	98597865	1.01E+08		98597
32	Spares / flight	1994892	23867.86	1971957	2016930		1971
33	Total Recurring Costs ($M)*	1014.066	78.4289	967.4973	1099.314		1099.
34	Total / flight ($M)	20.28131	1.568578	19.34995	21.98628		21.98
35	Total / day ($k)	581.4329	2.468156	578.7512	582.915		578.7
36	Total / year ($M)	145.3582	0.617039	144.6878	145.7288		144.6
37	*costs include only labor, fuel and spares for regular turnaround						

Vehicle Configuration

Select vehicle config | Reusable Booster, Reusable

*leave any non-reusable stage

Booster Stage (S1) Parameters

How many crew are on this stage*	0
How long (in hours) is this stage's	0.25
How long (in hours) is this stage's	2
What is the dry weight of this stag	137763
How many flights are allowed bef	10
How many flights are allowed bef	40

*if expendable, enter '0'

Thermal Protection Systems (TPS)

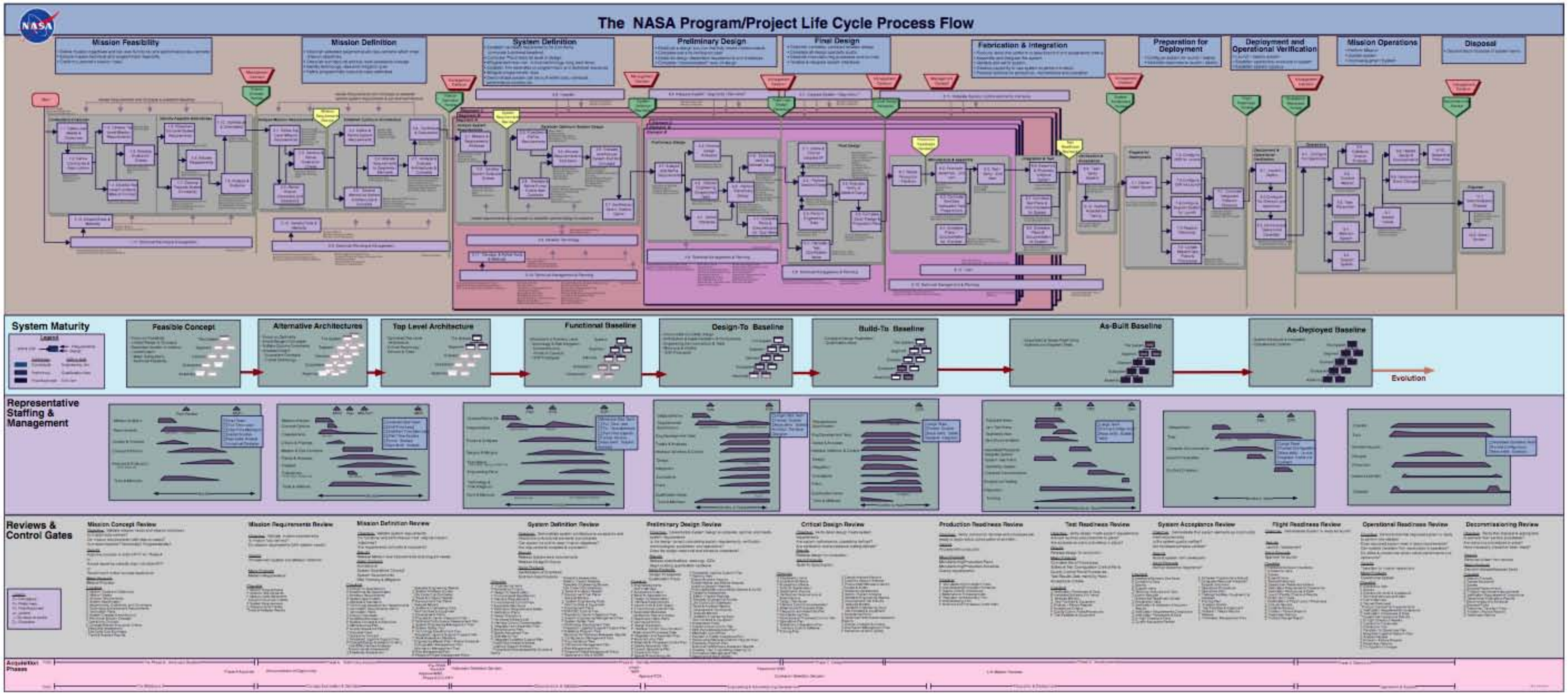
Component	Name*	Type	Area (ft2)
1	Fuselage	Adv. C-C C	250

- Each orange block contains processes modeling a major portion of the turnaround process, such as activity at a single facility
- Model takes over 100 vehicle inputs, along with labor and facility availabilities
- Outputs include:
  - Turnaround times broken down by stage and subsystem
  - Recurring costs including labor, fuel, spares, and periodic depot visits

Hyperport Model (see AIAA 2009-6484, AIAA 2010-2326)

