Pi Blue Software, Inc.

Non-Gradient Based Optimization Using ModelCenter and ProbWorks

April 2003

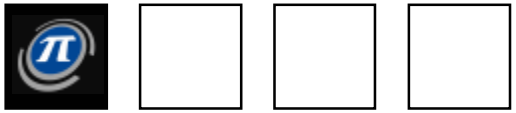
Introduction to the Firm

Overview of ProbWorks: ModelCenter

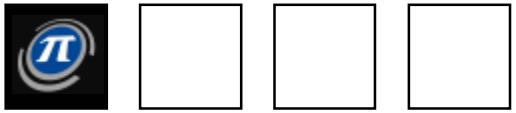
ProbWorks: ModelCenter Case Studies

ProbWorks: ModelCenter Demonstration

Summary



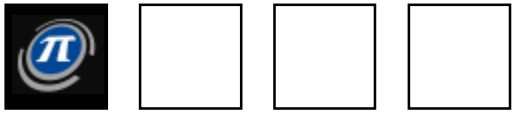
Agenda



Introduction to the Firm

About

Pi Blue Software, Inc. (Pi Blue) specializes in developing easy-to-use software products for advanced numerical analysis, risk/uncertainty assessment, and optimization. Our flagship products are OptWorks: ModelCenter© and ProbWorks: ModelCenter©. Pi Blue's products provide powerful numerical simulation and probabilistic design capabilities for users of all skill levels, from professionals to students.



Overview of ProbWorks: ModelCenter

ModelCenter© Collaborative Environment

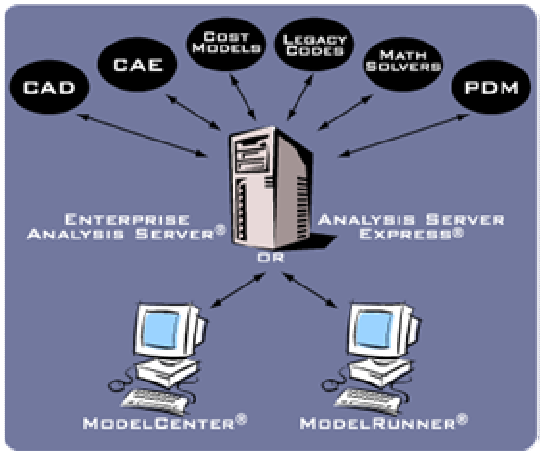
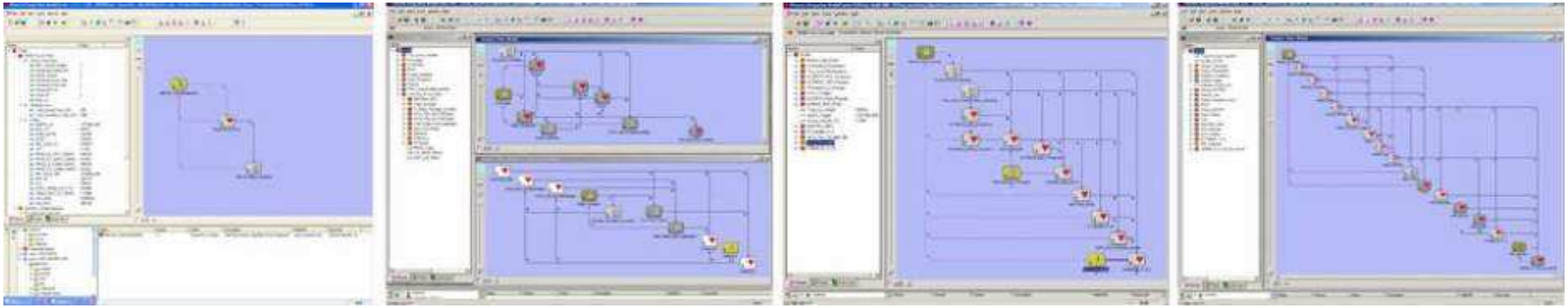


Image Source: Phoenix Integration Inc.
http://www.phoenix-int.com/products/index.html

"Phoenix Integration allows manufacturing companies to integrate and automate numerous software tools, remote locations, and different computing platforms into a cohesive environment for systems design…

…Our client software and back-end server software products help you build an integrated process for your engineering design team."

Phoenix Integration Inc.
http://www.phoenix-int.com



The Need for Robust Design

- A prudent decision maker can use Robust Design to calculate the 80% or 90% confidence value for a program metric to assure themselves that they will meet or exceed the desired metric 80% or 90% of the time
- Robust design is concerned with the objective and the variance in the objective
- Program "risk" is generally a measure of the standard deviation of some output distribution about a mean value
- Robust Design can be implemented by Monte Carlo techniques based on a variety of numerical methods that use sequences of random numbers to perform statistical simulations
- Alternative methods coupled and in addition to Monte Carlo can reduce computational and temporal expense
- Design tools and robust design drivers can be coupled in a collaborative design environment such as Phoenix Integration's ModelCenter© for Probabilistic Data Assessment (PDA)

Pi Blue Software, Inc. introduces a new suite of uncertainty and sensitivity analysis tools for use with Phoenix Integration's ModelCenter© collaborative design environment.

Entitled ProbWorks: ModelCenter©, this suite consists of four tools to help employ uncertainty analysis techniques, each implemented as a Java-based component which can function on any platform running Phoenix Integration's ModelCenter© and Analysis Server©.

ProbWorks: ModelCenter

The ProbWorks: ModelCenter©, suite is aimed at users who must treat uncertainty and risk in their product designs. The direct Monte Carlo driver and the faster DPOMD approximation driver propagate uncertainty in input parameters to assess statistical parameters such as mean, standard deviation, certainty level, and skewness. Supporting tools allow for the generation of fast-acting polynomial response surface equations (RSEs) and Pareto sensitivity analysis.

This package is currently available for purchase through individual/group site licenses. The full product suite includes optimizers in Java byte code, documentation with case study examples, and selected online support.

ProbWorks: ModelCenter Capabilities

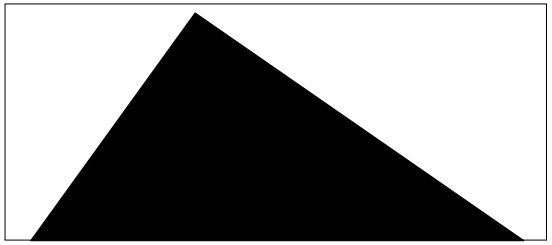
Uncertainty in design models and simulations

