Multidisciplinary System Design Optimization Using Model-Based Engineering to Support Phased Array Antenna Architectural Trades

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Baltimore, MD

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Outline

I. What is Model-Based Engineering (MBE)?

II. Objectives & Value Proposition of Analytical MBE

III. Using MBE to Apply MSDO to Antenna System Design

IV. Using Data Science, Analytics, and Optimization for Trade Space Exploration

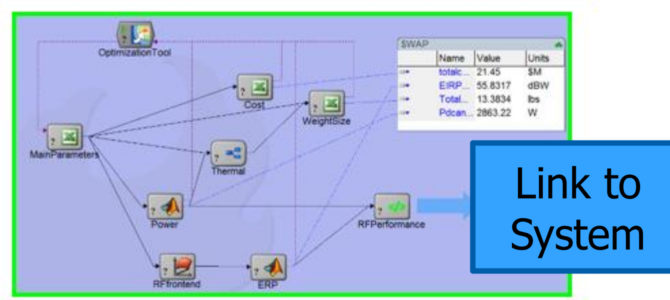
V. System Trades, Mission Visualization, & Cost Model Integration

VI. MBE Analytical Services: An Idea to Expand MBE Analytics

VII. Conclusions

Multi Disciplinary Models Leveraged & Connected

Integrated Cost-Performance Model



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What is Model-Based Engineering?

What is Model-Based Engineering?

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Definition: Model Based Engineering (MBE) is the use of analysis and simulation tools throughout the product lifecycle to reduce the use of physical prototypes. In addition, MBE supports critical design decisions by allowing organizations to evaluate trade-offs between performance, cost, and risk. It also enables the identification and correction of potential problems before they become too costly.

MBE provides engineers the capability to:

- Create and maintain a library of analysis models and engineering workflows
- Perform multi-domain trade studies and ask “what-if” questions
- Visualize the design space and find the best designs
- Archive, manage, and share the resulting data and meta-data

MBE results in shorter development times, reduced costs, and better products

Source: Phoenix Integration (https://www.phoenix-int.com/application/mbe-model-based-engineering/)

Model-Based Engineering: Descriptive vs. Analytical Modeling

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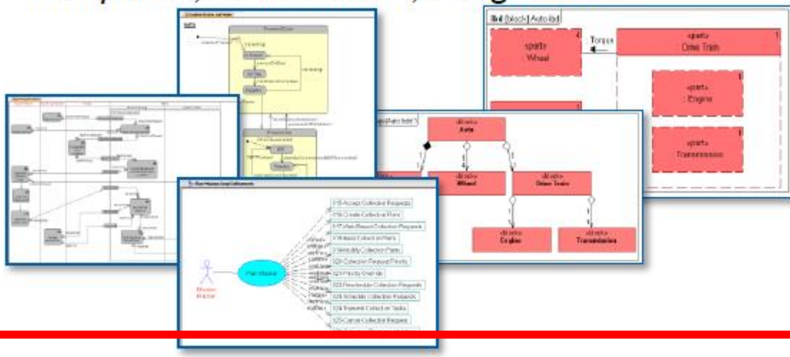
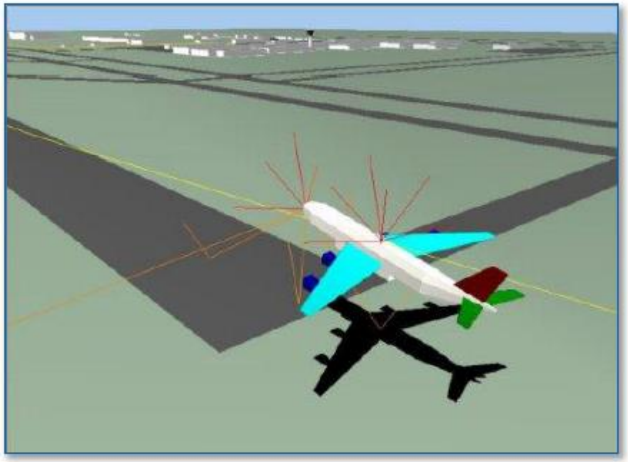
Descriptive"Model" (as in "Model Airplane")

