Discrete Event Simulation of Reusable Launch Vehicle Development, Acquisition, and Ground Operations

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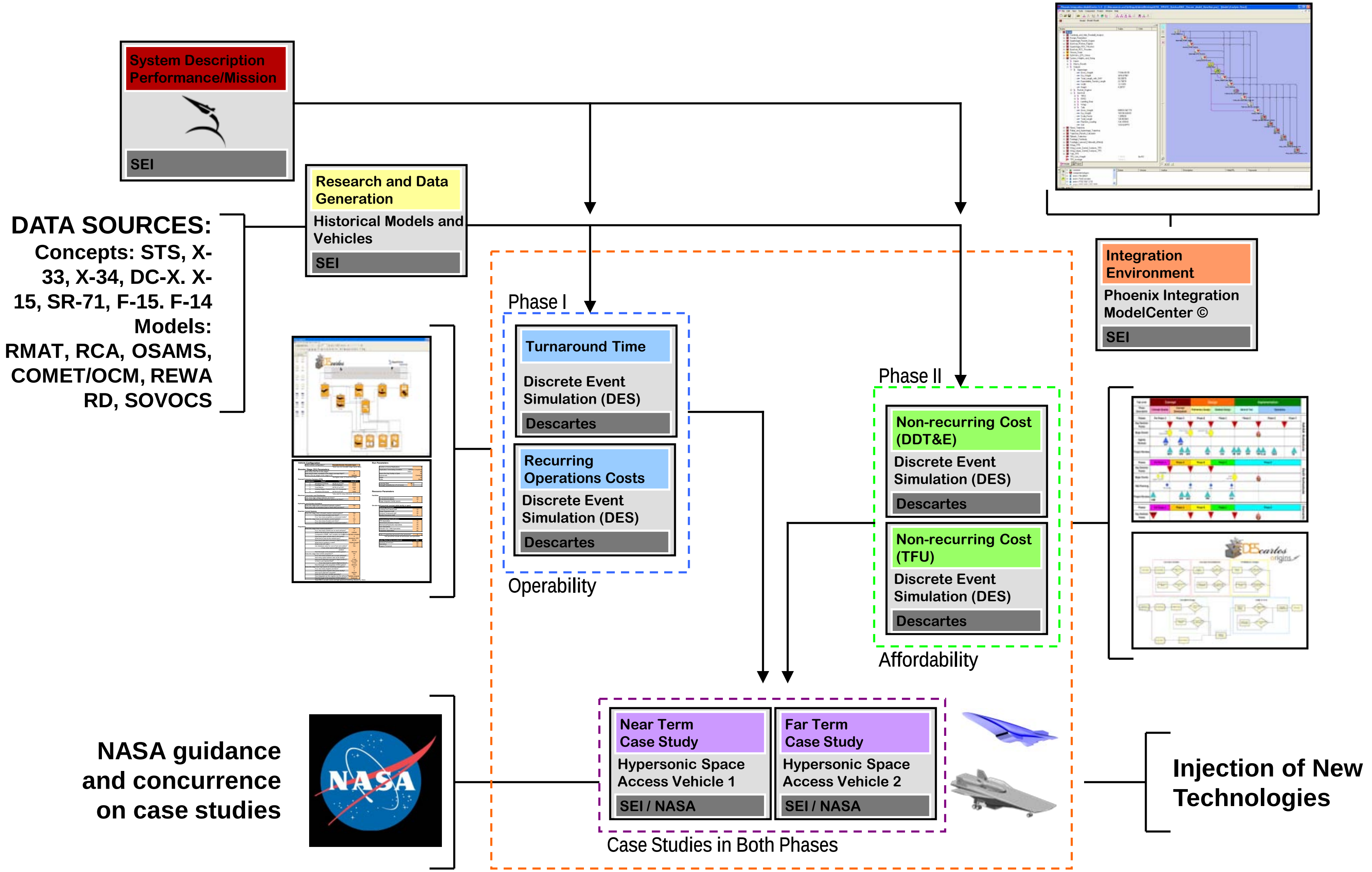
- History of predicting costs for Reusable Launch Vehicles shows room for improvement
- Leading cost driver for RLVs is the recurring ground operations
  - Existing estimation tools and methods focus on historical analogies (primarily Space Shuttle)
  - Shuttle may not be the paradigm future programs emulate
- Any cost-based design decisions must also account for DDT&E and TFU (design, development, and production) costs