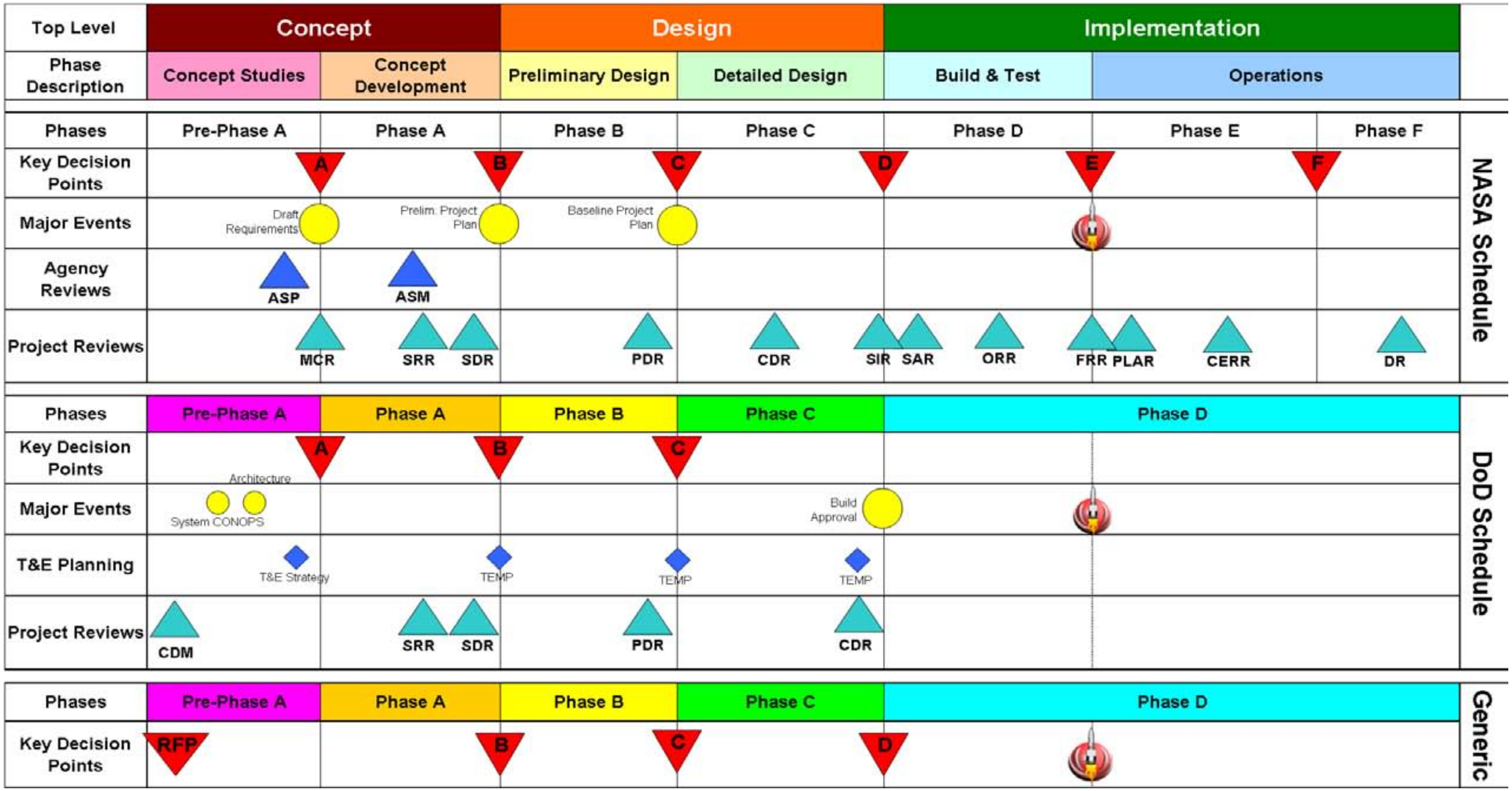
Descartes-Origins

- Hyperport gives estimates of recurring costs and turnaround times
- Initial non-recurring activity modeling is needed
- Same DES approach can be taken to quantify the variability of design, development, testing, and evaluation (DDT&E) and total first unit production (TFU) costs and schedules
- When completed, Origins can be used with Hyperport to generate full life-cycle estimates for next-generation reusable launch vehicles