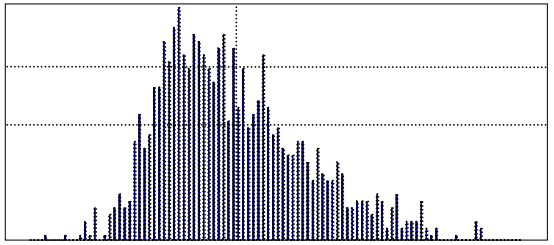
Prioritize impact of inputs into model

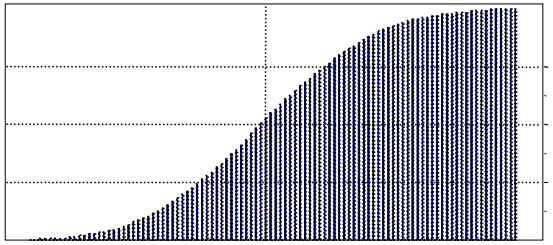
Approximate models and simulations

Reduce Monte Carlo computational and temporal expense

Visualize output results from Monte Carlo

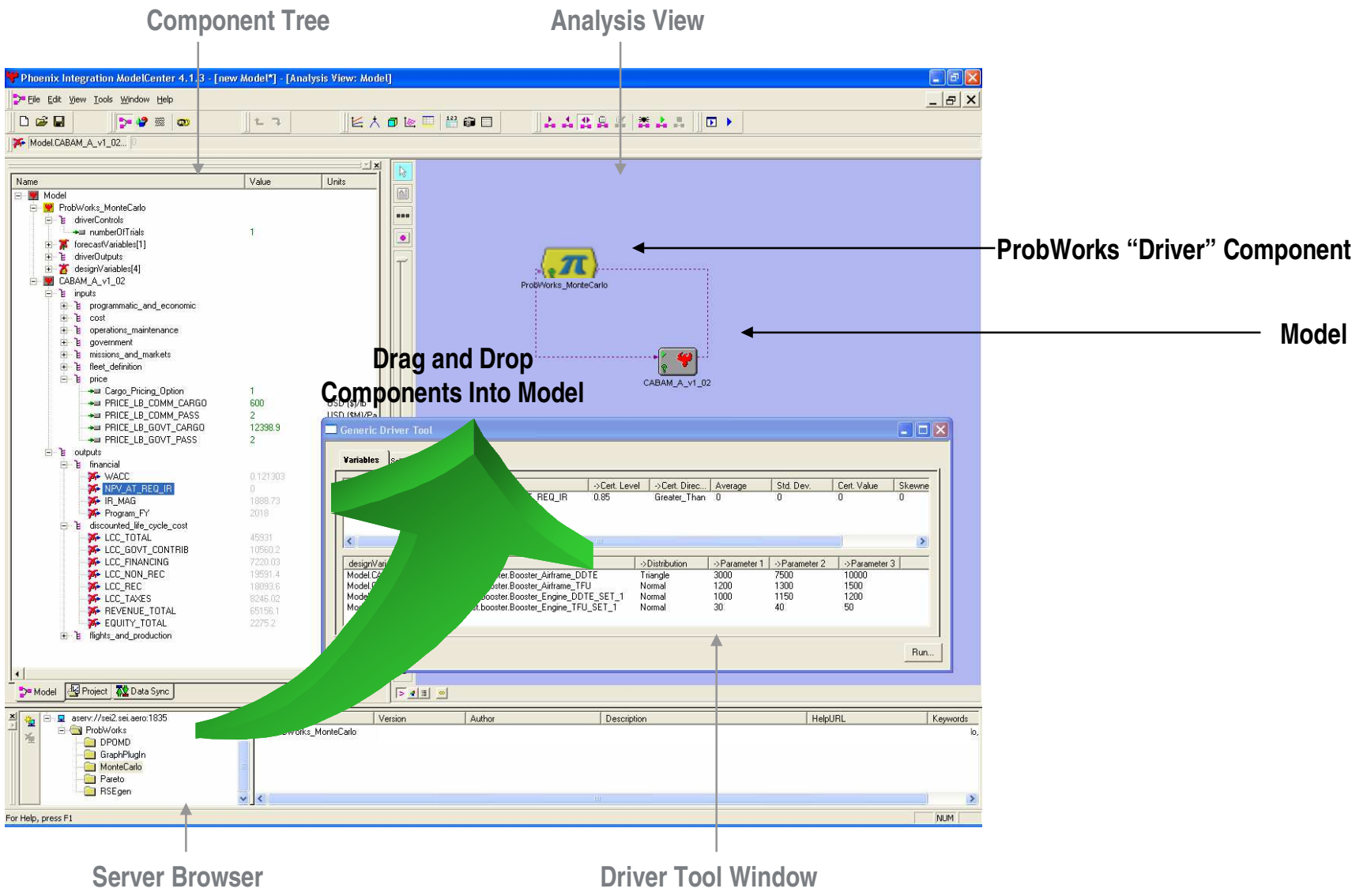




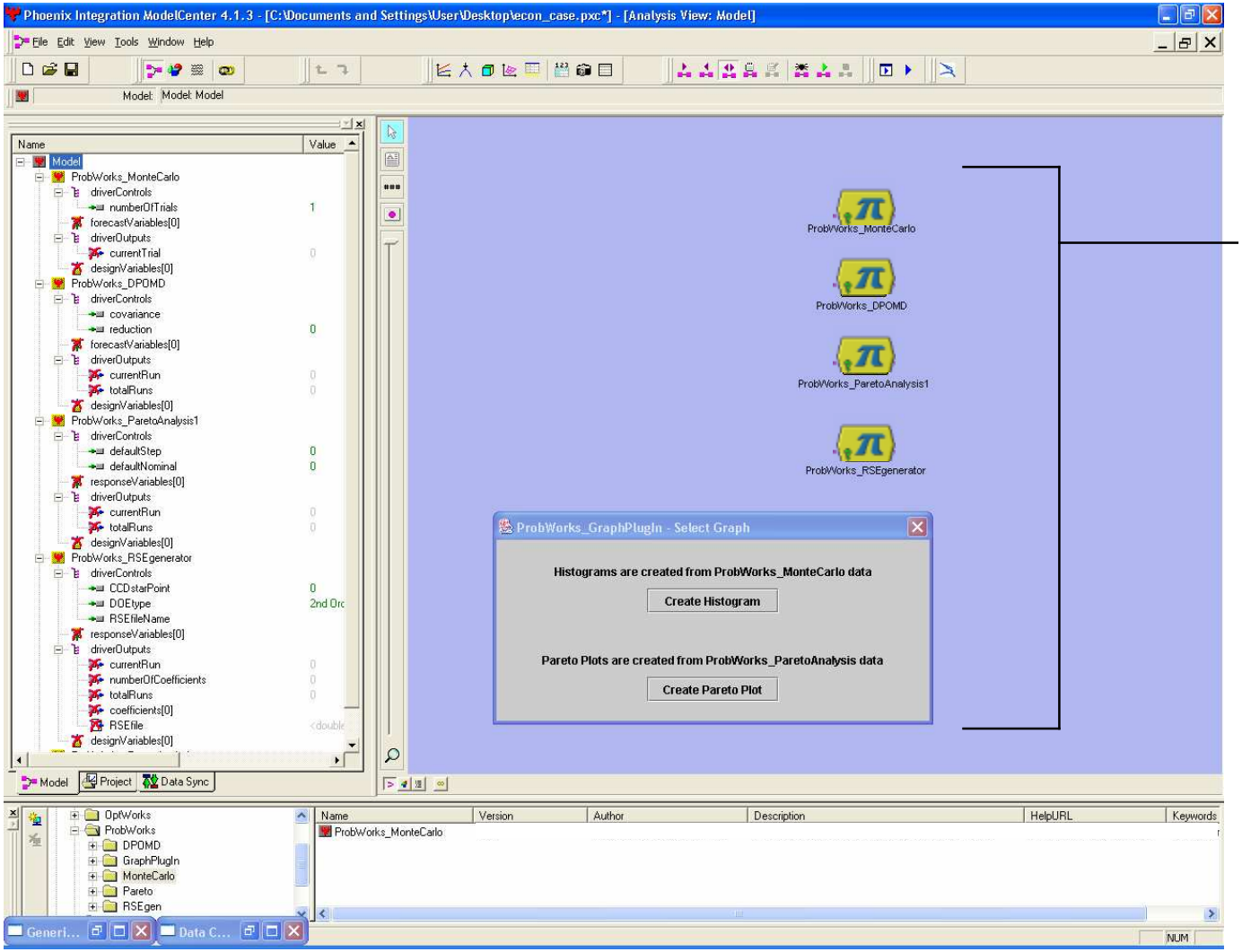


Why ProbWorks?

Basic Functionality of a ProbWorks Component Within ModelCenter©



ProbWorks Components Available from Pi Blue Software, Inc.



ProbWorks Suite

- Monte Carlo
- DPOMD
- Pareto Sensitivity
- RSE Generator
- Graph Plug-In

Monte Carlo Performs Monte Carlo uncertainty simulation using random variables by placing distributions (normal, triangular, Weibull, etc.) on inputs. Generates output statistics for the forecast variables (average, mean, certainty level, etc.) even as simulation is running.

DPOMD Implements the Discrete Probability Optimal Matching Distribution (DPOMD) technique that serves as an efficient alternative to direct Monte Carlo simulation for certain classes of problems. Allows estimation of a probabilistic output distribution with a small number of runs.

Pareto Sensitivity Determines the contribution or sensitivity of each selected input with respect to each selected output with appropriate ranking of contribution.

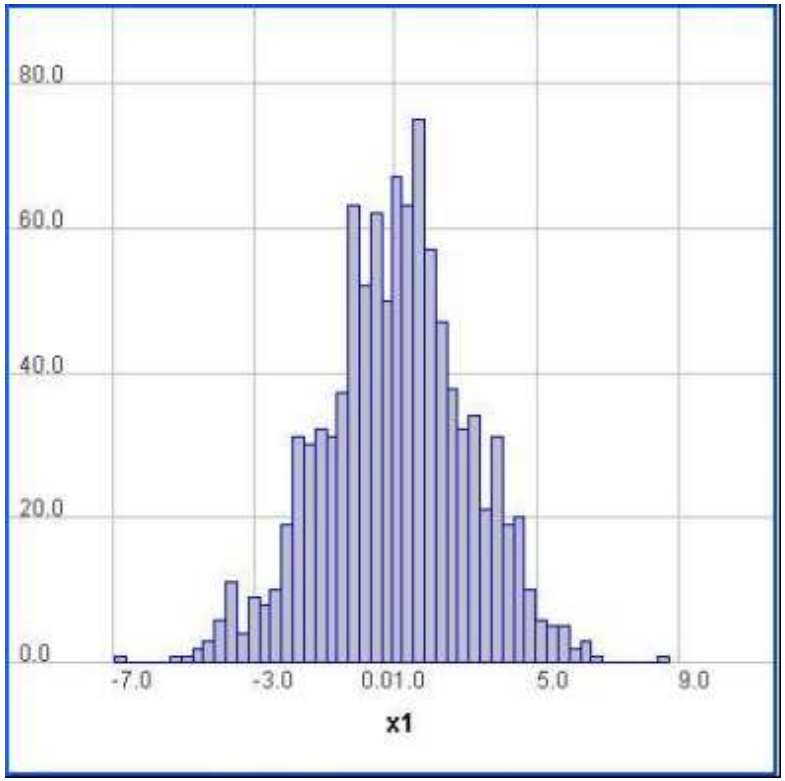
RSE Generator Produces polynomial regression equations to approximate more complex or time-consuming components enabling faster execution of probabilistic techniques such as Monte Carlo. Generates output statistics on goodness of fit to selected data. Enables subsequent use of regression coefficients.