STS turnaround projected to be 2 weeks

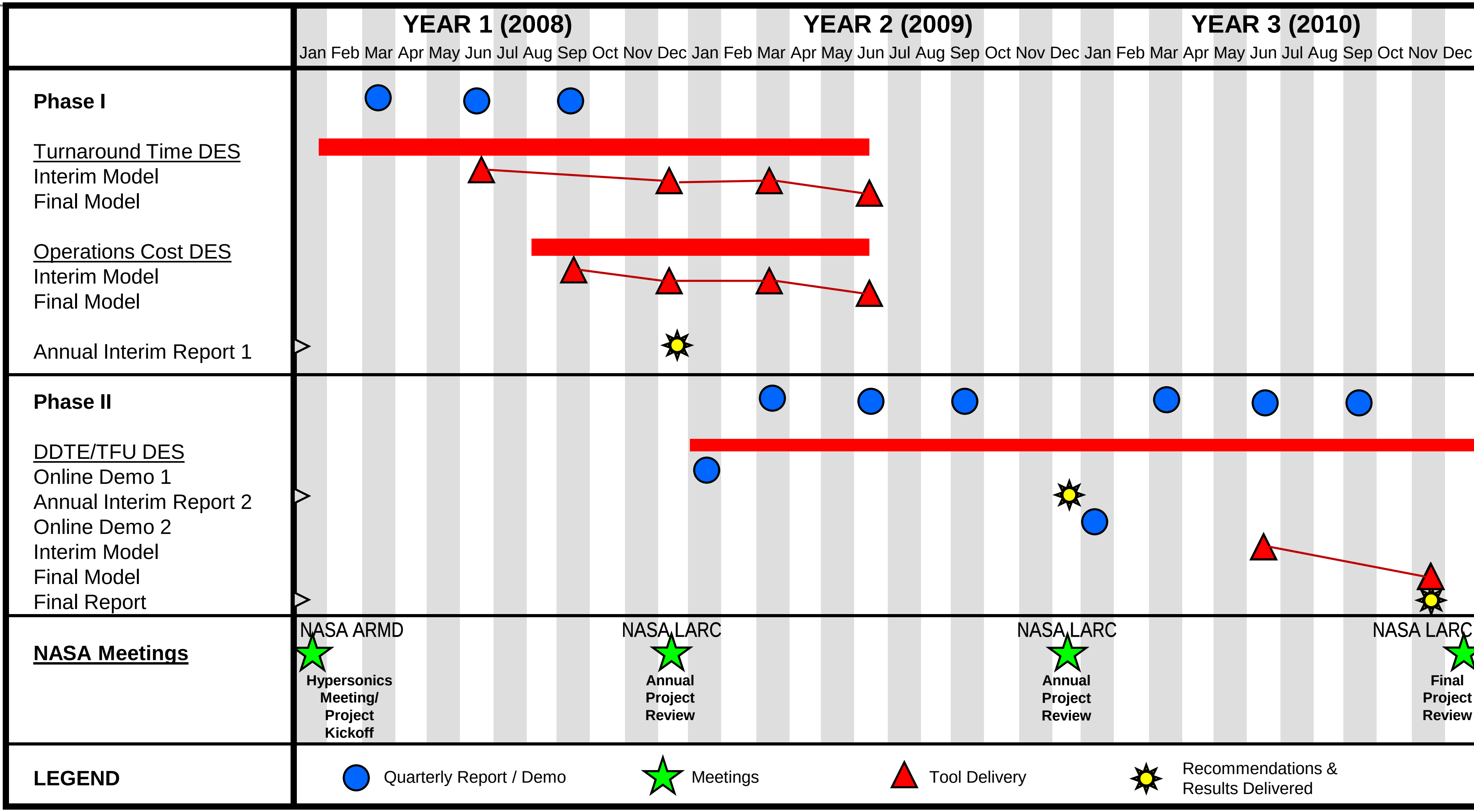
Actual turnaround takes over 3 months

- 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 VBA manipulation
  - SEI uses Arena Basic Edition version 12 for DES modeling