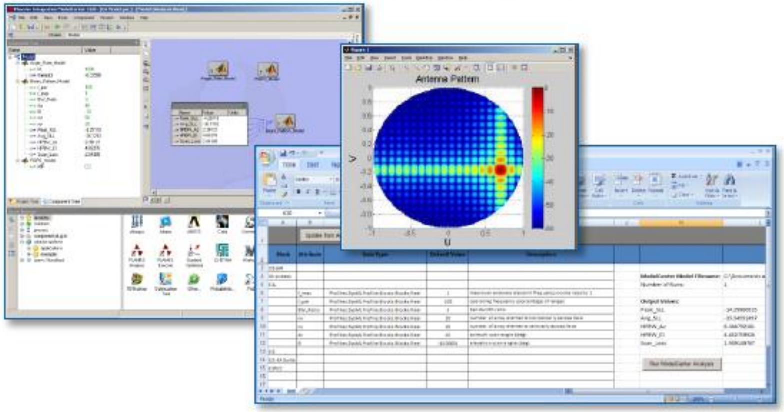
Blueprints, Schematics, Diagrams…





Analytical "Model" (as in "Flight Model")

Computational Models, Simulations…



A Complete Model-Based Systems Engineering Solution Integrates & Connects Both Descriptive and Analytical Models

Objectives & Value Proposition of Analytical MBE

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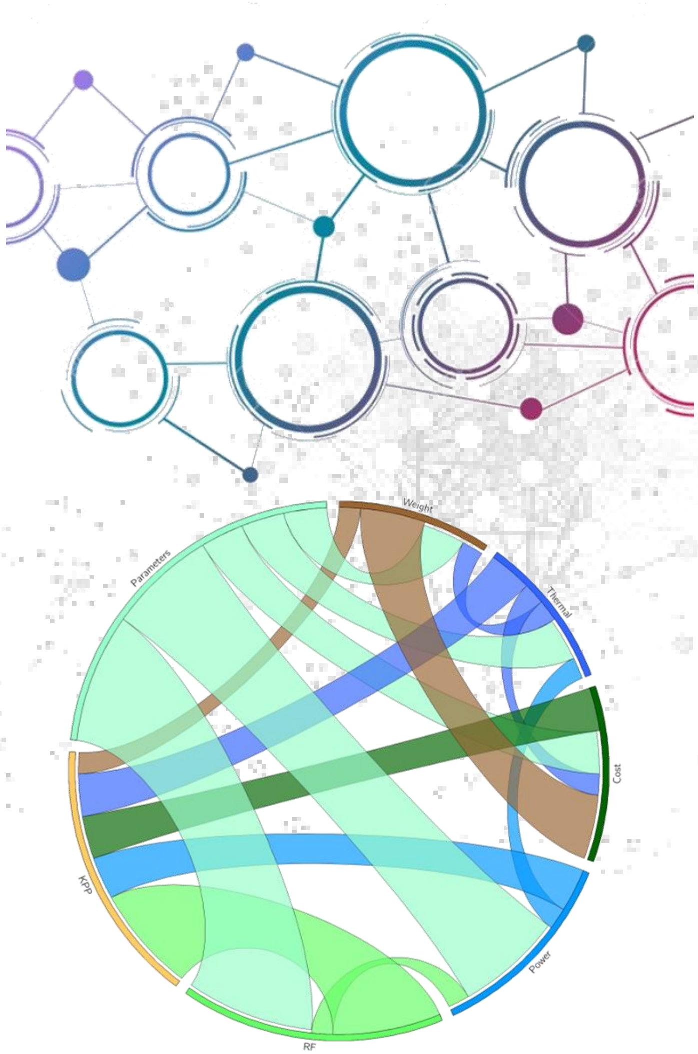
Objectives of This Work



- Develop an integrated, modular, and reconfigurable analytical cost-performance model of a phased-array antenna for EW, radar, and communication systems
- Perform combined aperture, module, and power system analysis using the subsystem hardware MBE Integrated Antenna Model
- Connect antenna model to system & mission modeling, simulation, and analysis frameworks to enable mission-level trade space exploration
- Extend lessons learned into Northrop Grumman's corporate modeling, simulation, and analysis initiatives using MBE