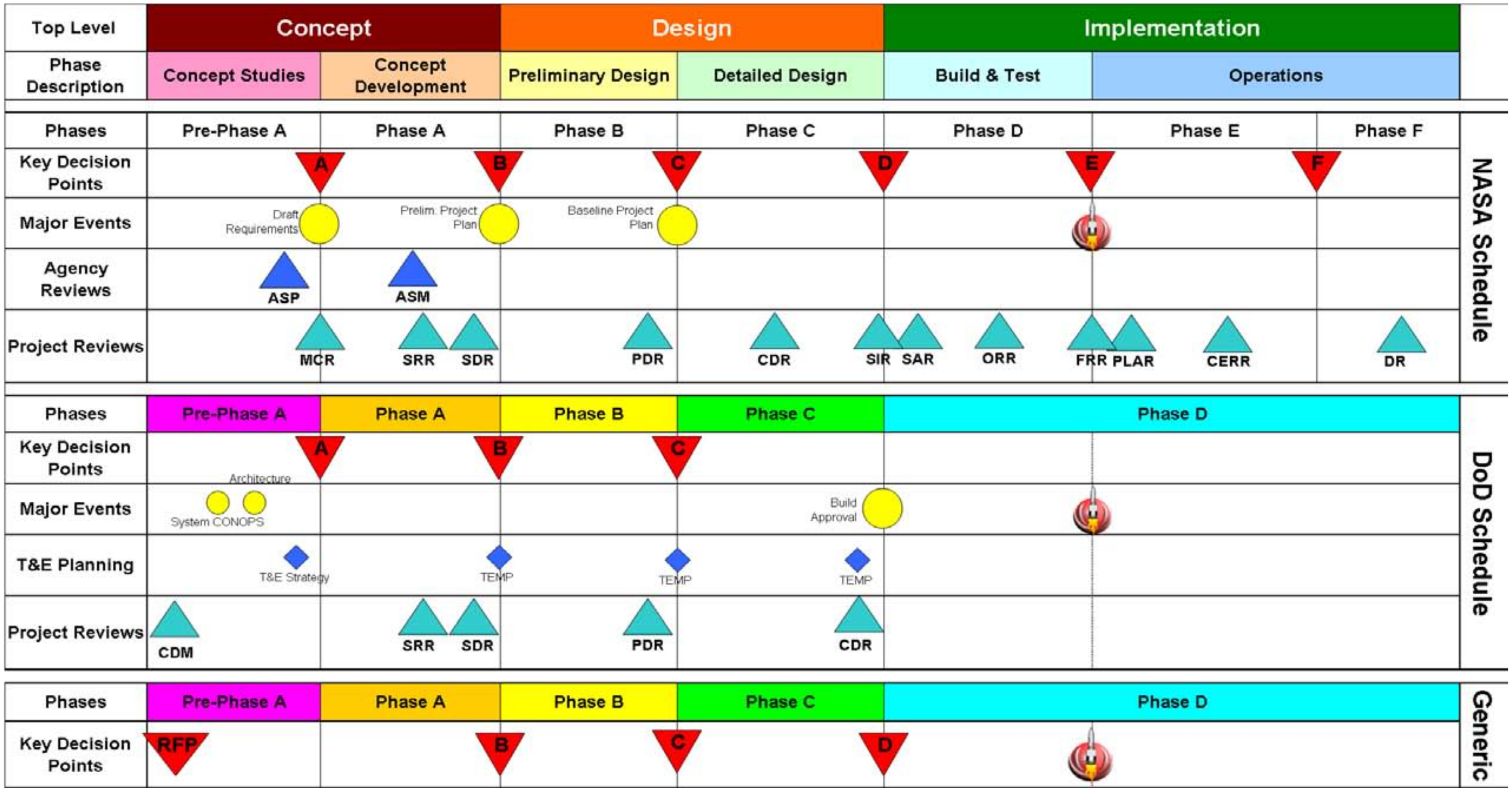
- Documents like this one lay out the various phases, milestones, processes, objectives, and other components of a large NASA acquisition program
- Similar information was gathered for DoD projects

Researching Program Process Flows



- Summary gathered from multiple sources of NASA and DoD design processes
- Some terminology differs, but general design phases are similar