Graph Plug-In ModelCenter© plug-in which generates histograms and Pareto plots from other ProbWorks component outputs.

ProbWorks Suite of Components

Monte Carlo

- Monte Carlo techniques based on variety of numerical methods that use sequences of random numbers to perform statistical simulations
- For each trial, design variables set to random values based on selected input distributions
- Value of each forecast variable recorded and certain key output statistics calculated
- For large number of trials, design variables approximate selected distributions and forecast variables show effect of design variables' variation
- Monte Carlo analyses performed on selected forecast variables by varying design variables
- User specifies both the design variables along with the associated distributions, distributions include: normal, uniform, triangular, exponential, Weibull, lognormal, and Beta
- Driver component collects data from forecast variables and maintains running calculations of mean, standard deviation, certainty values, skewness, and kurtosis for given certainly levels



Example Monte Carlo Output Frequency Distribution

DPOMD

- **Discrete Probability Optimal Matching Distribution (DPOMD) is new method that uses limited samples from input distributions**
- **Compares favorably to traditional Monte Carlo with respect to computing time and accuracy**
- **Effectiveness of DPOMD is enabled by reducing continuous multivariate input distribution to discrete distribution**
- **Two-level fractional factorial design of experiments produces discrete distribution with zero mean vector and identity covariance matrix in standardized normal space**
- **Using values for the mean and covariance matrix from input distribution, inverse Hasofer-Lind transform maps discrete distribution to problem**
- **Simplified discrete distribution in problem space maintains same first moment (mean) and second moment (standard deviation) as continuous input**
- **Simulation then executed at these discrete points to produce output distributions**

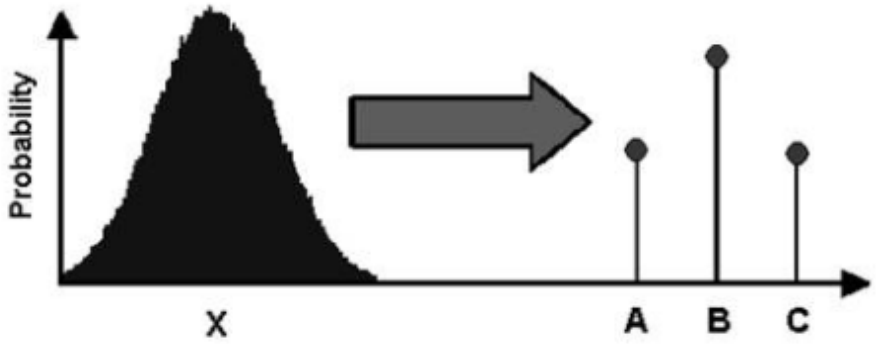
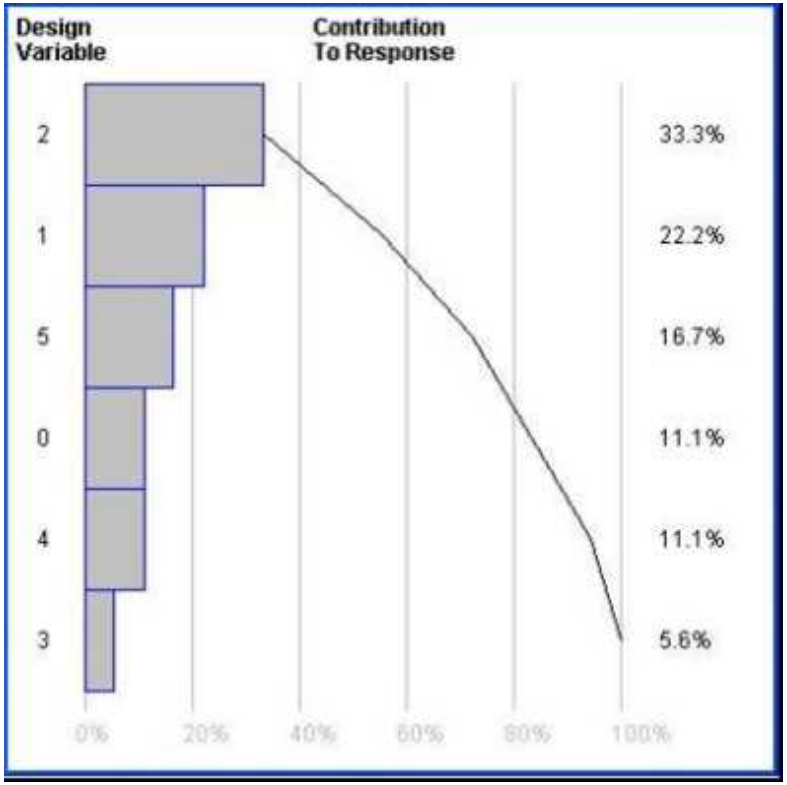


Illustration of Discrete Distribution Derived from Continuous Distribution

Based upon work performed by Dr. David McCormick, Space Systems Design Lab (SSDL), School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA, For more information see: McCormick, D., Olds, J., "Approximation of Probabilistic Distributions Using Selected Discrete Simulations," AIAA 2000-4863, 8th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Long Beach, CA, September 6-8, 2000.

Pareto Sensitivity

- Determines most important design variables
- Quickly and easily assess which variables will provide most improvement or which should be included in later analyses, such as creating response surface approximation or executing Monte Carlo
- Each design variable varied and change in response recorded
- Variables then ranked in importance according to how much each contributes to variance about the mean of an output variable
- Set of design variables ranked and their contribution to the response graphically displayed



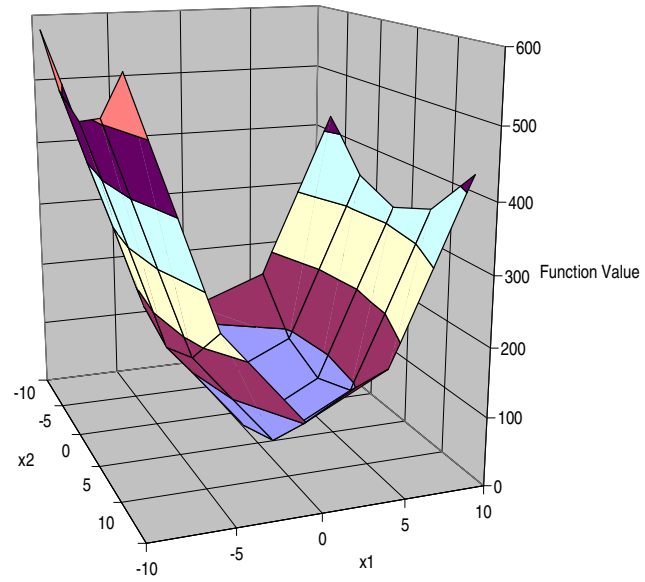
Pareto Sensitivity Chart

Response Surface Equation (RSE) Generator

- **Creates Response Surface Equation (RSE) quadratic approximation to substitute slower executing computational codes with analytical approximations**
- **Resulting RSE in ModelCenter©-runnable script used in current model file or placed in another**
- **Performs specific set of runs based upon Design of Experiments (DOE) methodologies, each design variable set to specific value and all response variables are recorded**
- **DOE includes: Central Composite Design (CCD) for second order terms, a D-Optimal design for second order (max 15 design variables), or Fractional Factorial (FF) design for all linear and mixed cross terms (but not pure quadratic terms)**
- **Least squares quadratic equation of form:**

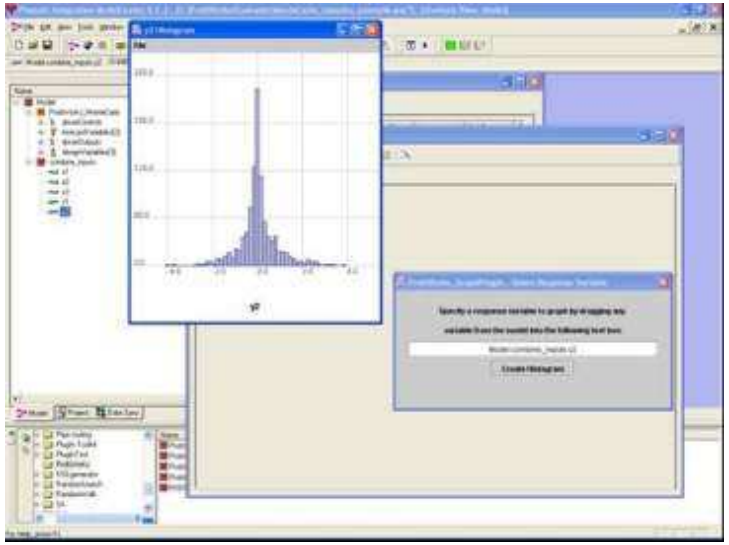
$$\sum_{i=1}^{n} a_i x_i^{\,2} + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} b_{ij} x_i x_j + \sum_{i=1}^{n} c_i$$