Descartes NRA Project



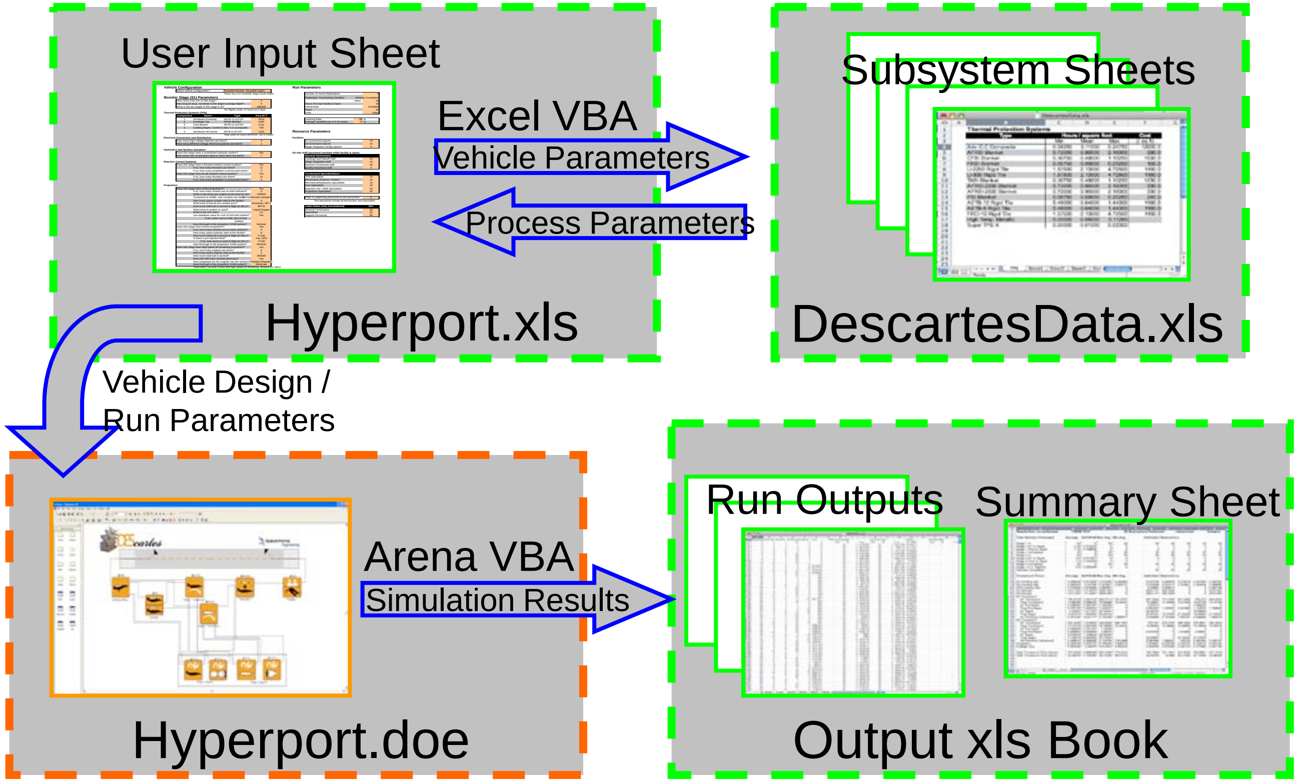
Descartes NRA Project Overview



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

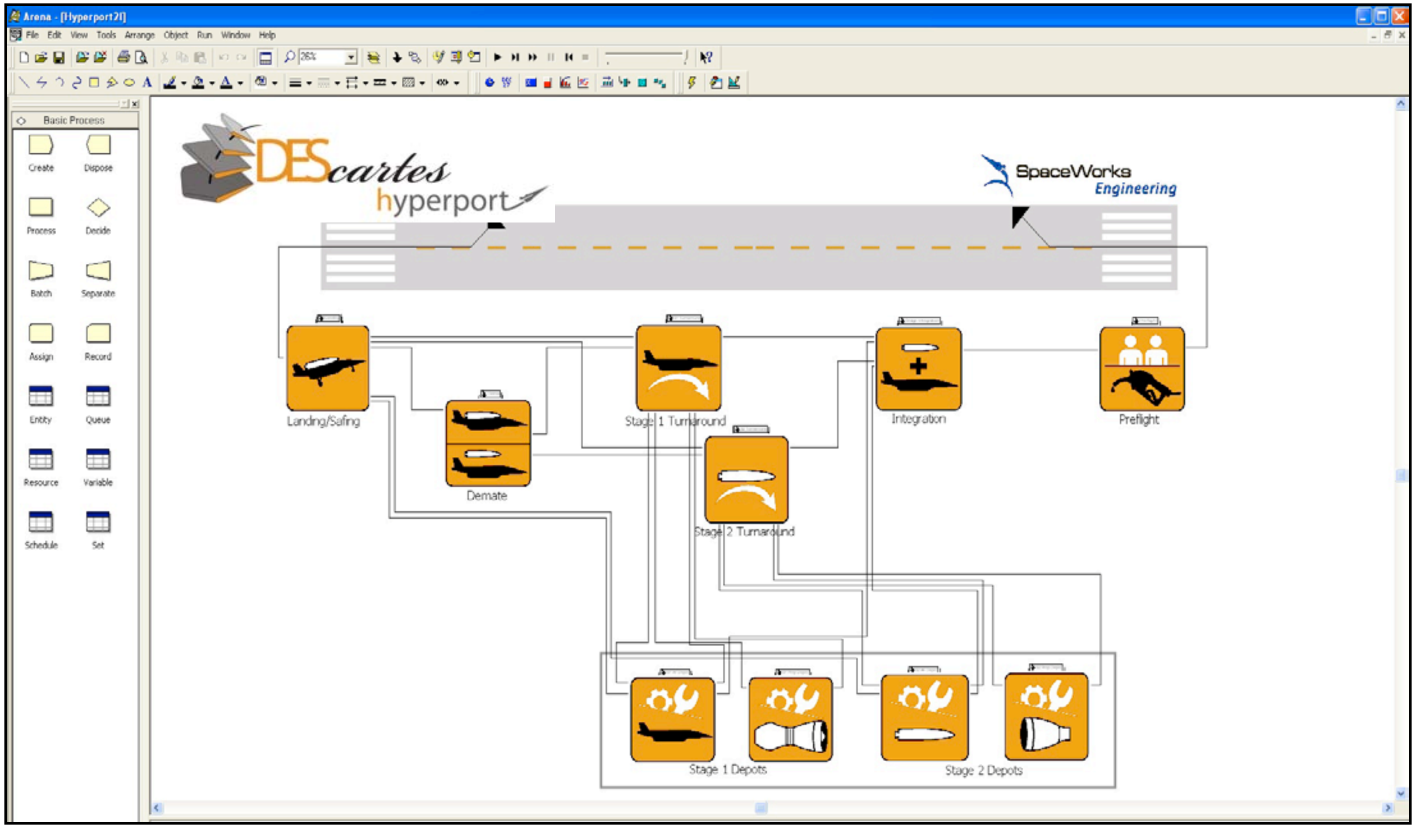
Descartes NRA Project Timeline

Descartes-Hyperport



- Descartes models consist of several files:
  - Hyperport.xls: user input, including Visual Basic (VBA) code
  - DescartesData.xls: database of historical vehicles and models
  - Arena (.doe) model file, including some VBA code
  - A user-named .xls output workbook

Hyperport Model File Interaction



- Each orange block represents a major portion of the turnaround process, potentially a unique facility
- Behind each block lies an Arena submodel

Arena Model

Creation Submodel

- Uses create blocks to instantiate entities representing stage airframes and propulsion systems
  - Entities are batched into ‘S1’ (booster) and ‘S2’ (orbiter) entities
  - First creations all occur at time 0, future creations can be spaced at intervals defined by the user
  - All entities are given unique serial numbers used to track them through their lifetime to depot visits and retirement

Mission Submodel

- Uses reliability-driven random decision blocks to determine in what condition the vehicle lands
  - Flights can be successful or result in LOV (loss of vehicle) or LOM (loss of mission)
  - LOV and LOM have model-wide consequences beyond arrival condition of vehicle

Landing Submodel

- Includes various landing processes that are performed, some depending on condition of vehicle upon arrival
  - Generally includes runway, taxi, engine safing, crew egress
  - After LOM, order is different as priorities change
  - Arrival at landing is the first ‘Event History Checkpoint’

Demate Submodel

- Needed if a LOM event happens while stages remain mated and they have to land in mated configuration
  - Demate modeled after Shuttle-747 mate/demate operation

Stage Turnaround Submodels

- Main focus of Hyperport modeling research
  - Include parallel processing of major vehicle subsystems
  - Home to 7 different labor specializations
  - More detail in a few slides

Depot Submodels

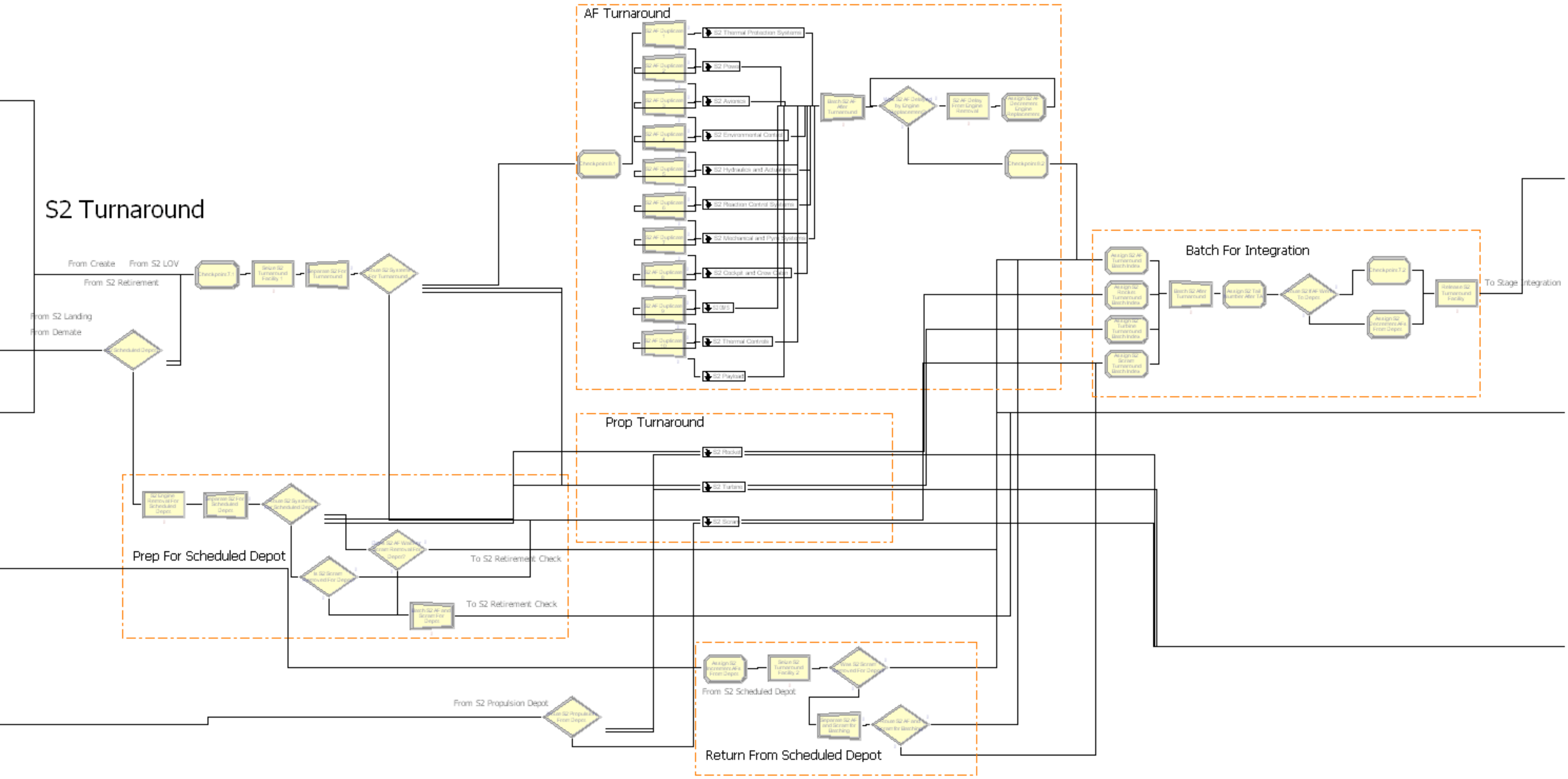
- Model both scheduled (flight count) and unscheduled (after LOM event) overhaul maintenance
  - Visit frequencies are a user input
  - Separate depots modeled for each stage and each type of propulsion system
  - Depot facility schedules tracked to limit concurrent airframe depot visits, improving fleet efficiency