Digitally Connecting Models for System Optimization – Value Proposition

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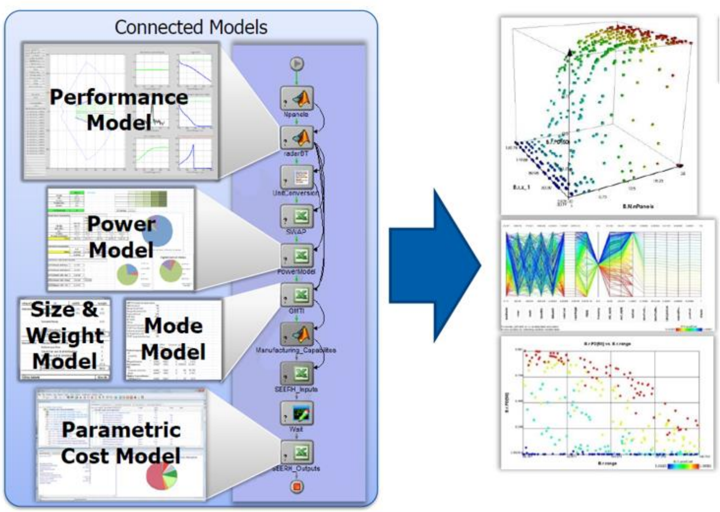
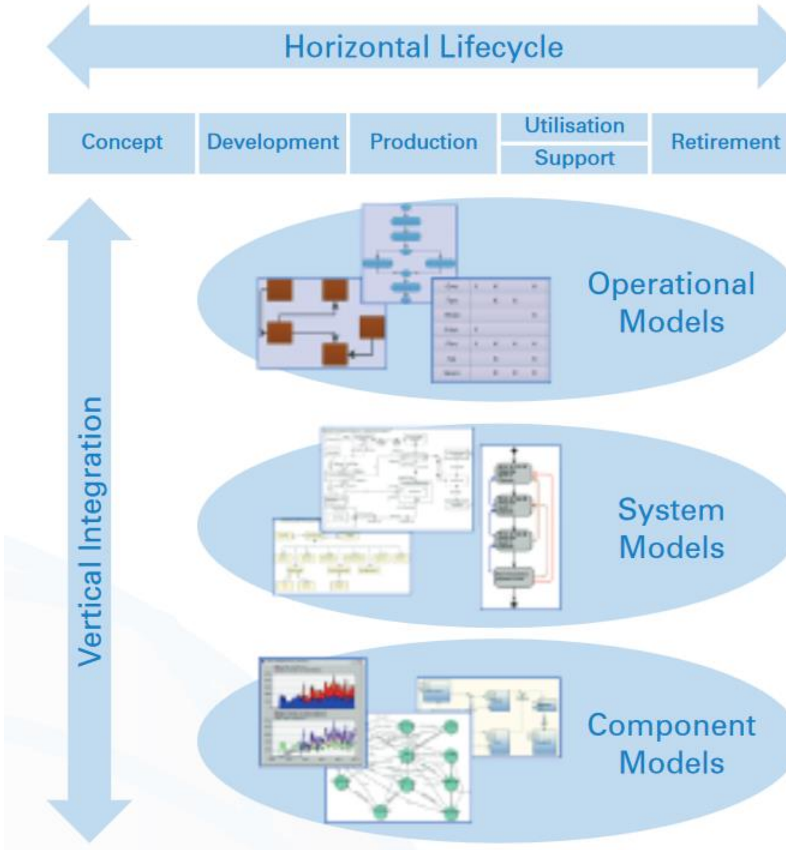
- Typical Challenge for RF Sensor System Design (Radar, EW, MF, etc.)
  - Customer need for certain system or mission performance
  - Customer constraints for example in cost, weight, space, available power
- Non-Connected Solution
  - Individual performance models: Weight, Power, Performance, Reliability, …
  - Separate Descriptive Models: Architecture, Redundancy
  - System optimization for all constraints difficult, time consuming, and error prone
  - Typically takes multiple days to determine performance of a single solution
- Digitally Integrated & Connected Solution
  - Automates connections between related models and eliminates transcription error
  - Performance of a single solution can be performed in seconds, minutes (depending on complexity of individual models)
  - Ability to apply multidisciplinary design, analysis, and optimization (MDAO) techniques to system development & trade studies

Integrated & Connected Analytical Models are Needed to Manage Increasing System Complexity in the Design & Development Process

Applying Model-Based Engineering Techniques to Antenna Array and Radar Design

- Improved technical communication
- Improved design quality
- Increased productivity
- Reduced design & execution risk