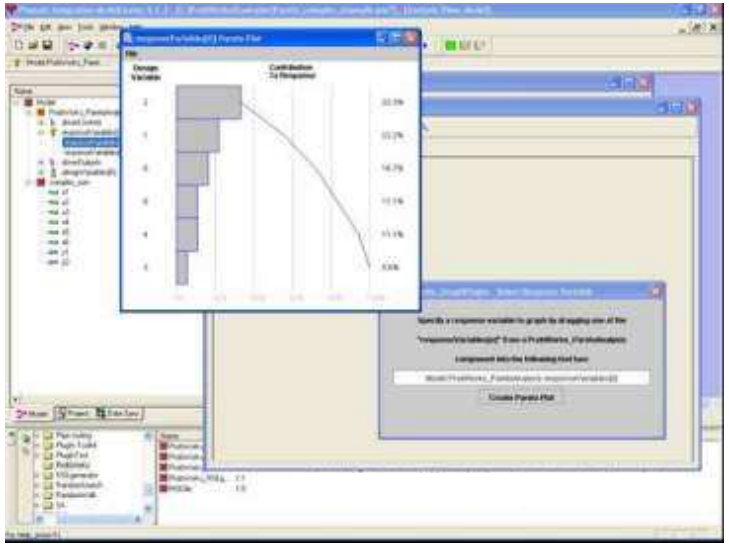
where n is number of design variables, x_i and x_j are design variables, a_i and a_j are quadratic coefficients, b_{ij} are cross term coefficients, and c_i are constant coefficients

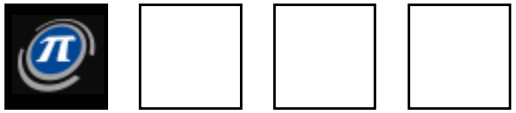


Graph Plug-In

- Not analysis component but plug-in utility to provide fast-acting graphical analysis of results of other analyses
- Once installed, available from the Data Collector after analysis is performed in ModelCenter©
- Graph plug-in produces histograms from Monte Carlo and Pareto charts from sensitivity analyses
- User selects either histogram from Monte Carlo data or Pareto chart from Pareto analysis
- User specifies variables to graph by either typing complete variable name into text box, or dragging variable from Component Tree into text box and then clicking “Create Histogram” or “Create Pareto Plot”
- Histograms can be created from nearly any numerical variable within ModelCenter©
- Pareto charts can only be created from individual response variables in Pareto Analysis component