Stage Integration Submodel

- Models integration of booster and orbiter into single launch vehicle
  - Separate process flows exist depending on reusable/expendable elements of vehicle configuration

Preflight Submodel

- Includes fueling of vehicle, crew boarding, late access payload, and taxi/takeoff/launch
  - 'Launch clearance' and 'Launch facility' resources used to regulate flight rates and enforce stand-down periods after LOM/LOV events



Stage Turnaround Submodels

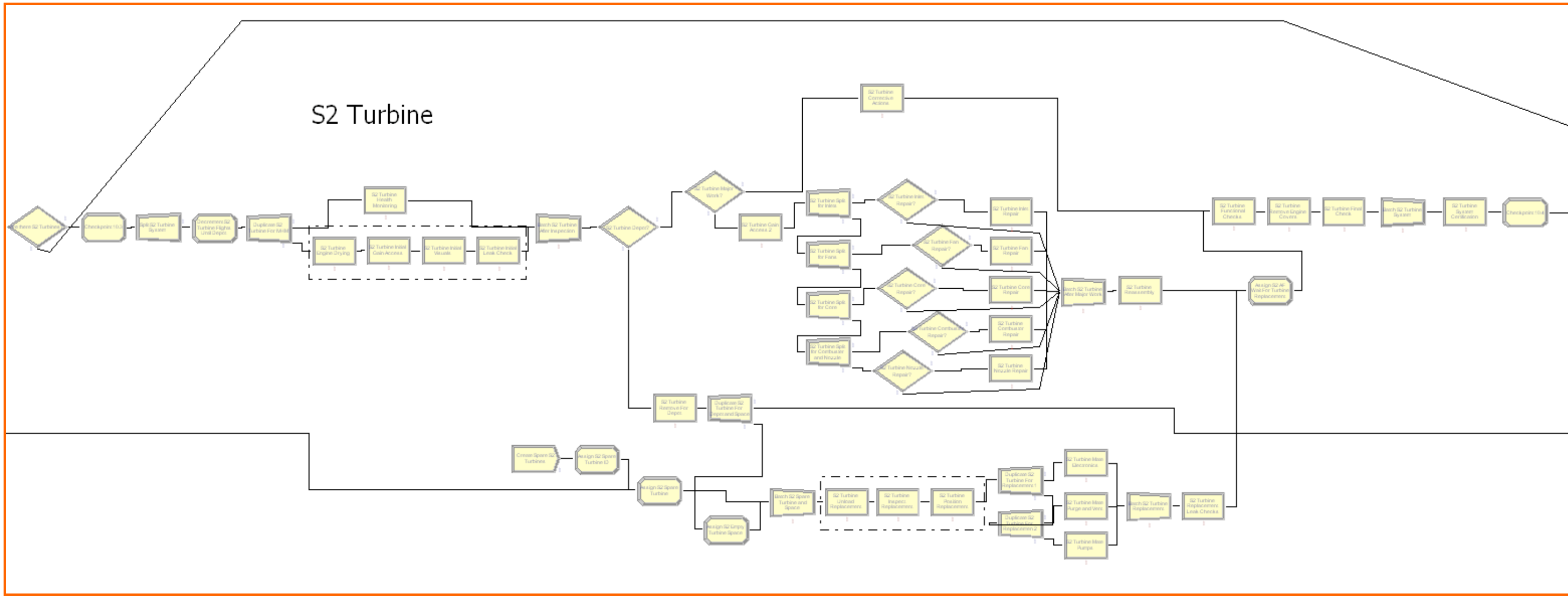
- Stage Turnaround submodels include:
  - Logical checks for scheduled depot visits
  - Division into airframe and propulsion subsystems:

    Airframe - TPS, power, avionics, environmental controls, hydraulics and actuators, reaction control systems, mechanical systems, cockpit and crew cabin, orbital maneuvering systems (S2 only), thermal controls (S2 only), payload (S2 only)

    Propulsion - rocket, turbine, and ram/scramjet
  - Various labor specializations needed for appropriate subsystem maintenance
  - Subsystem submodels include inspections, repairs, and any necessary replacements
  - Total turnaround time is tracked, as well as time for TPS and propulsion submodels independently

