Application of Design of Experiments and Surrogate Modeling within the NASA Advanced Concepts Office, Earth-to-Orbit Design Process

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Outline

1. Introduction
2. Current Design Process and Tools
3. Design Process Augmentation
4. Example Problem
Decisions made during early conceptual design can have a profound impact on life-cycle cost (LCC)
- Widely accepted that nearly 80% of LCC is committed
- Decisions made during early design must be well informed

Advanced Concepts Office (ACO) at Marshall Space Flight Center aids in decision making for launch vehicles
- Provides rapid turnaround pre-phase A and phase A studies
- Provides customer with preliminary vehicle sizing information, vehicle feasibility, and expected performance
ACO toolset consists of three primary tools for launch vehicle design

- **INTegrated ROcket Sizing (INTROS):** Excel based tool utilizing MERs derived from historical vehicles to estimate system/sub-system masses

- **Launch Vehicle Analysis (LVA):** Visual Basic tool for structural mass estimation using direct solution methods

- **Program to Optimize Simulated Trajectories (POST):** Legacy code using direct shooting method to approximate the control function for an optimal trajectory
Current design process is well suited for rapid turnaround trades that only require a handful of cases.

Analyst availability prohibitive for full design space exploration.

Augmentation of current ACO process was desired in order to provide the customer with more information for decision making during early design.

Additional information includes:

- Vehicle performance sensitivities
- Broad vehicle architecture trades
- Technology assessment

Providing such information requires large increase in case throughput!
Case throughput first improved via automation of design tools

- All automation achieved using Python
- INTROS and LVA integrated together
- POST automated separately

Tool automation ultimately enables execution of Design of Experiments (DOE) for the purpose of fitting surrogate models

Surrogate models used to implement sensitivity analyses, trade space exploration, technology assessment, etc.
Vehicle Inputs $\{x_1, \ldots, x_n\}$ \rightarrow INTROS Excel Files \rightarrow Outputs $\{y_1, \ldots, y_m\}$

- Liquid booster
- Core stage
- Upper stage

Each stage executes macros.
Vehicle Inputs \( \{ x_1 \} \)

\[ \cdots \]

\( x_n \)

\( \{ \}

\( \}

Input Decks

Output Decks

Parsed by

Creates

Read by

LVA

\( y_1 \)

\( \cdots \)

\( y_m \)

Outputs
INTROS/LVA Integration

DOE Inputs
- Thrust
- Isp
- Max Q
- Max G
- Etc.

INTROS Sizing
- Initial GLOW
- Liftoff T/W for LVA loads
- Vehicle dimensions

LVA Structural Analysis

Updated structure masses

Updated GLOW

Converged?
- No
- Yes

Gather outputs

| Updated GLOW | INTROS GLOW | < 100 lbs |

Outputs

Updated GLOW

INTROS Excel Files

Vehicle Inputs

Outputs

Updated structure masses

Gather outputs

Updated GLOW

Converged?
- No
- Yes

Gather outputs

Updated GLOW

Converged?
- No
- Yes

Gather outputs

Updated GLOW

Converged?
- No
- Yes

Gather outputs

Updated GLOW

Converged?
- No
- Yes

Gather outputs
1. Develop ground rules and assumptions
   - Vehicle architecture
   - Customer requirements and constraints
   - Trades of interest

2. Develop INTROS/LVA DOE inputs and ranges
   - Identify desired DOE variables
   - Develop ranges to capture trades of interest

3. Run screening DOE to determine mass ranges for POST DOE
   - Matches INTROS/LVA mass output ranges with input ranges
   - Ensures proper integration of surrogate models
4. Execute INTROS/LVA and POST DOEs
   - Separation of tools allows for simultaneous execution
   - INTROS/LVA can complete 7,200 cases in 16 hours
   - POST can complete 2,500 cases in 2 hours
5. Fit surrogate models
   - Fit vehicle masses from INTROS/LVA
   - Fit payload mass delivered from POST
6. Integrate surrogate models
   - Connect surrogate models within JMP software
   - Perform analysis and create visualizations for delivery to customer
Example Problem: DOE

- Assume two-stage vehicle with solid boosters
- Trades will focus on design of upper stage
  - Propellant loading of the stage
  - Engine parameters
- Trades incorporated into INTROS/LVA DOE
- POST DOE includes vehicle masses from INTROS/LVA

<table>
<thead>
<tr>
<th>Variable</th>
<th>Range</th>
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</thead>
<tbody>
<tr>
<td>Number of Engines</td>
<td>2, 3, 4, 5</td>
</tr>
<tr>
<td>Thrust per engine</td>
<td>20,000 – 65,000 lbf</td>
</tr>
<tr>
<td>Engine $I_{sp}$</td>
<td>440 – 470 sec.</td>
</tr>
<tr>
<td>OFR</td>
<td>5.4 – 6.0</td>
</tr>
<tr>
<td>LOX Tank cyl. length</td>
<td>3 – 12 ft</td>
</tr>
<tr>
<td>Max G</td>
<td>3 – 4</td>
</tr>
<tr>
<td>Max Q</td>
<td>540 – 700 psf</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variable</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper stage burnout mass</td>
<td>40,000 – 70,000 lbm</td>
</tr>
<tr>
<td>Upper stage prop. mass</td>
<td>205,000 – 375,000 lbm</td>
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<tr>
<td>Upper stage $T/W$</td>
<td>0.2 – 0.75</td>
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<tr>
<td>Upper stage $I_{sp}$</td>
<td>440 – 470 sec.</td>
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<tr>
<td>Upper stage total thrust</td>
<td>60,000 – 325,000 lbf</td>
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<tr>
<td>Core burnout mass</td>
<td>200,000 – 255,000 lbm</td>
</tr>
<tr>
<td>Destination ($C_3$)</td>
<td>-15 – 3 km²/s²</td>
</tr>
<tr>
<td>Max G</td>
<td>3 – 4</td>
</tr>
<tr>
<td>Max Q</td>
<td>540 – 700 psf</td>
</tr>
</tbody>
</table>
Example Problem: Surrogate Modeling

- Surrogate model fitting performed in JMP
  - Response surface equations (RSE)
  - Stepwise regression
- Goodness-of-fit testing
  - Residual-by-predicted and actual-by-predicted plots
  - $R^2$ and Root Mean Square Error (RMSE)
  - Percent error distribution

$$R = \beta_0 + \sum_{i=1}^{n} \beta_i x_i + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \beta_{ij} x_i x_j + \sum_{i=1}^{n} \beta_{ii} x_i^2 + \epsilon$$
POST and INTROS/LVA surrogates are combined within JMP

JMP “Profiler” is used as a standard visualization of the integrated surrogate models
Results

- Profiler also provides capability to perform Monte Carlo simulation, which can enable:
  - Inverse design
  - Probabilistic design
  - Risk assessment
  - Technology assessment
Conclusions

- ACO launch vehicle design process successfully augmented
  - Automated design tools to improve case throughput
  - Integrated INTROS and LVA tools
  - Developed process for application of DOE and surrogate modeling to enable trade space exploration

Automated process can ultimately be used to provide customer with vast amount of information for use in decision making during early conceptual design

Questions?