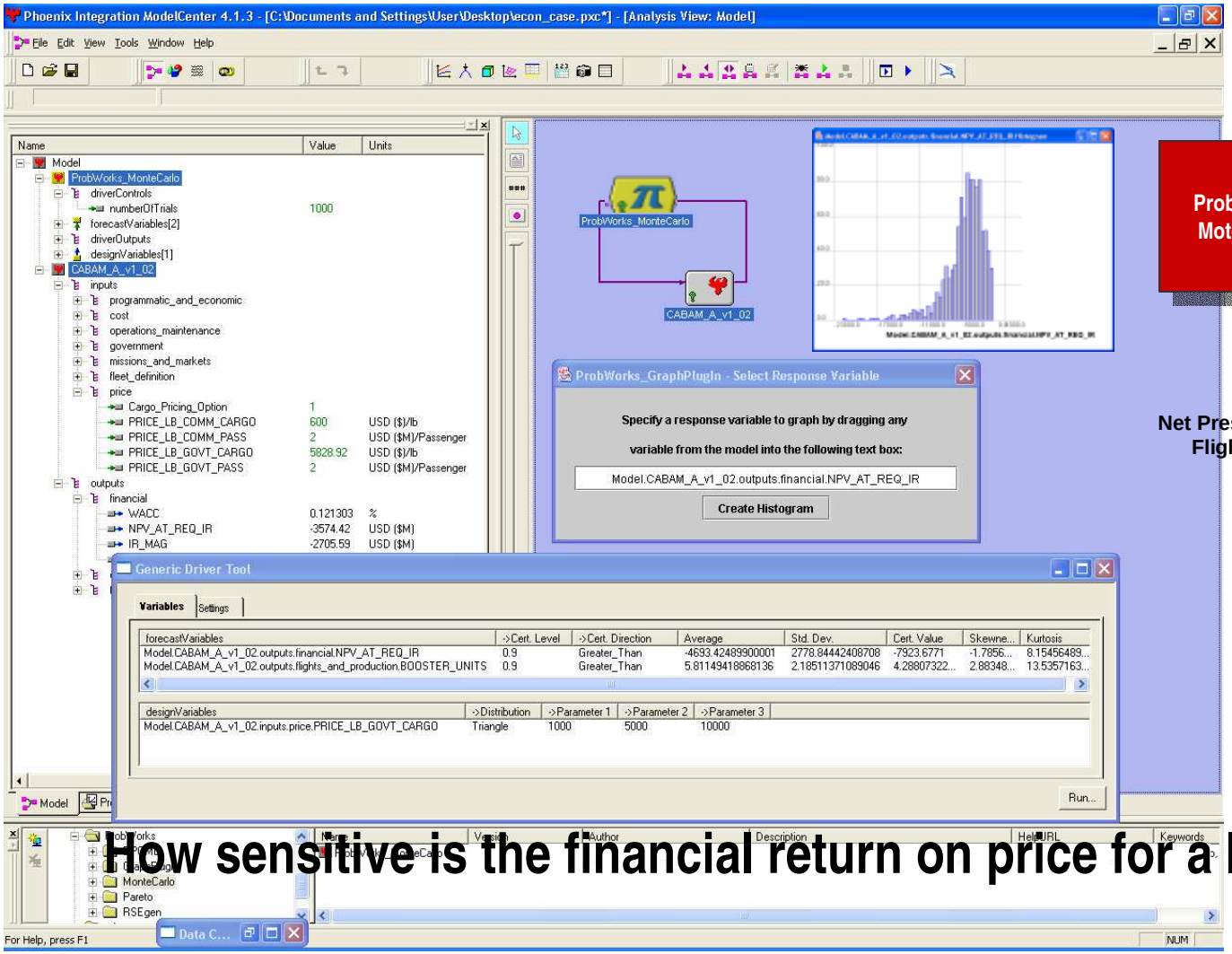


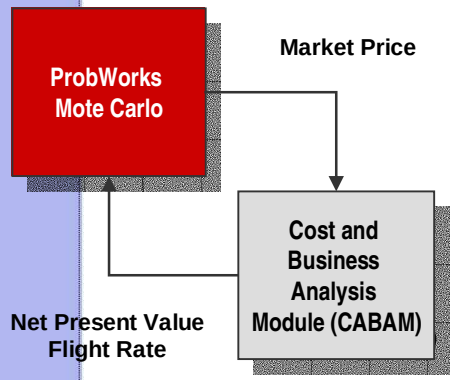




ProbWorks Case Studies

Case Study: Economic Uncertainty



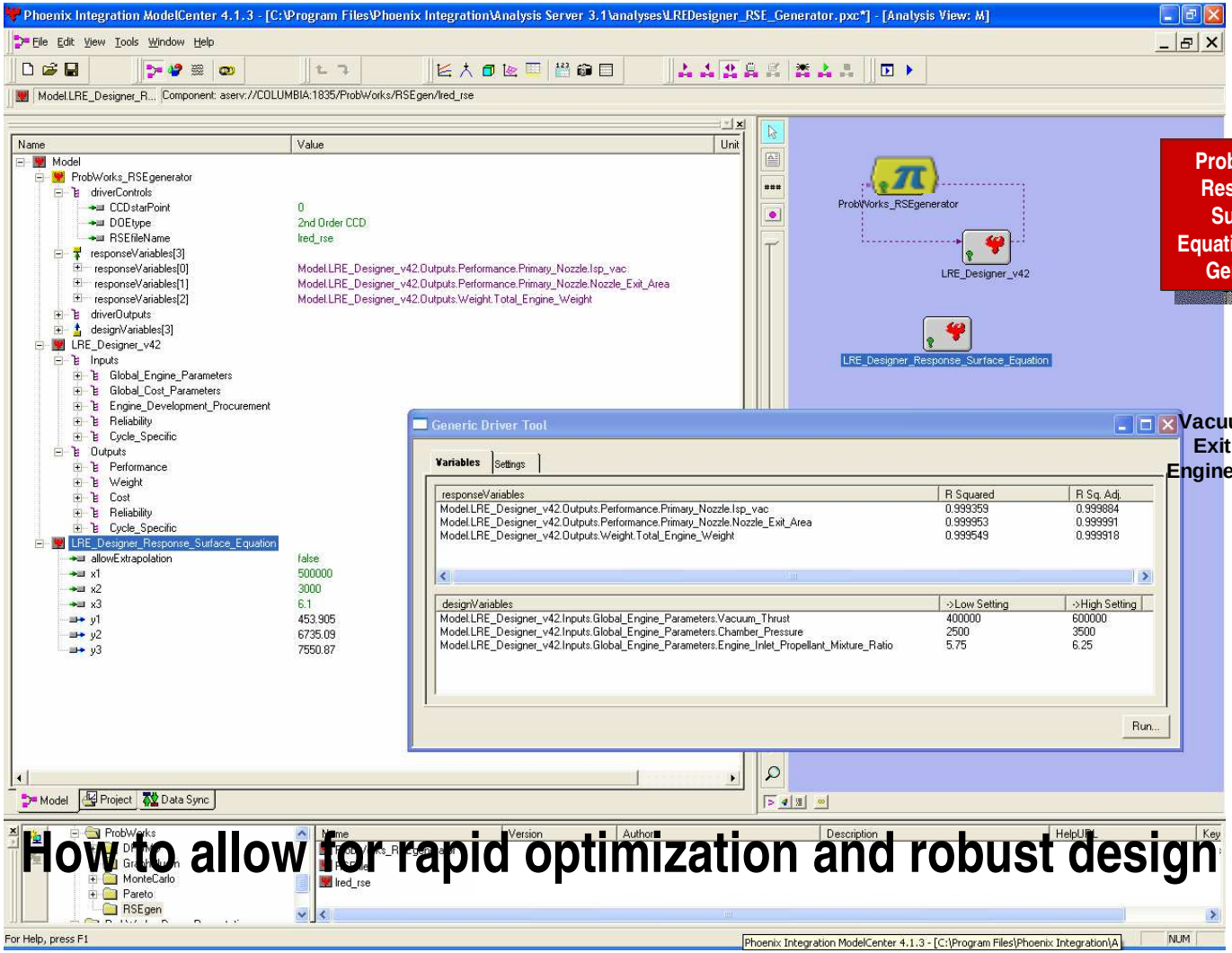


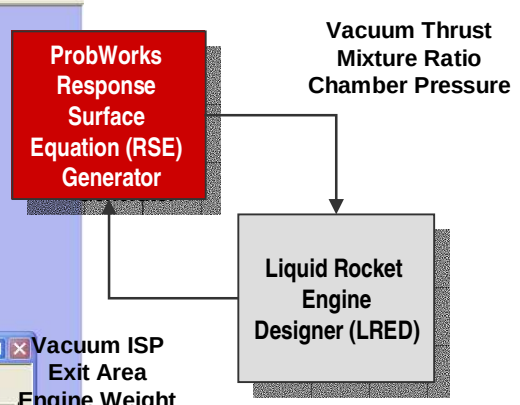
Why ProbWorks?

Unknown Market Conditions
Visualize ModelCenter© Data

How sensitive is the financial return on price for a launch vehicle

Case Study: Meta Model Generation for Liquid Rocket Engine Analysis



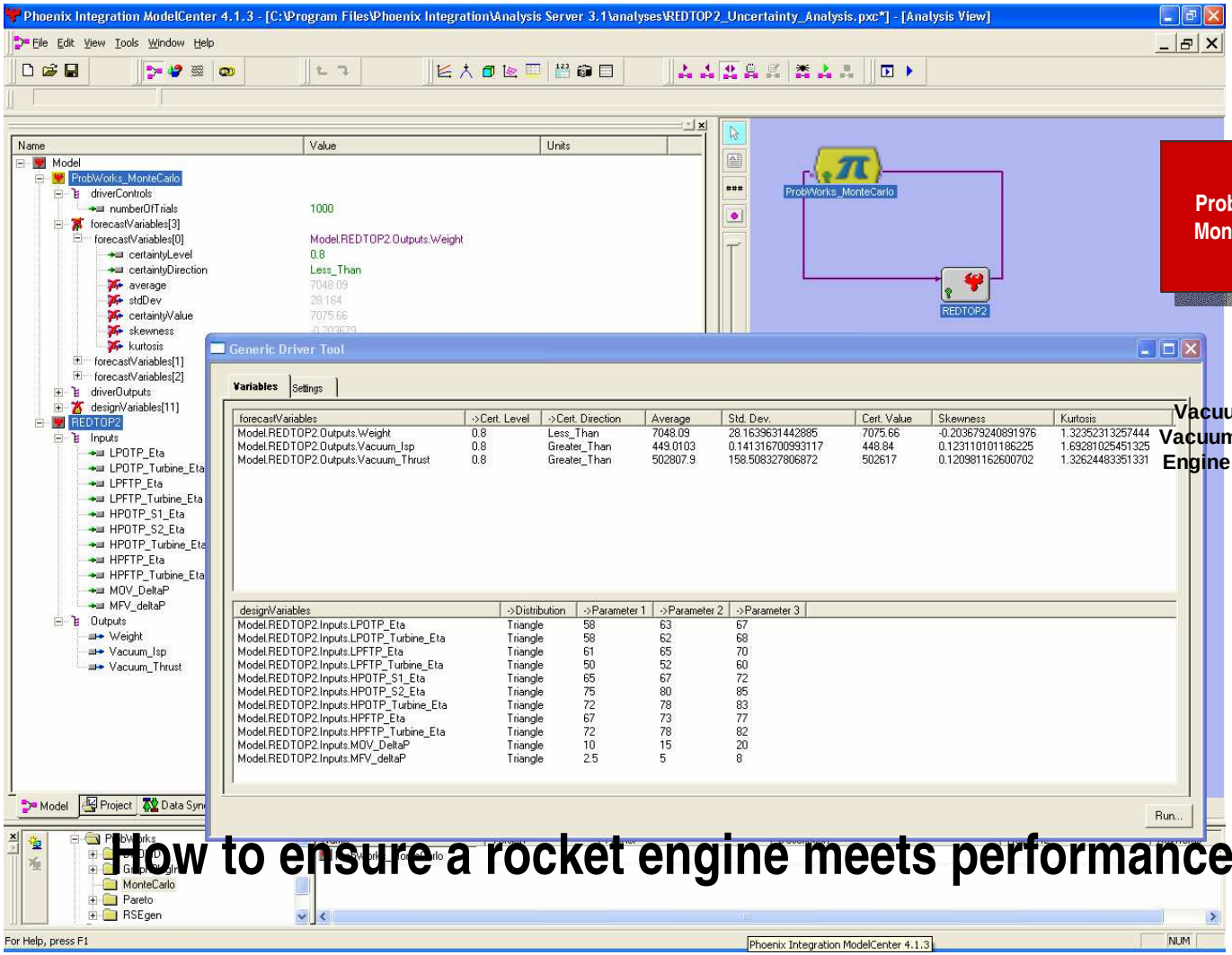


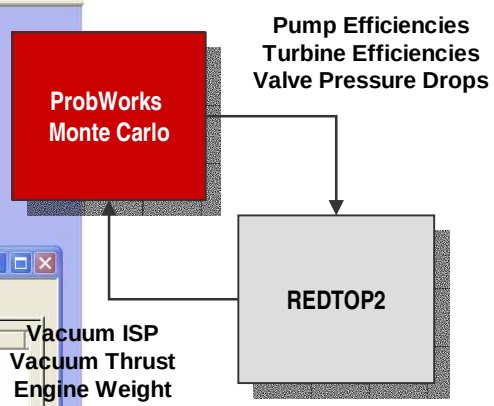
Why ProbWorks?

Protect proprietary models
Reduce model execution time

How to allow for rapid optimization and robust design of a rocket engine

Case Study: Probabilistic Simulation for Liquid Rocket Engine Analysis

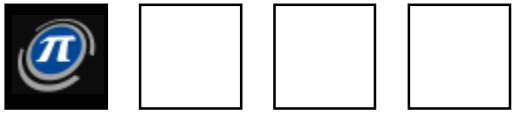




Why ProbWorks?