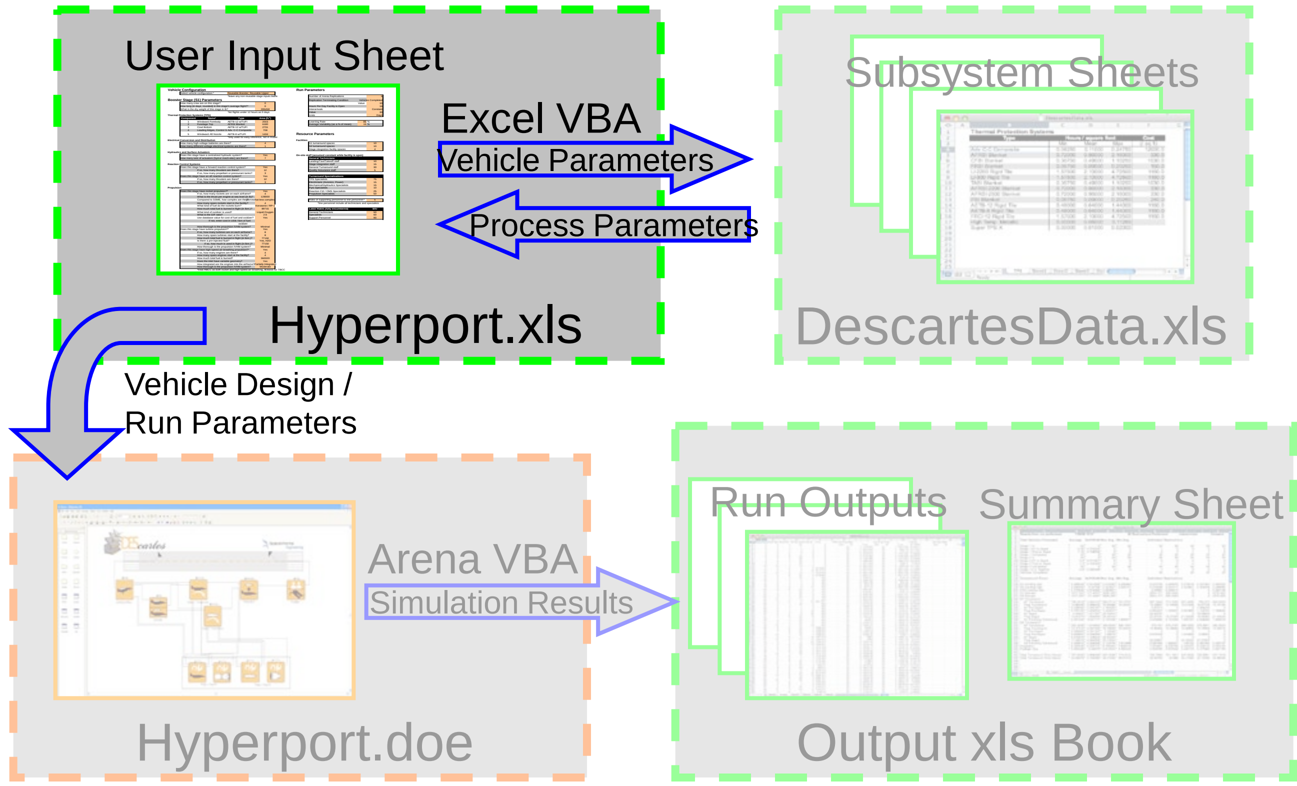
Stage Turnaround Submodels

- Propulsion submodels include around 25 processes each



- Possible flows include regular maintenance, major work (potentially requiring engine removal from airframe), and removal for depot work
- All removals also require engine replacement, possibly from supply of spares

Propulsion Submodels



- Hyperport.xls is the central user input sheet and primary VBA driver of Descartes-Hyperport
  - UserInput sheet takes vehicle, program, and simulation inputs
  - ArenaInput sheet converts these into form used by .doe file
  - LaborGuess sheet helps make initial estimates of labor required

- Almost 100 vehicle design questions including:
  - Types and acreages of TPS components
  - RCS thruster and tank counts
  - Types of engines with quantities, thrust levels, and fuel required
- Other questions include:
  - Quantity of Arena replications to perform
  - Program length
  - Vehicle reliability metrics
  - Quantities and costs of various labor specializations

Vehicle Configuration

Select vehicle configuration:*	Reusable Booster, Reusable Upper

*leave any non-reusable stage inputs blank

Booster Stage (S1) Parameters

How many crew are on this stage?	0
How long (in days, rounded) is this stage's average flight?*	0
What is the dry weight of this stage in lb?	285458

*list flights under 12 hours as 0 days

Thermal Protection Systems (TPS)

Component	Name*	Type	Area ($ft.^2$)
1	Windward Forebody	AETB-12 w/TUFI	2015
2	Fuselage Top	AFRSI Blanket	6180
3	Cowl Bottom	AETB-12 w/TUFI	2731
4	Leading Edges, Control S	Adv. C-C Composite	708
5	Windward Aft Nozzle	AETB-8 w/TUFI	1434

*only used for easy reference, not in model

Electrical Conversion and Distribution

How many high-voltage batteries are there?	4
How many different-voltage electrical systems are there?	1

Hydraulics and Surface Actuators

Does this stage have a centralized hydraulic system?	Yes
How many sets of actuators (hyd.or mech-elec) are there?	7

Reaction Control Systems

Does this stage have a forward reaction control system?	Yes
If so, how many thrusters are there?	12
If so, how many propellant or pressurant tanks?	3
Does this stage have an aft reaction control system?	Yes
If so, how many thrusters are there?	12
If so, how many propellant or pressurant tanks?	3

Propulsion

Does this stage have rocket propulsion?*	Yes
If so, how many rockets are on each airframe?	4
What is the thrust per engine at sea level (in lb)?	128000
Compared to SSME, how complex are they?	Somewhat less complex
How many spare rockets start in the facility?	4
What kind of fuel do the rockets burn?	Kerosene / RP-1
How much total fuel is burned in flight (in lbm.)?	89715
What kind of oxidizer is used?	Liquid Oxygen
What is the O/F ratio?	2.6
Use database value for cost of fuel and oxidizer?	Yes
If not, enter cost in US$ / lbm of fuel:	
oxidizer:	
How thorough is the propulsion IVHM system?	Minimal
Does this stage have turbine propulsion?*	Yes
If so, how many turbines are on each airframe?	8
How many spare turbines start at the facility?	8
How much total fuel is burned in flight (in lbm.)?	77150
Is there a pre-injected fluid?	Yes, H2O
If so, how much is used in flight (in lbm.)?	77150
How thorough is the propulsion IVHM system?	Minimal
Does this stage have high-speed air-breathing propulsion?*	Yes
If so, how many engines are there?	4
How many spare engines start at the facility?	4
How much total fuel is burned?	360320
Does the inlet have variable geometry?	Yes
How integrated are the engines into the airframe?	Partially Integrated
How thorough is the propulsion IVHM system?	Moderate

*treat RBCC as both rocket and high-speed air-breathing, likewise for TBCC

Run Parameters

Number of Arena Replications	5
Replication Terminating Condition	Vehicles Completed
Value	10
Hours Per Day Facility is Open	16
Interarrivals	Constant
Value	30
Units	Days

Learning Rate	85	%
Average Variability (as a % of mean)	15	%

Resource Parameters

Facilities

S1 turnaround spaces	10
S2 turnaround spaces	10
Stage integration facility spaces	4

On-site staff (assumed constant while facility is open)

General Technicians	
Landing/Taxi/Takeoff staff	10
Stage Integration staff	15
General Turnaround staff	30
Quality Assurance staff	5

Turnaround Specializations	
TPS Specialists	75
Electricians (Avionics, Power)	15
Mechanical/Hydraulics Specialists	15
Pyro Specialists	10
Reaction Ctrl / OMS Specialists	25
Propulsion Specialists	50