Consolidating Program Process Flows



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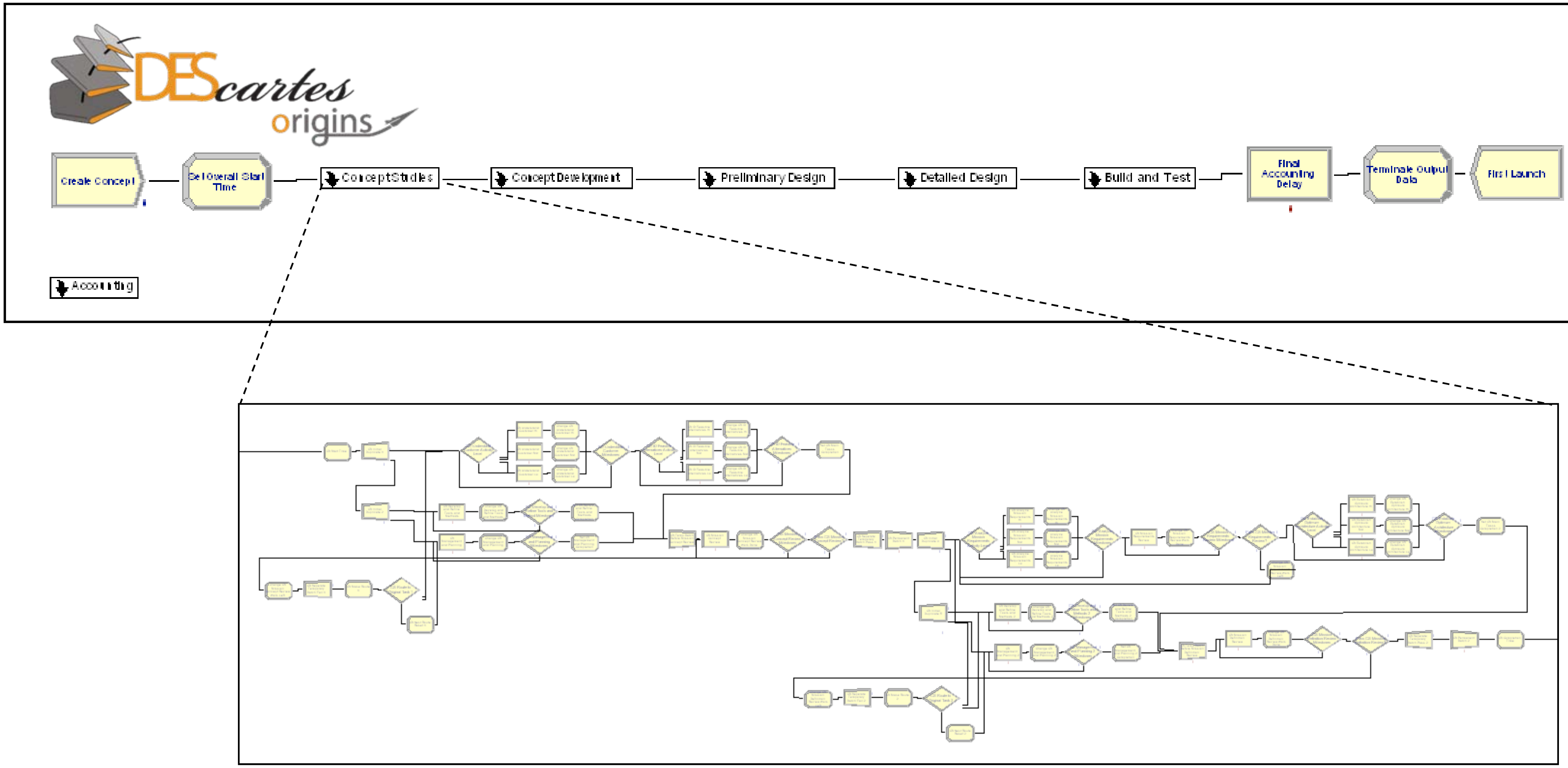
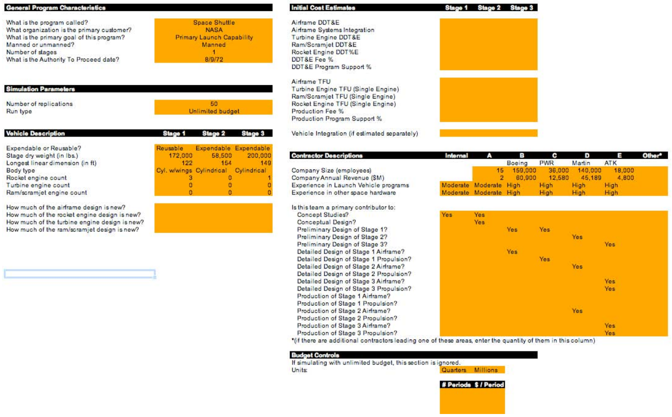
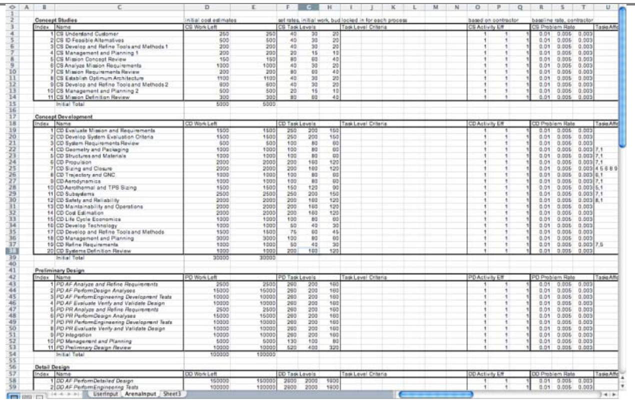
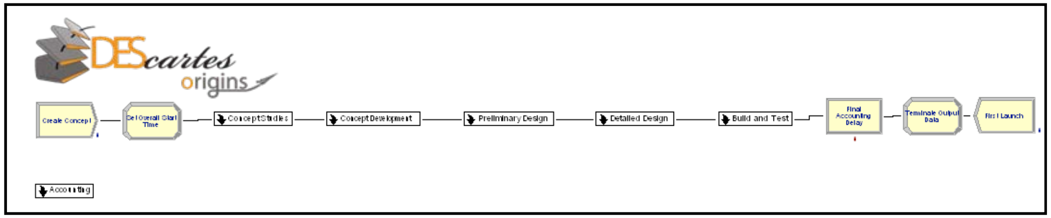


