Formulating Discrete Event Simulation for Development and Acquisition Cost Analysis of Reusable Launch Vehicles

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INTRODUCTION
KEY CUSTOMERS AND PRODUCTS
SpaceWorks-Software (SEI-S) Products

Aerospace Engineering

- REDTOP-Lite (propulsion)
- REDTOP-Pro (propulsion)
- Remix (scripting for cost tools)
- Sentry (TPS sizing)

Optimization and Robust Design

- OptWorks: Excel (non-gradient optimizers)
- ProbWorks: Excel (robust design)
- TraGE-X (trajectory visualization)
- Bullseye (interplanetary trajectories)
- Two-Stage-to-Orbit (TSTO) All-Rocket Military Space Plane Design
  - Air Force Research Laboratory (AFRL) - Wright Patterson Air Force Base
- Ares V Payload Uncertainty Quantification Analysis
  - NASA Marshall Space Flight Center (NASA Constellation)
- Hero Collaborative Engineering Environment for Reusable Launch Vehicle (RLV) Design
  - Air Force Research Laboratory (AFRL) - Wright Patterson Air Force Base
- Reusable Rocket-back Booster Demo Vehicles Study
  - Air Force Research Laboratory (AFRL) - Wright Patterson Air Force Base
- Novel Scram-Rocket RBCC Engine Design Research (SCAAT Engine)
  - DoD Small Business Innovative Research (SBIR) grant
- Discrete-Event Simulation of Hypersonic Launch Vehicle Development and Acquisition Cost
  - NASA Langley Research Center, NASA Aeronautics Research Mission Directorate (ARMD)
- Human Lunar Surface Systems Cost Assessment
  - NASA's Human Lunar Exploration Program (NASA Constellation Strategic Analysis Cost Team)
- Innovative Space Access Vehicle Studies (C&I Research)
  - NASA Langley Research Center
- FastForward Study
  - Industrial team to research high-speed intercontinental package/passenger delivery
- Economic Analysis of Space Solar Power (SSP)
  - International Academy of Astronautics (IAA) study
- Future Demand Projections for Small Satellites (Market Quantification Study)
- Google Lunar X-Prize (GLXP) Partnership with Astrobotic Technologies, Inc.

SAMPLE OF PROJECTS IN 2009
BACKGROUND
“The Space Shuttle Orbiter is designed for a 2-week ground turnaround, from landing to relaunch. About 160 hours of actual work will be required.”

Source: NASA SP-407, Space Shuttle, ca. 1976; p. 4

Average STS calendar days in Orbiter Processing Facility (OPF) from 1990 to 1997 was 88 days

History of predicting costs for Reusable Launch Vehicles (RLVs) 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
− The world is complex
− Complex interactions (human to human, human to machine, machine to machine)
− Dynamic events happen -> outcomes change
− **Methods such as MS Excel strain to model dynamic complexity**
- 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 OVERALL PROJECT MAP: 2008-2010

Phase I (Hyperport) was completed June 2009.
Phase II (Origins) is currently underway.

DESCARTES NRA PROJECT
**System**
HTHL TSTO with RTLS, Reusable Booster and Expendable Upperstage
Gross Weight: 682,000 lbs
Booster: 575,000, Upperstage: 88,435
Payload: 13,090

**Booster**
2-D lifting body capable
Fully autonomous flight
Mach-8 SOL with 3-ramp compression
H₂O₂/JP-7 propellants
(6) advanced turbines Mach 0-3.6
(4) DMSJ from Mach 3.6–8
(4) Tail Rockets for transonic and from Mach 8 to ~9 (staging)
ACC, AFRSI, and CRI TPS
EHAs, IVHM
Gr-Ep airframe, Ti-Al wings/tails

**Upper stage**
H₂O₂/JP-7 propellants
Single aft rocket
Orbital Insertion: 70x197 nmi. @28.5°

SAMPLE CASE STUDY VEHICLE: QUICKSAT MILITARY SPACE PLANE
- **Descartes**: SpaceWorks Engineering’s aerospace discrete event simulation modeling framework using Arena® by Rockwell Automation