Ratio of supporting personnel to line personnel:*	5

*line personnel include all technicians and specialists

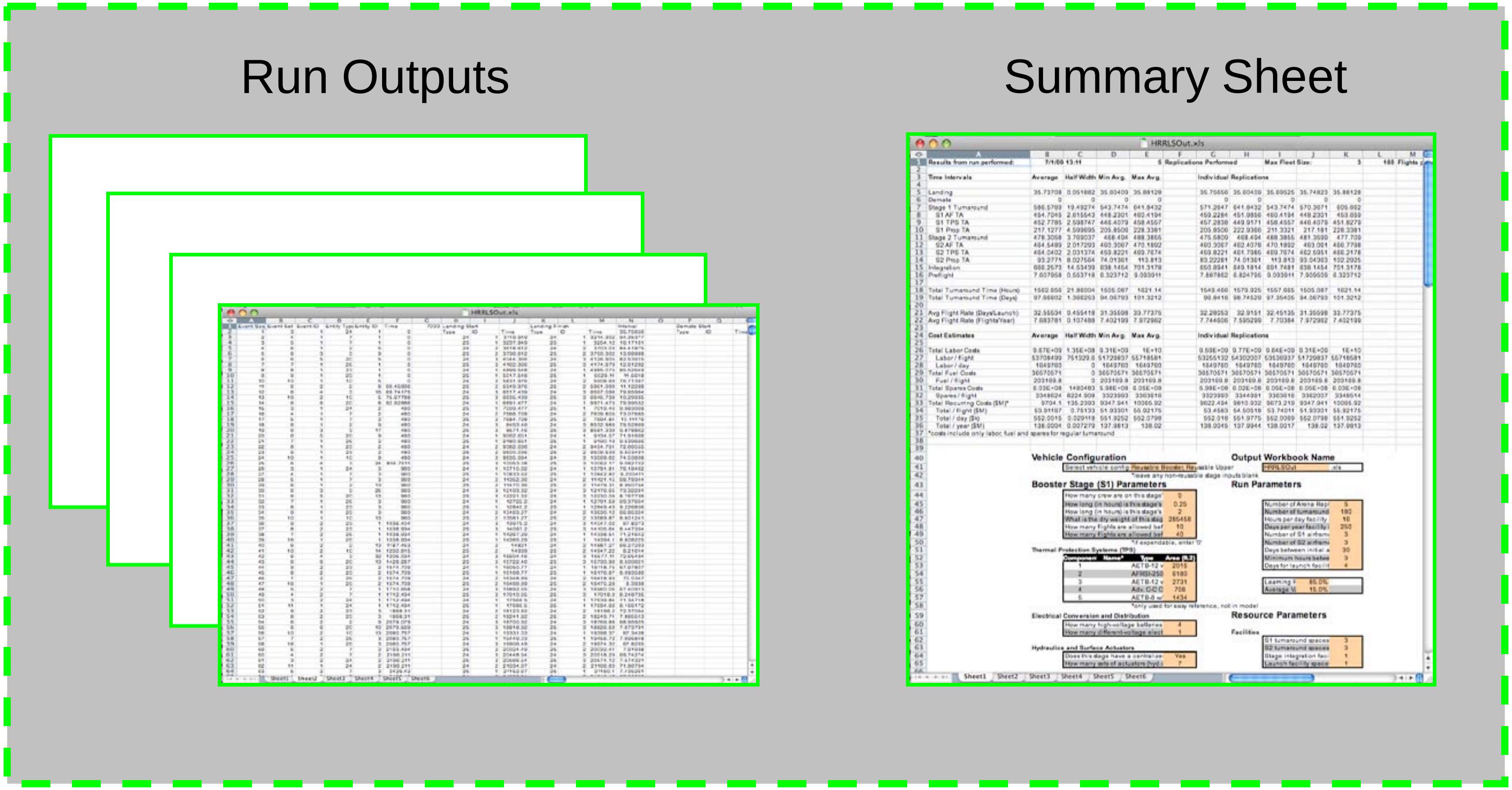
Labor Rates (fully encumbered)	$/hr
General Technicians	50
Specialists	60
Support Personnel	90

UserInput Sheet

- Excel VBA is used to convert user inputs into process characteristics needed by Arena
  - Accesses DescartesData, a subsystem-level database of historical man-hour requirements
  - Combines DescartesData with UserInput to generate arrays of variables of process times and labor requirements for over 300 processes
  - Stores data arrays in ArenaInput sheet
- Before running simulation, LaborGuess sheet can be used to save time by focusing trials on feasible region
  - Uses Excel Solver to solve mixed integer program
  - Taking inputs of desired flight rate and ArenaInput sheet, generates estimate of labor quantities needed to achieve rate
  - Can be used iteratively after initial trials to refine estimates

DescartesData, ArenaInput, and LaborGuess

- Event history is recorded for each simulation run and exported to Excel
- This list of events is used to calculate summary statistics



Running Arena and Processing Outputs

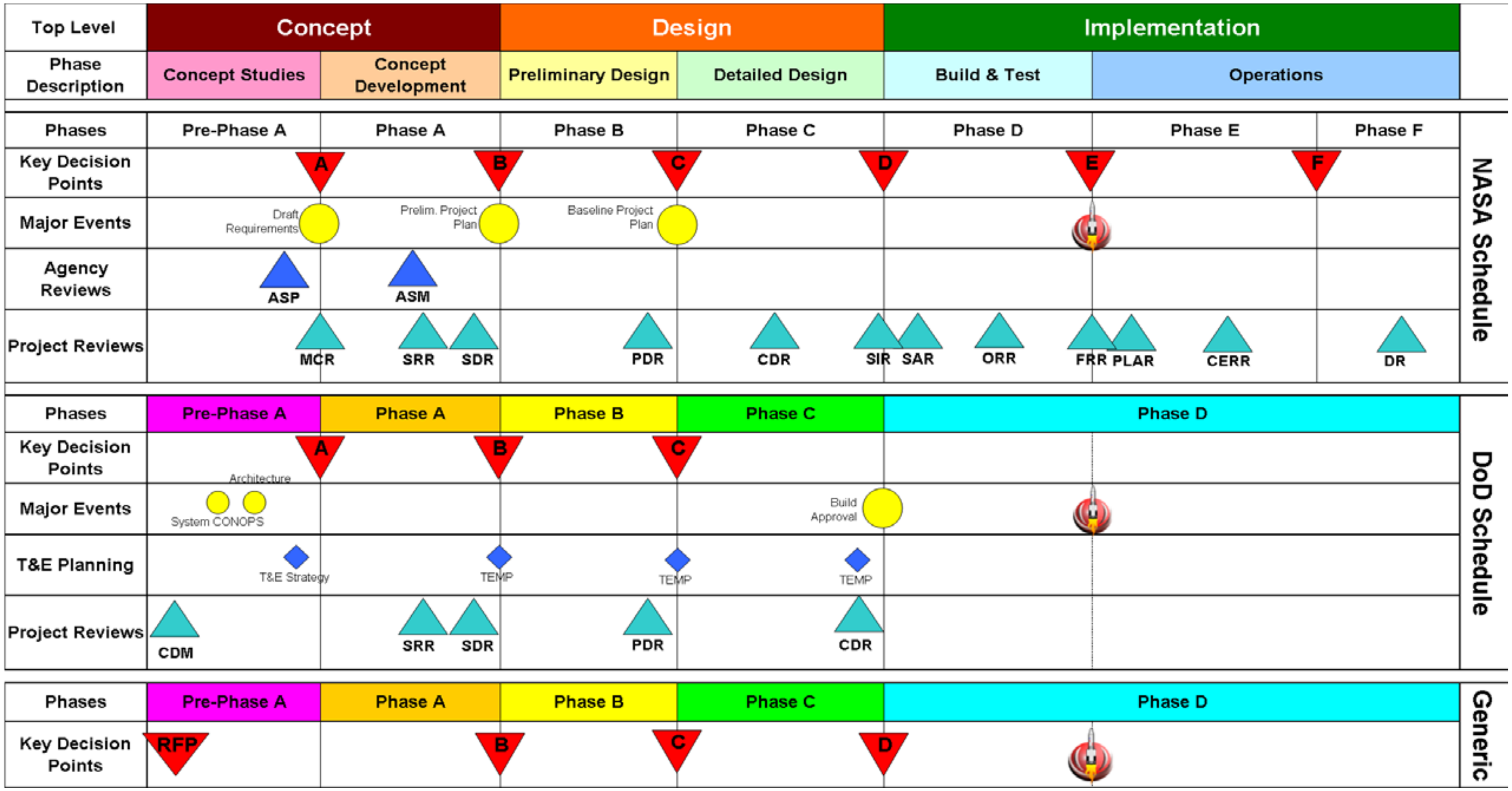
- Hyperport outputs turnaround times and recurring costs
- Turnaround times are broken down into:
  - Average time for each phase (landing, integration, etc)
  - Average time for each stage's TPS, airframe, and propulsion
  - Flight rate (days/flight and flights/year)
- Recurring costs are composed of:
  - Fuel cost (total and per flight)
  - Spares cost (total and per flight)
  - Labor cost (total, per flight, and per year)
- Taken together, these metrics give a picture of how frequently an RLV can be flown, and at what cost