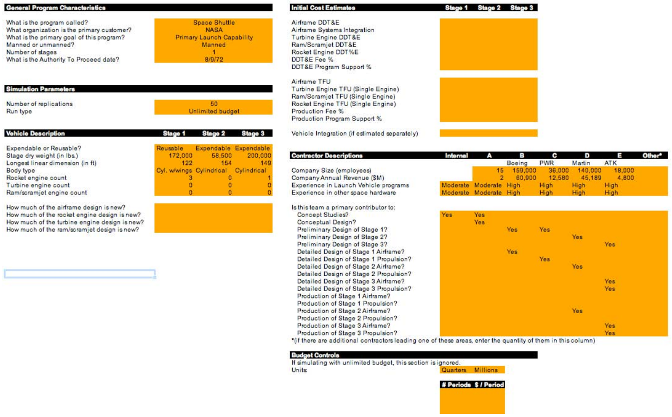
Modeling Program Process Flows

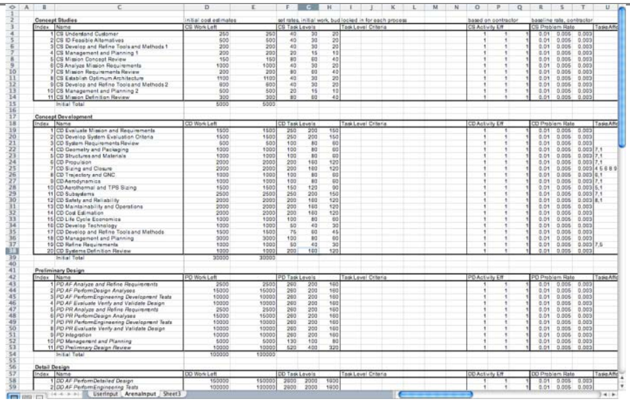


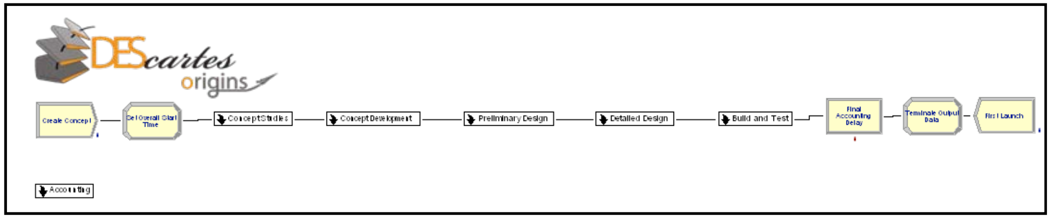


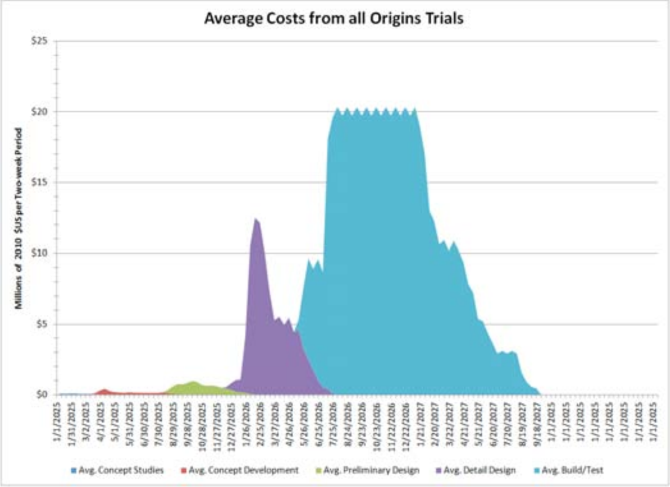


Running Origins









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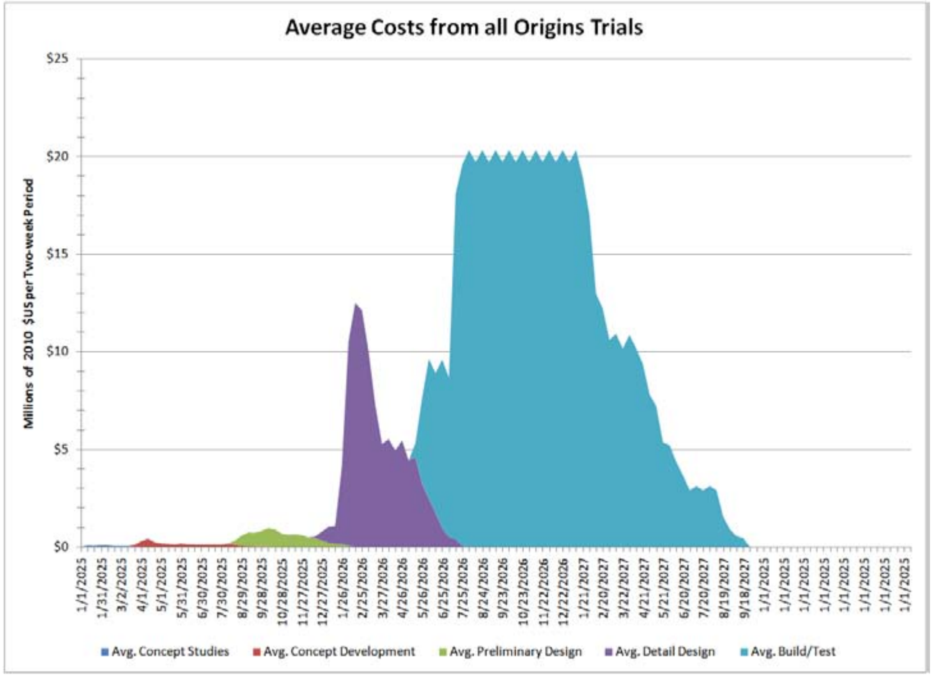
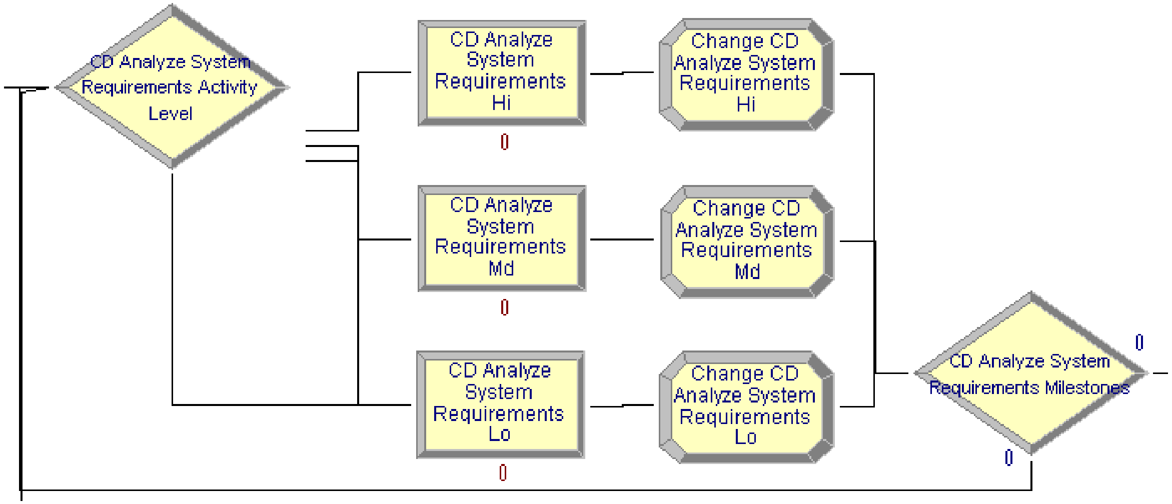


- Sand chart shows expected costs over time based on averages of numerous trials
- Separately, the model calculates averages and various measures of spread for:
  - Phase length
  - Phase completion dates
  - Total phase cost in various forms