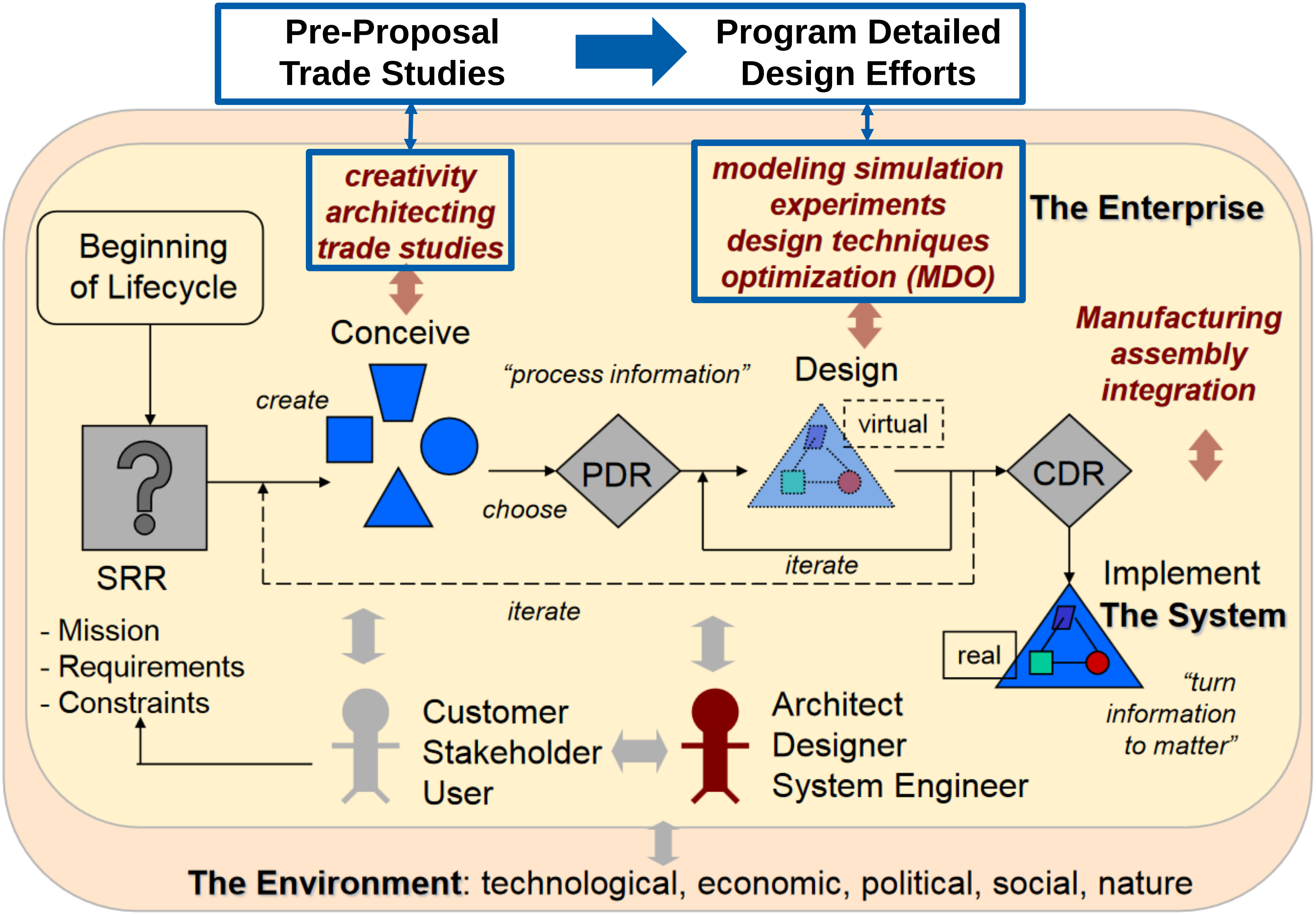




**From INCOSE: Why do MBSE? (2012)*

Using Integrated Analytical Models to Identify System Configurations that Provide the Best Cost, Performance, & Risk Trade