Actual values requires testing
Ease of integration with tool

How to ensure a rocket engine meets performance requirements



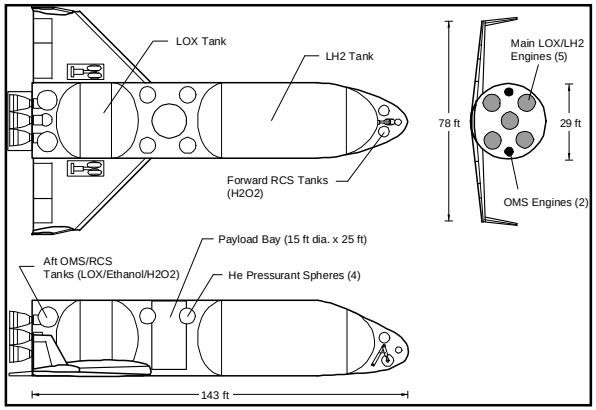
ProbWorks Demonstration

Future?	-	Ubiquitous Space Transportation Systems
Need?	-	Revolutionary Improvements in Enabling and Enhancing Technologies
Uncertain Technologies?	-	Technology Impacts on Vehicle Design Parameters
Uncertain Models?	-	Limitations of Design Codes to Model Reality
Techniques?	-	Faster Acting Monte Carlo Probabilistic Data Assessment (PDA)

Probabilistic Vehicle Design

Design Study: ACRE-92 Reusable Launch Vehicle (RLV)

Item	Characteristics
Concept	Single-Stage-To-Orbit (SSTO) Vertical Take-Off Horizontal Landing (VTHL) Earth-To-Orbit (ETO) Reusable Launch Vehicle (RLV); commercial focus with initial flight capable in 2025, technology freeze date of 2018
Reference Mission	Payload: 40k lbs. (100 nmi. @ 28.5 degrees inclination from KSC), Cargo delivery or passenger delivery and return
Propulsion	Engines: 5 Advanced Staged Combustion Engines (Pc 4000 psi, mixture ratio 6.9) Propellants: NBP LOX and NBP LH2 T/We: ~92
Sizing	GLOW: 2.3M lbs. (system), Dry Wt.: 224k lbs Length: 163 ft
Analyses Performed	Creation of ROSETTA analysis model for probabilistic examination; modeled in ModelCenter distributed framework with eight disciplines

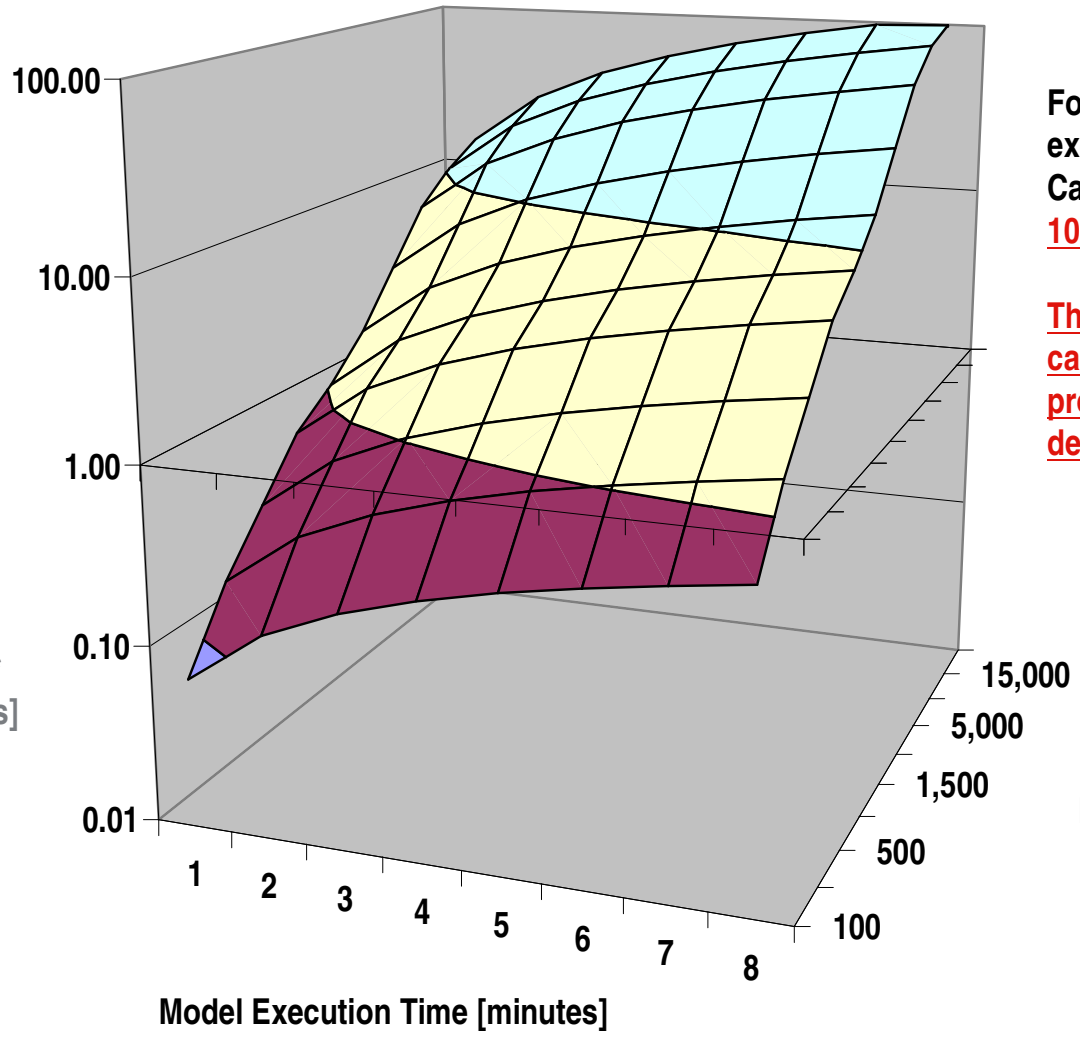


The Need to Speed Up Probabilistic Design

Total Run Time For All Monte Carlo Simulations [days]

=

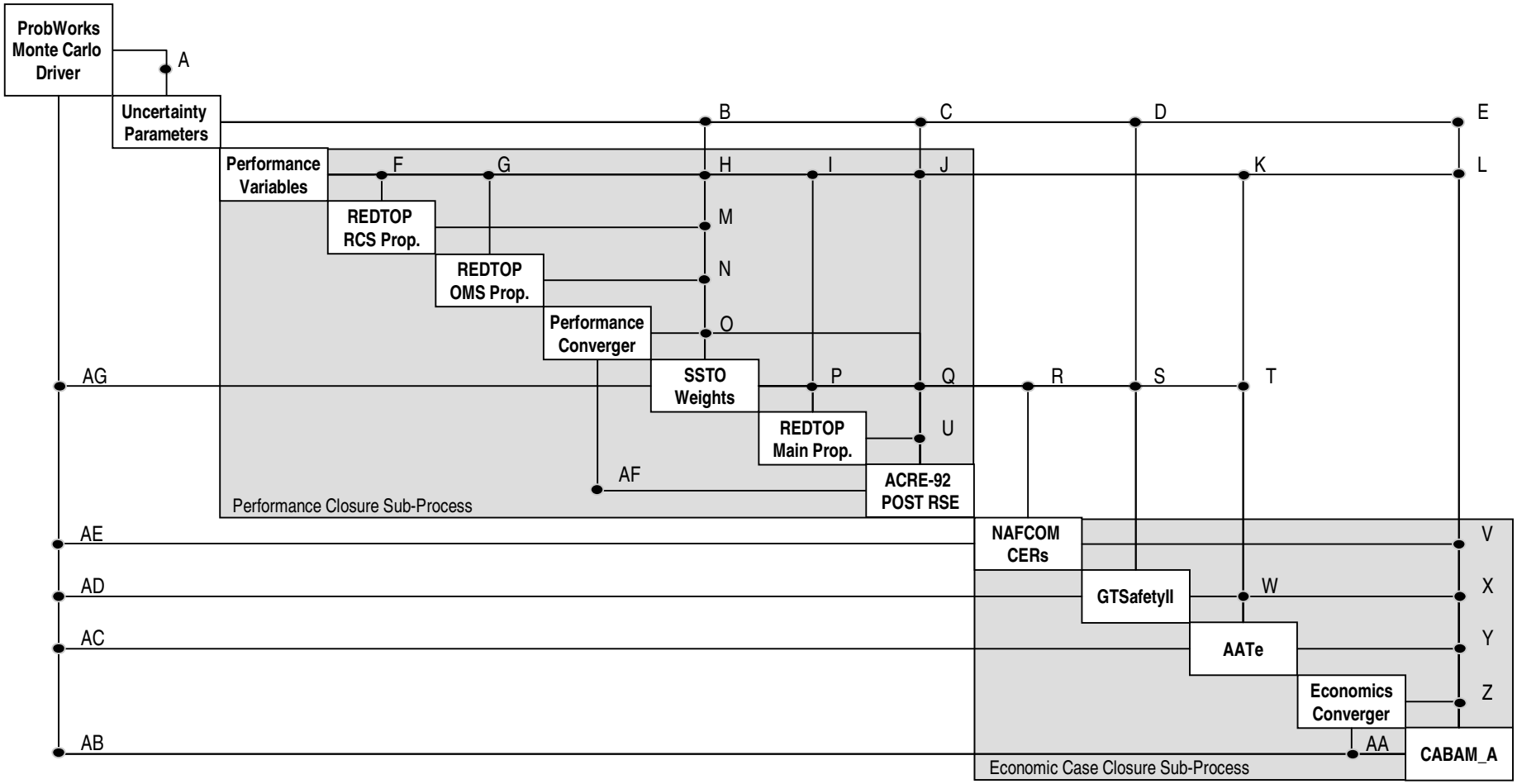
Monte Carlo simulations * model execution time [days]