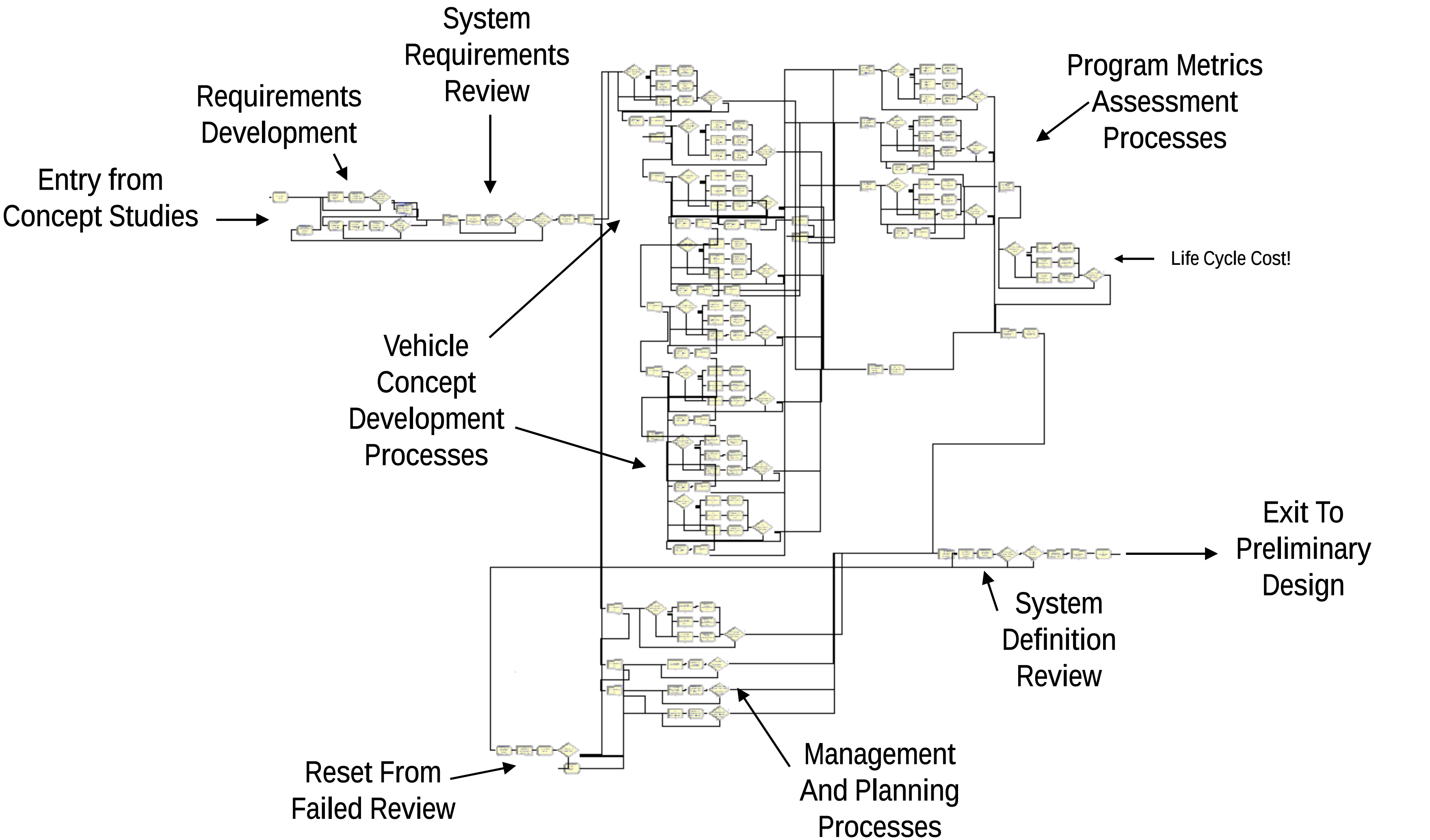
Origins Output Statistics

Model Details



- Primary ‘tasks’ are modeled using a set of 8 blocks
- A decide block routes the design entity to a process
- Process blocks represent different ‘activity levels’
  - Activity levels describe quantity of work done in a single day
  - Each process lasts exactly one day
- Assign blocks account for work done and update work left
  - Can also randomly generate ‘problems’ that increase work left
- Depending on work left, final decide can route entity back for another day of work or trigger another task to start

Origins Process Modeling



Example: Concept Development (Phase A)

- Vehicle Concept Development:
  - Geometry and Packaging
  - Structures and Materials
  - Propulsion and Integration
  - Sizing and Closure
  - Trajectory and GNC Simulation
  - Aerodynamics
  - Aerothermal and TPS Sizing
  - Subsystems
- Program Metrics Assessment:
  - Reliability and Safety
  - Maintainability and Operations
  - Cost Estimation
  - Life Cycle Cost
- Management and Planning:
  - Technology Development
  - Develop and Refine Tools and Methods
  - Refine Requirements
  - Management and Planning

- Various processes can interact with each other
  - One may trigger another once it reaches a certain % completion
  - When one finds a ‘random problem,’ that may propagate to related processes
    - Ex: if trajectory changes, aerothermal may require some do-over work
  - Failed reviews add time back on to all processes in their area

Concept Development Processes

General Program Characteristics	
What is the program called?	Space Shuttle
What organization is the primary customer?	NASA
What is the primary goal of this program?	Primary Launch Capability
Manned or unmanned?	Manned
Number of stages	1
What is the Authority To Proceed date?	8/9/72

Simulation Parameters	
Number of replications	50
Run type	Unlimited budget

Vehicle Description	Stage 1	Stage 2	Stage 3
Expendable or Reusable?	Reusable	Expendable	Expendable
Stage dry weight (in lbs.)	172,000	58,500	200,000