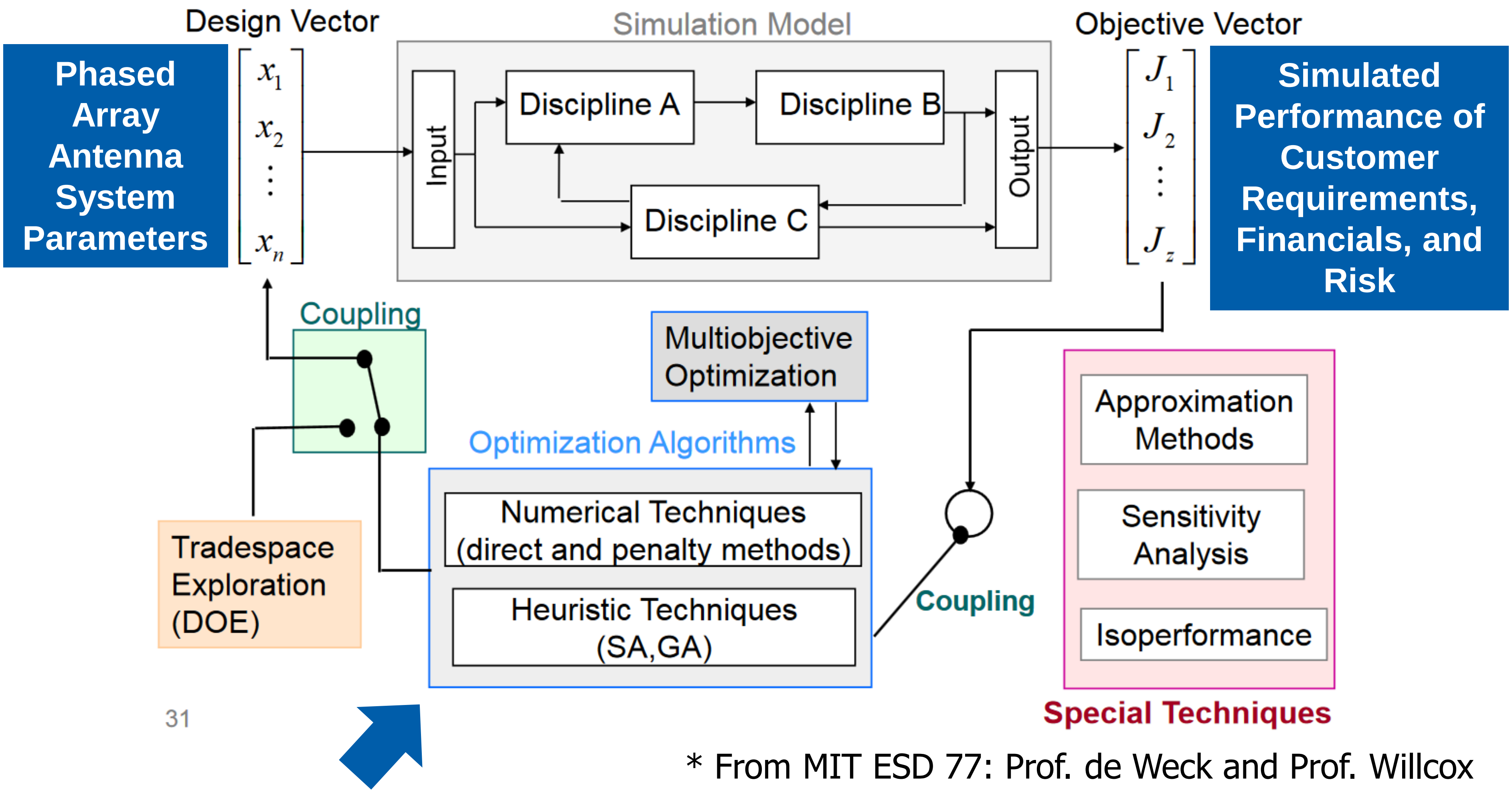
MBE Enhances the Engineering Product Dev Process and Speeds Up Design Iteration



* From MIT ESD 77: Prof. de Weck and Prof. Willcox

Using MBE to Apply MSDO to Antenna System Design

Multidisciplinary System Design Optimization (MSDO) Framework Enhances Product Design



* From MIT ESD 77: Prof. de Weck and Prof. Willcox

MBE Enables Faster Simulation Iteration Time Enabling Broader Trade Space Exploration, Increased Design Variables, and Mission Effectiveness Design Evaluation