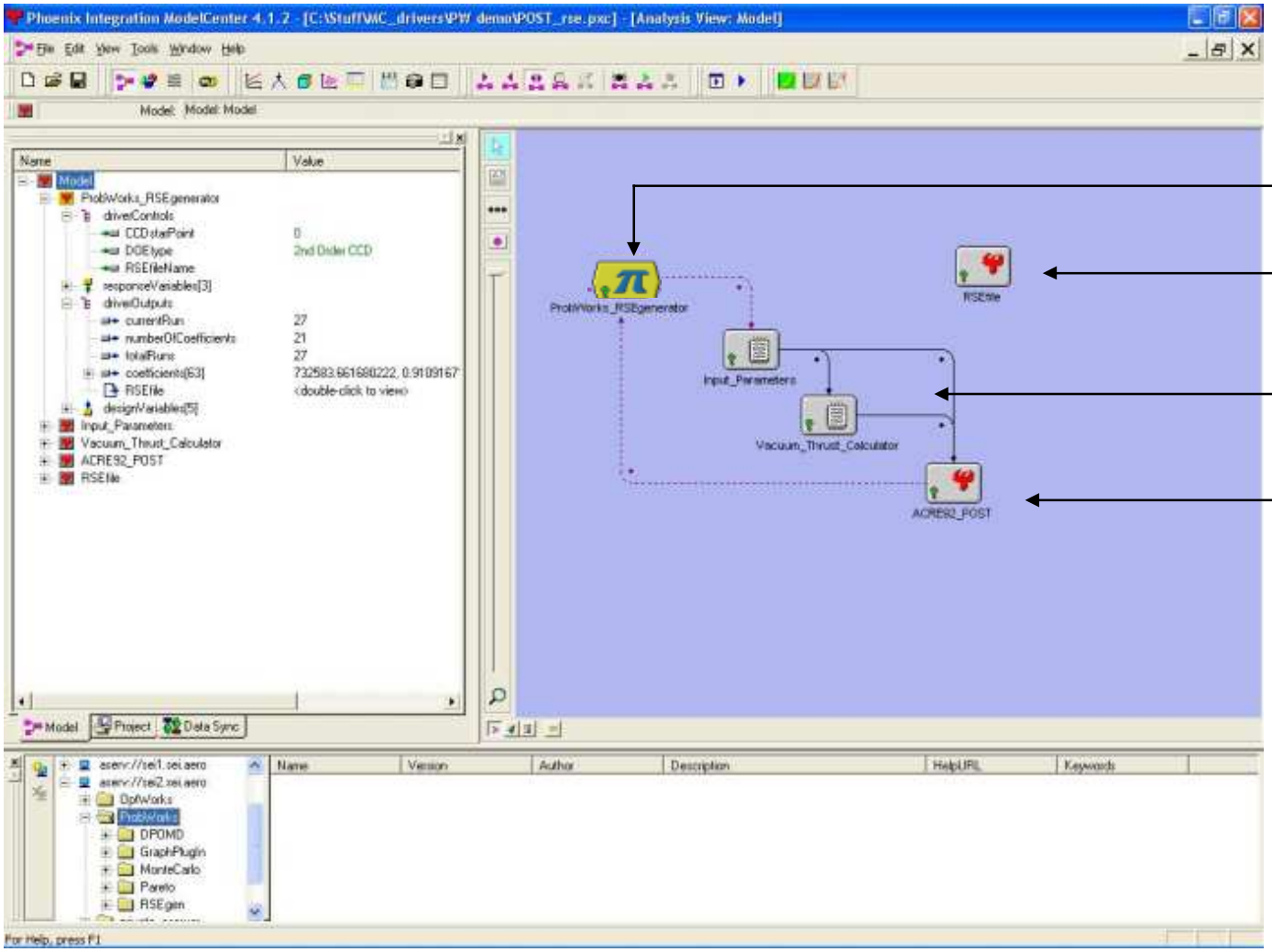
For an 8 minute model execution time, 20,000 Monte Carlo simulations require over 100 days

The components in ProbWorks can dramatically speed up this process to obtain probabilistic design data

ACRE-92 Reusable Launch Vehicle (RLV) Design Structure Matrix (DSM)



ProbWorks Response Surface Equation (RSE) Generation in ModelCenter© Environment



ProbWorks RSE Generator

Generated RSE

Preprocessing Scripts

Trajectory Model (POST)

Why ProbWorks?

To Reduce Long Run Time
Easy RSE Generation

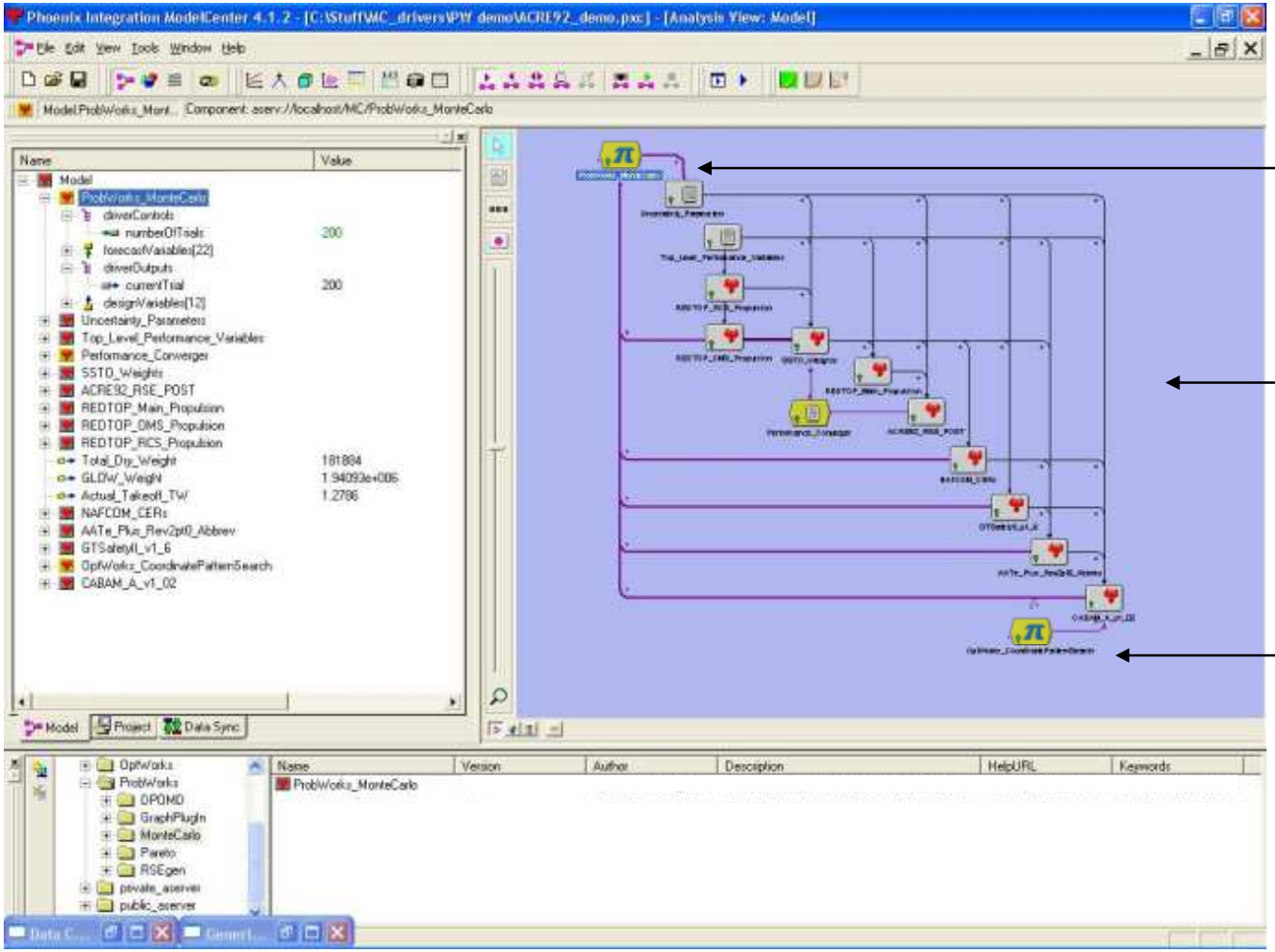
Speeding Up The Performance Closure Design Loop Using ProbWorks

- **Since Probabilistic Data Assessment (PDA) sometimes requires many thousands of Monte Carlo simulations (i.e. converged design points), reduced code calculation time is essential in obtaining time relevant uncertainty assessments**

- **Two different formulations of vehicle performance sub-process closure loop generated**
  - **High fidelity trajectory code (POST tool) on an SGI**
  - **ProbWorks Response Surface Equation (RSE) of POST tool in MS Excel (RSE POST)**

- **If performing a Monte Carlo simulation of this performance closure sub-process by itself for 2,000 simulations:**
  - **Full fidelity process would take approximately 8.3 days**
  - **RSE trajectory would take approximately 22.2 hours**
  - **RSE POST method was only 0.8% higher in terms of Gross Lift-Off Weight (GLOW) full fidelity**
  - **RSE POST method was only 0.65% higher in terms of dry weight versus full fidelity**

ProbWorks Vehicle Design Demonstration in ModelCenter© Environment



ProbWorks Monte Carlo Driver

Launch Vehicle Performance and Life Cycle Analysis

OptWorks Coordinate Pattern Search (CPS) Optimizer

Why ProbWorks?