Longest linear dimension (in ft)	122	154	149
Body type	Cyl. w/wings	Cylindrical	Cylindrical
Rocket engine count	3	0	1
Turbine engine count	0	0	0
Ram/scramjet engine count	0	0	0
How much of the airframe design is new?			
How much of the rocket engine design is new?			
How much of the turbine engine design is new?			
How much of the ram/scramjet design is new?			

Initial Cost Estimates	Stage 1	Stage 2	Stage 3
Airframe DDT&E			
Airframe Systems Integration			
Turbine Engine DDT&E			
Ram/Scramjet DDT&E			
Rocket Engine DDT%E			
DDT&E Fee %			
DDT&E Program Support %			
Airframe TFU			
Turbine Engine TFU (Single Engine)			
Ram/Scramjet TFU (Single Engine)			
Rocket Engine TFU (Single Engine)			
Production Fee %			
Production Program Support %			
Vehicle Integration (if estimated separately)			

Contractor Descriptions	Internal	A	B	C	D	E	Other*
			Boeing	PWR	Martin	ATK	
Company Size (employees)		15	159,000	36,000	140,000	18,000	
Company Annual Revenue ($M)		2	60,900	12,580	45,189	4,800	
Experience in Launch Vehicle programs	Moderate	Moderate	High	High	High	High	
Experience in other space hardware	Moderate	Moderate	High	High	High	High	
Is this team a primary contributor to:							
Concept Studies?	Yes	Yes					
Conceptual Design?		Yes					
Preliminary Design of Stage 1?			Yes	Yes			
Preliminary Design of Stage 2?					Yes		
Preliminary Design of Stage 3?						Yes	
Detailed Design of Stage 1 Airframe?			Yes				
Detailed Design of Stage 1 Propulsion?				Yes			
Detailed Design of Stage 2 Airframe?					Yes		
Detailed Design of Stage 2 Propulsion?							
Detailed Design of Stage 3 Airframe?						Yes	
Detailed Design of Stage 3 Propulsion?						Yes	
Production of Stage 1 Airframe?							
Production of Stage 1 Propulsion?							
Production of Stage 2 Airframe?					Yes		
Production of Stage 2 Propulsion?							
Production of Stage 3 Airframe?						Yes	
Production of Stage 3 Propulsion?						Yes	

*(if there are additional contractors leading one of these areas, enter the quantity of them in this column)

Budget Controls

If simulating with unlimited budget, this section is ignored.