- **Descartes-Hyperport**: Implementation of a discrete event simulation model for turnaround time and recurring operations cost analysis of future reusable launch vehicles
  - Consists of multiple submodels within Arena
    - Full Arena animation, with entity and facility icons, basic on-screen statistics
    - Full run control: length, replications, fleet sizes
  - MS Excel-based set of user inputs for vehicle concept
    - Arena-embedded inputs for various subsystem-level parameters based upon historical process times and costs
  - Range of simulation statistics output to MS Excel
    - Entity counters from several checkpoints
    - Turnaround time, broken down by facility
    - Recurring operations costs (labor, fuel, spares)
    - Show inputs from run in same sheet for easy reference
  - Application of Descartes-Hyperport to various hybrid and reusable launch vehicle specific case studies

**DESCARTES-HYPERPORT**
Mission → Landing → Turnaround → Integration → Flight Operations

Inputs / Outputs
(user inputs of vehicle, Arena run parameters)
MS Excel Workbook

Database (historical times/costs)
MS Excel Workbook

Per Stage
Per Airframe Subsystem
Per Propulsion System

Mate/DeMate

Depot

DESCARTES-HYPERPORT: MODEL SCHEMATIC
Each orange block represents a major portion of the turnaround process, potentially a unique facility.

Behind each block lies an Arena submodel.

DESCARTES-HYPERPORT: ARENA MODEL
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**
DESCARTES-HYPERPORT MODEL

**Stage 1 Turnaround Submodel Detail**

**Turnaround Activities**
- Stage 1 Depots
- Stage 2 Depots

**Depot Activities**
- Turnaround Time (hours)

**Arrival Activities**
- Landing/Boarding

**Integration Activities**
- Stage 1 Turnaround
- Stage 2 Turnaround

**Flight Ops Activities**

**Turnaround Time (hours)**

**Stage 1 Turnaround Submodel Detail**

**Breakdown of Turnaround Man-Hours**
- S1 TPS
- S1 other AF
- S1 Prop
- S2 TPS
- S2 other AF
- S2 Prop
- Other

**Outputs: Turnaround Times and Recurring Operations Cost**

**Inputs: Vehicle and Arena**
Stage turnaround currently consists of airframe processing submodels and propulsion processing submodels:

- **Airframe**: TPS, Structures, Power, Avionics, Env. Control, Hydraulics/Actuators, RCS, Mechanical/Pyro; OMS, Thermal Control, Payload, Cockpit/Cabin
- **Propulsion**: Rocket, Turbine, High-speed Air-breathing

**DESCARTES-HYPERPORT SUBMODEL: TURNAROUND**
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.

DESCARTES-HYPERPORT SUBMODEL: PROPULSION
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

**INPUTS**
- Event history is recorded for each simulation run and exported to Excel
- This list of events is used to calculate summary statistics
- 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
- For a set labor quantity and fleet size, what flight rate can be achieved?
- For a set fleet size, how much labor is needed to achieve a certain flight rate?
- How much can a flight rate be improved by increasing various labor specializations?
- Which vehicle systems are contributing the most to overall turnaround time?
- How much would certain configuration changes improve overall turnaround time?
- What are the O&M cost tradeoffs between larger fleet sizes and the potential higher labor utilization rates?
- What is the ‘call up time,’ or fastest turnaround possible for a short series of high-priority flights?
- What is the marginal cost of extending a program by a single flight?
- How do vehicle replacement decisions affect times and costs?
- How does flight rate improve over time with learning?

More complex questions can also be answered
- How given technology updates would affect overall turnaround times
- Data collection available on lower-level processes to more precisely identify bottlenecks and trouble spots
- Improved labor optimization to predict ideal groupings of specializations (or cross-training) required to minimize turnaround time and/or cost

QUESTIONS ANSWERED WITH DECARTESES-HYPERPORT
- Descartes-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

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<tr>
<th>Top Level</th>
<th>Concept Studies</th>
<th>Concept Development</th>
<th>Preliminary Design</th>
<th>Detailed Design</th>
<th>Build &amp; Test</th>
<th>Operations</th>
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<td>Phase C</td>
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NASA Schedule

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<td>TEMP</td>
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DoD Schedule

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<th>Phase C</th>
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Generic
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

DESIGN PROCESS SCHEDULE
- 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
  - Descartes Hyperport has performed well as a proof-of-concept
  - Descartes Origins will take advantage of lessons learned to become an equally helpful tool

- 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

CONCLUSIONS