Descartes-Origins

- Hyperport gives estimates of recurring costs
- Initial non-recurring cost estimates needed
- Government and commercial models include NAFCOM, SEER, and Transcost
- Same DES approach can be taken to quantify design, development, testing, and evaluation (DDT&E) and total first unit production (TFU) costs

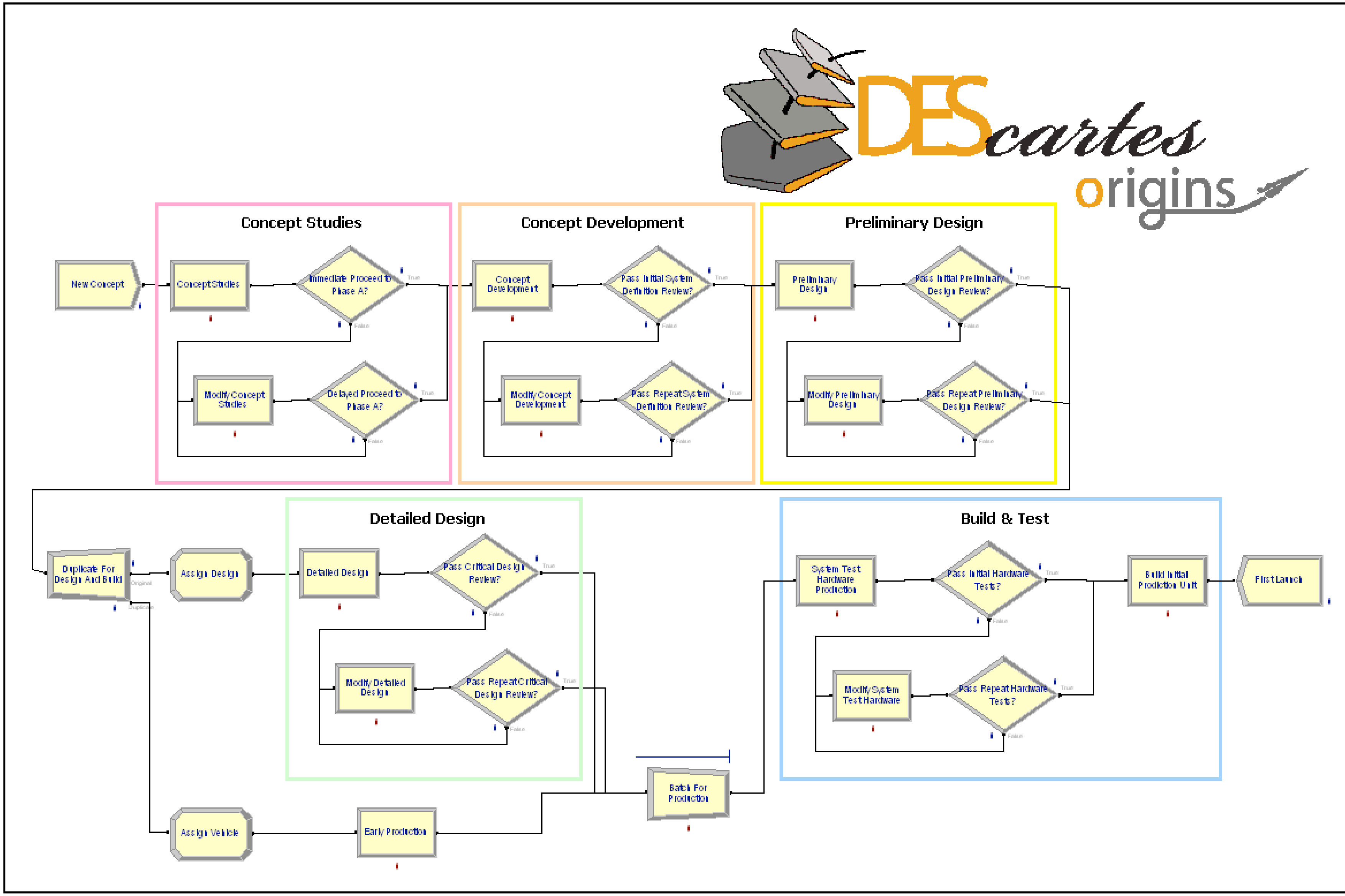
- When completed, Origins can be used with Hyperport to generate full life-cycle cost estimates for next-generation reusable launch vehicles