Units:	Quarters	Millions
	# Periods	$ / Period

User Input Sheet (in progress)

- Each task has a set of variables and arrays related to it

- Work Left (2 values)
  - The initial expected work to be done
  - The current quantity of work remaining
- Task Levels (3 values)
  - Amount of work done per day in high, medium and low-workload situations
- Activity Efficiency (3 values)
  - If many people are working on a task, the extra communication required lowers the efficiency
  - If a person spends very little time on a task, the work tends to be less productive due to start-up costs

Origins Input Variables 1

- Problem Rate (3 values)
  - The chance of a day’s worth of work uncovering some sort of problem that will require additional time/work to fix
  - Chances are higher on days working at higher activity levels
- Tasks Affected, New Work (n values)
  - A problem found in one task will add work to itself, but may also add work for other tasks
  - Actual quantity of new work is randomly generated but with a mean defined here
- Review Success Chance (1 value)
  - If a review immediately follows a task, the chance of passing the review on the first attempt
  - This value is increased on a second review attempt

Origins Input Variables 2

Conclusions

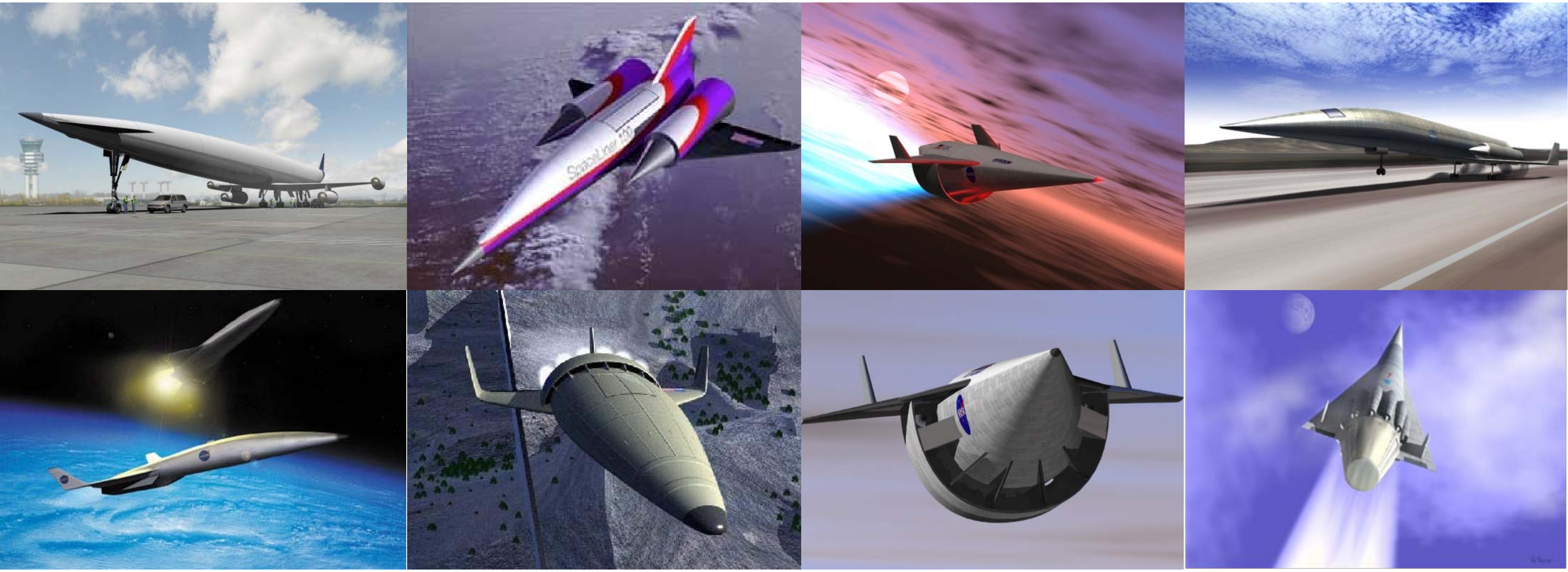
- What aspects of launch vehicle programs make them susceptible to cost overruns and/or schedule slippages?
- Are there particular phases of a project where minor slippages tend to ‘snowball’?
- Which phases tend to create the most overall variability?
- What can be done to reduce both cost and variability of cost for these programs?

…and the Big Question:

- From a complete Life Cycle standpoint, are RLVs or ELVs cheaper for a given flight rate?

Current Status and Validation and Future Work

- Private companies and government programs are developing next-generation RLVs
- Design decisions will be made based on vehicle performance, but also on cost, reliability, and long-term maintainability projections
- SEI’s Descartes tools will give programs the Life Cycle estimates they need to help make those decisions



RePast Sources: ***http://www.duncanrobertson.com/research/simulation.htm, http://sourceforge.net/projects/repast/, http://complexityworkshop.com/cw/tutorial/RePast/index.html***

Conclusions

SPACE IS GO

Engineering Today Enabling Tomorrow

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