Monte Carlo Analysis Directly on Complex Distributed Model

Sample Input and Output Uncertainty Parameters

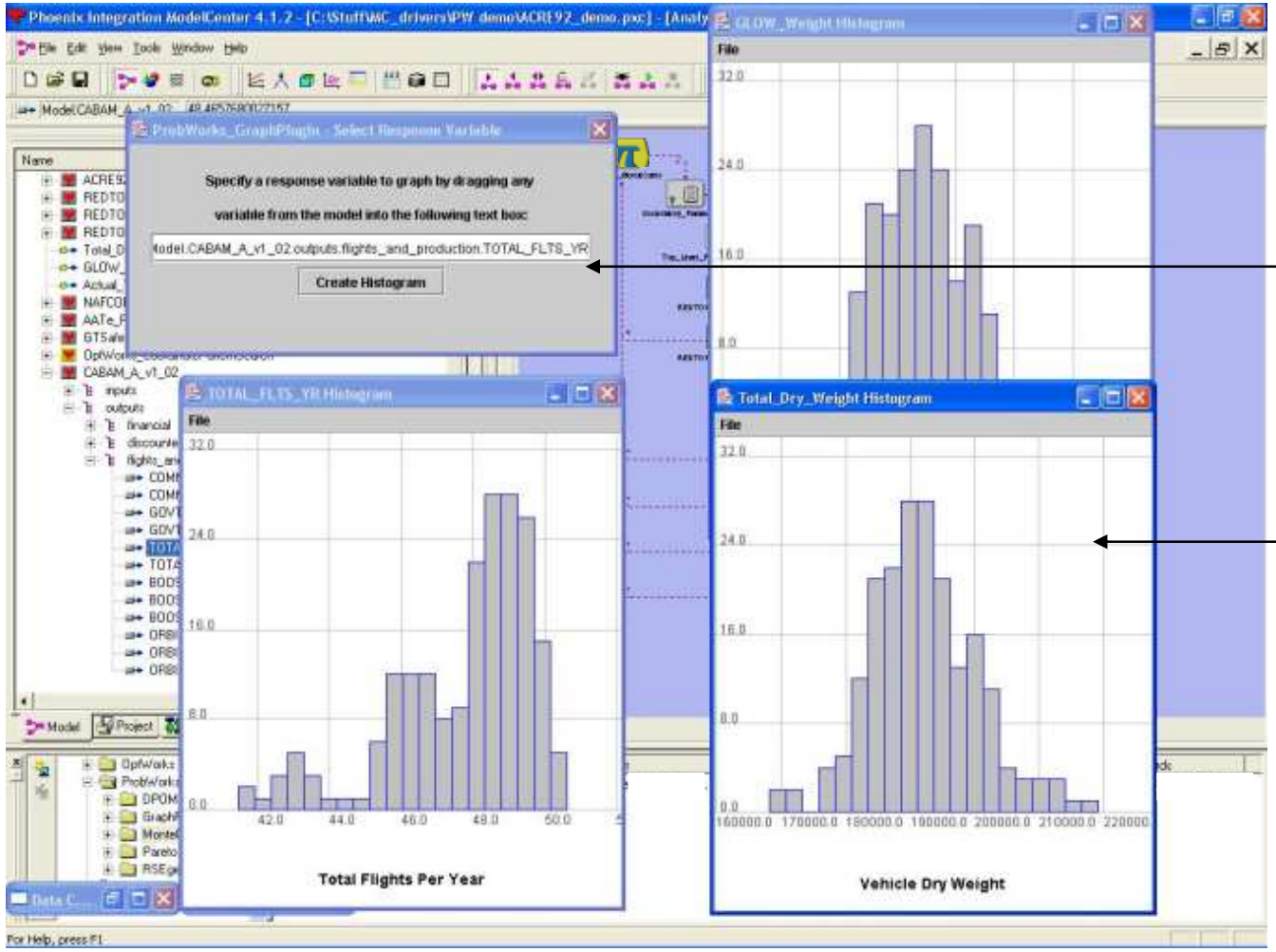
INPUT UNCERTAINTY DISTRIBUTIONS (NON-DIMENSIONAL)

Item	Low	Most Likely	High	Distribution Type
Main Engine Thrust to Weight Ratio	0.85	1	1.1	Skewed Triagular
Main Engine Vacuum Isp	0.99	1	1.01	Triangular
Main Engine Thrust	0.95	1	1.05	Skewed Triagular
OMS Engine Weight	0.95	1	1.04	Skewed Triagular
OMS Engine Vacuum Isp	0.95	1	1.2	Skewed Triagular
RCS Engine Vacuum Isp	0.95	1	1.04	Skewed Triagular
Primary Structure Weight	0.95	1	1.2	Skewed Triagular
Landing Gear Weight	0.98	1	1.2	Skewed Triagular
Passenger Flight Rate	0.5	1	1.5	Triangular

OUTPUT PROBABILISTIC STATISTICS FOR 100 MONTE CARLO SIMULATIONS

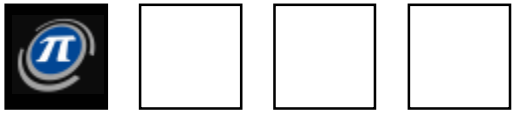
Item	Mean	Standard Deviation	90% Certainty	Skewness	Kurtosis
Vehicle Dry Weight	191,855	9,413	204,420	0.3	3.35
Vehicle Gross Weight	2041,476	101,266	2,175,385	0.219	3.34
Vehicle Length	155.5	2.616	158.9	0.105	3.20
Price per Pound for Govt Cargo	2238	88.8	2283	2.35	9.67
Fixed Operations Cost Per Year	40.75	0.276	41.1	0.276	3.38
Variable Operations Cost	3.202	0.013	3.22	0.283	3.37
Booster Airframe DDTE	7,121	195	7,365	0.254	3.16
Booster Airframe TFU	1,683	54.1	1,750	0.263	3.17
Total Flights Per Year	47.8	1.70	49.7	-0.983	8.03

ProbWorks Probabilistic Data Assessment (PDA) in ModelCenter© Environment



Conclusions from Demonstration

- Probabilistic Data Assessment (PDA) allows designers to quantify risks of various projects and determine the likelihood of meeting programmatic goals
- Comparison of nominal (or deterministic) output values versus probabilistic mean output values reveals a substantial difference for some vehicle metrics
- Ranges of some of output variables are greater than the potential error in the RSE
- Response Surface Equations (RSEs) are a critical piece for making these probabilistic processes accessible to management who cannot wait a few weeks for output results
- These analyses are most relevant when evaluation of new concepts or technologies is required



Summary

ProbWorks: ModelCenter© suite consists of four tools to help employ uncertainty analysis techniques implemented as Java-based components which can function on any platform running Phoenix Integration's ModelCenter© or Analysis Server©. ProbWorks: ModelCenter© easy to implement as drag-and-drop components for treating uncertainty and risk in product designs

Phoenix-Integration, Inc. serves as the primary reseller for Pi Blue's Optworks: ModelCenter©, and ProbWorks: ModelCenter©, products. For sales and pricing info, please contact sales@phoenix-int.com or call Phoenix Integration at 1.800.500.1936. Individual and discounted division-wide licenses with annual maintenance plans are available. Individual-user licenses are priced at $1999.00 (one-time charge).

Conclusion

Pi Blue Software, Inc. introduces a new suite of optimization tools for incorporation with Phoenix Integration's ModelCenter© collaborative design environment.

Entitled OptWorks: ModelCenter©, this suite consists of eight non-gradient based optimizers each implemented as Java-based components which can function on any platform running Phoenix Integration's ModelCenter© or Analysis Server©.

OptWorks: ModelCenter

These tools enhance the current gradient based optimization tools in ModelCenter© to allow solution of previously intractable problems.

Characteristics of these sets of applications include the capability to handle problems with high dimensionality, discrete or mixed variables (continuous and discrete), and multi-modal solutions spaces.

This package is currently available for purchase through individual/group site licenses. The full product suite includes optimizers in Java byte code, documentation with case study examples, and selected online support.

OptWorks: ModelCenter Capabilities

Pi Blue Software, Inc.

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