Descartes-Origins Objective

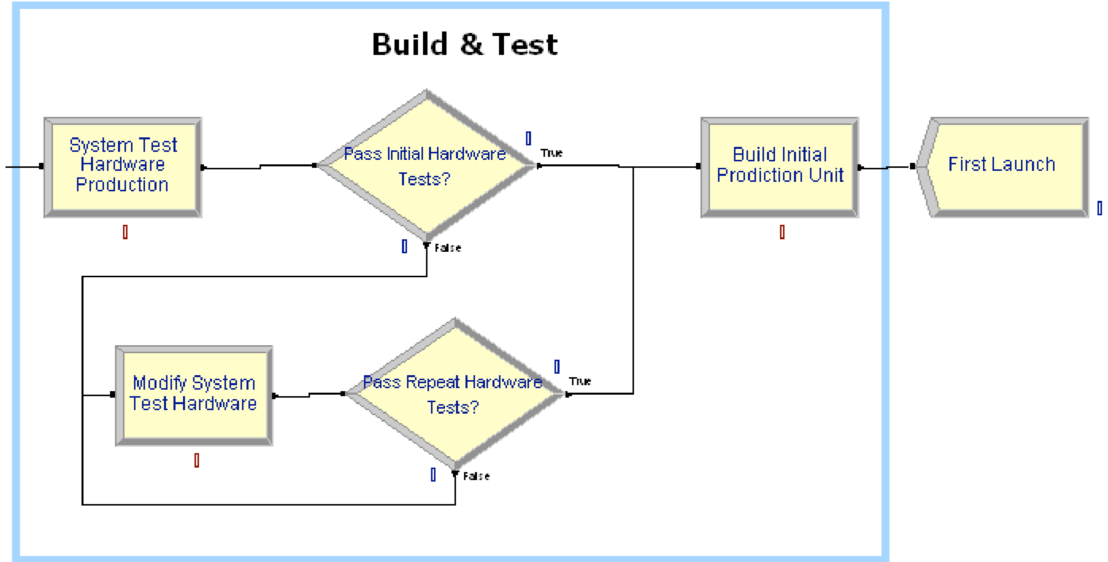


- Summary gathered from multiple sources of NASA and DoD design processes
- Some terminology differs, but general design phases are similar
- Is being used to help identify key steps and requirements for each phase and gateway

Design Process Schedule

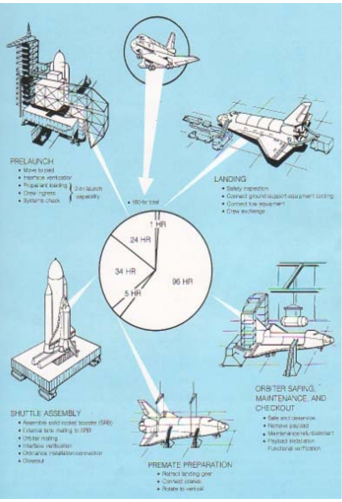


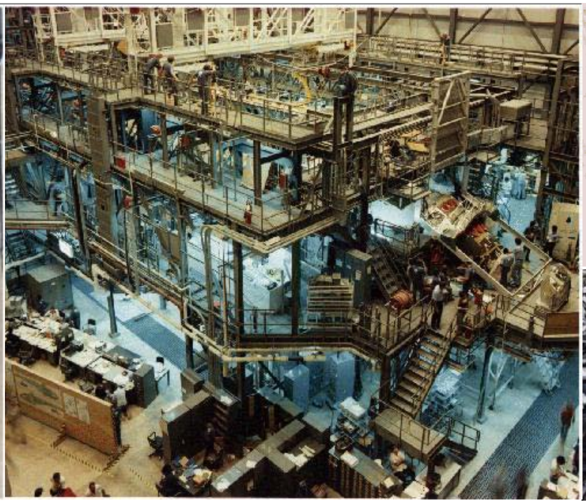
Arena Model In Progress



- Process times will be based on vehicle systems and complexity
  - Some questions will be similar to Hyperport subsystem inputs
  - Others will be similar to NAFCOM, like % new design
- Program characteristics matter too
  - Contractor design vs in-house design
  - Skunkworks approach vs Constellation approach
- Review success probabilities will be based on the same sorts of input metrics
  - There may be variables that make design take longer, but review success more likely, and/or modification times take less time

Conclusions

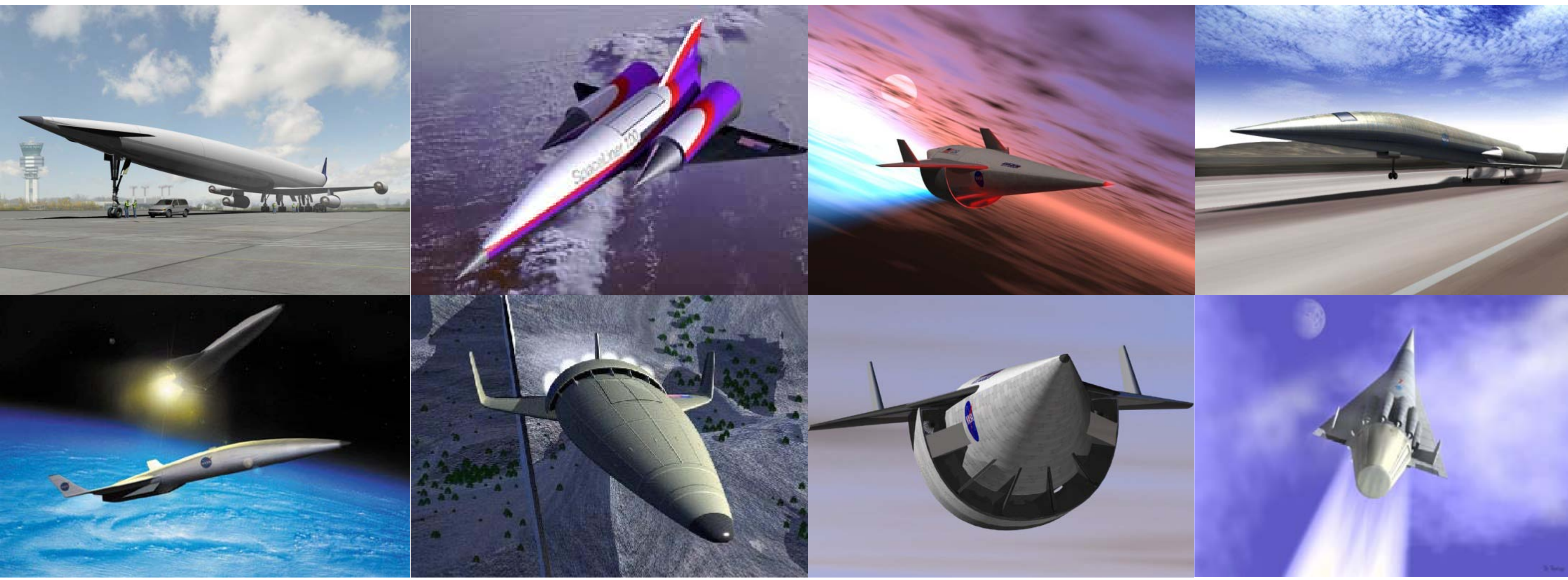


- A need exists to consistently and reliably estimate reusable launch vehicle program costs and timelines
- DES’ ability to model complex systems is well-suited to solving this problem
- Hyperport has performed well as a proof-of-concept
- Origins will take advantage of lessons learned to become an equally helpful tool

Conclusions

- 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 estimates they need to 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

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