Antenna Array Multi-Disciplinary Model Interdependence

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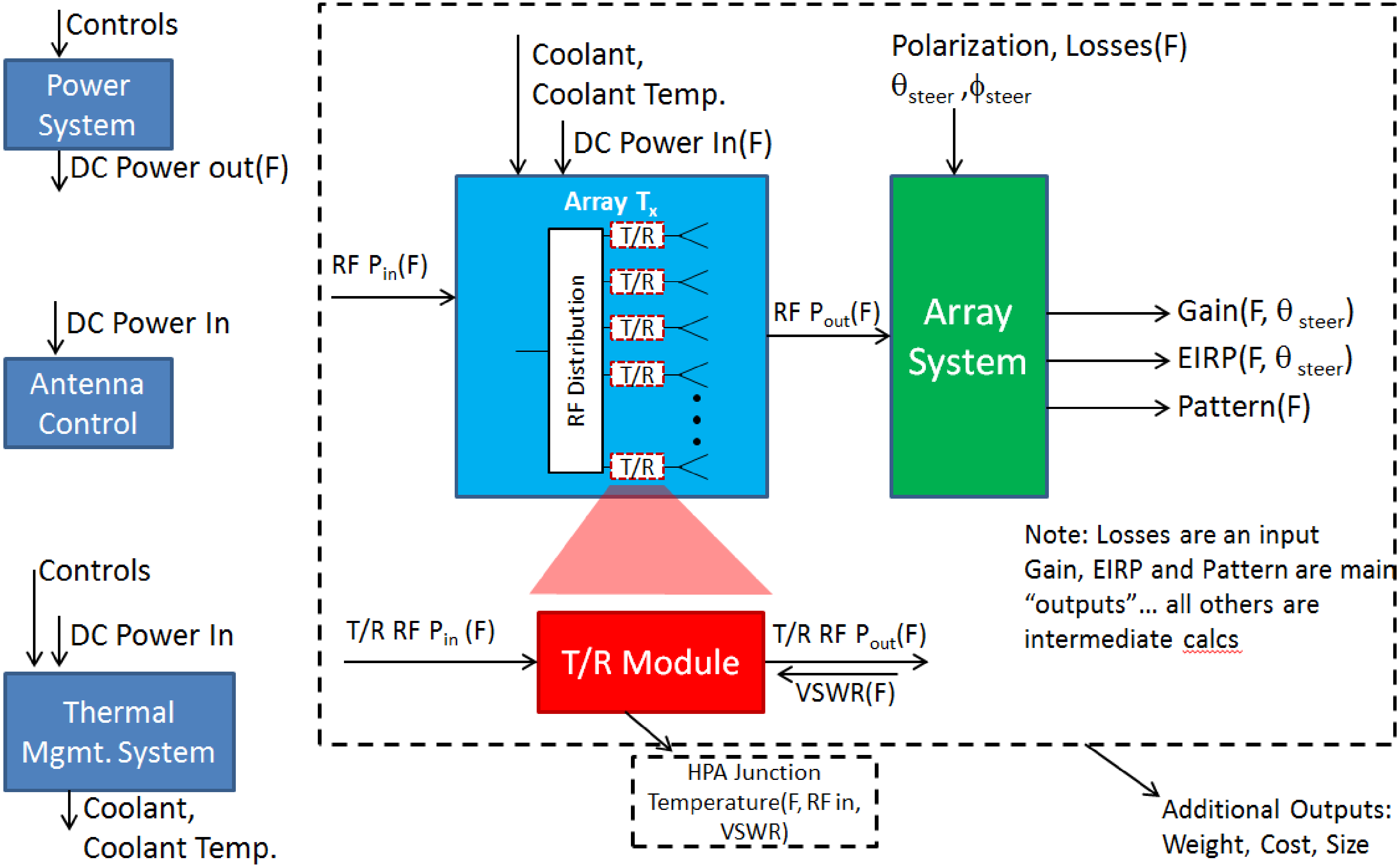
From NGMS Consulting RF Engineer

(Not a system block diagram)



Integrating Disparate Subsystem & Component Models to Perform Antenna System-Level Trades

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Example: Integrating Multiple Performance Models & SWaP Estimates Into a Unified Metamodel

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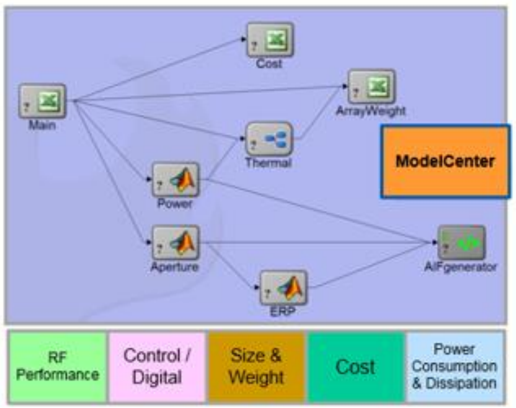
Current Integrated Models:

- HPA Performance [MMIC Design]
- Power System [Power Conversion]
- Antenna Patterns [Radiator Design]
- Installed Performance [Subsystem Hardware]
- Antenna System [Subsystem Hardware]
- SEER-H Cost Models [PTW]
- System-Level Models [EW Systems]
- Mission-Level Simulations [EW Systems]



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Coordinated w/ Power Systems to Consolidate 20+ Excel Tabs Into Usable Dashboard

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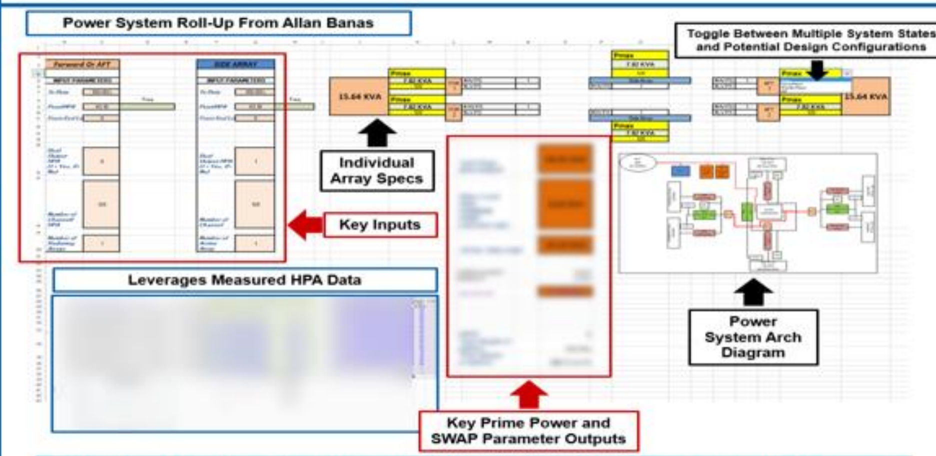

15 **Enables Quick & Easy Integration into Integrated Subsystem Models**

Integrating Models from Matlab, Excel, HFSS, and Measured Data to Perform System-Level EIRP Trades

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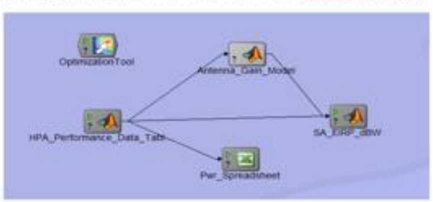
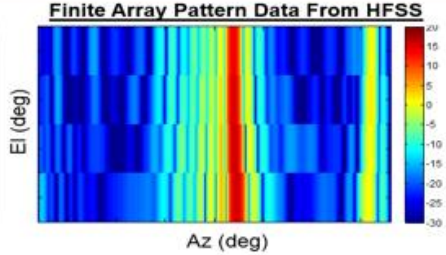
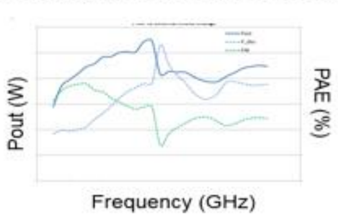
Integrated Antenna Model in ModelCenter



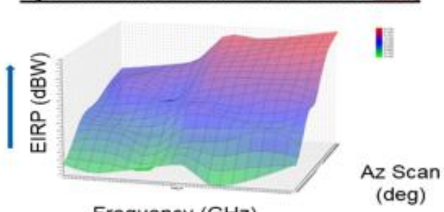
Finite Array Pattern Data From HFSS



Leveraging Measured HPA Performance



System Trades of EIRP vs. Scan & Freq



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Integrated Antenna Model Outputs

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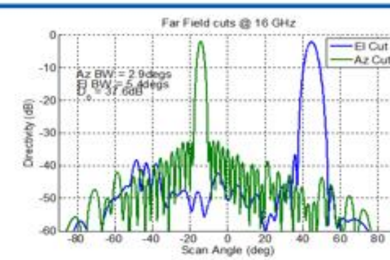
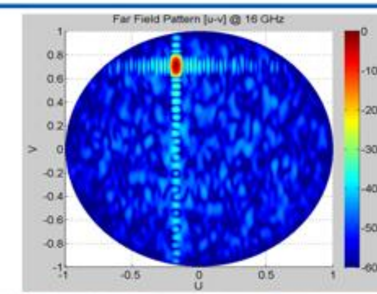
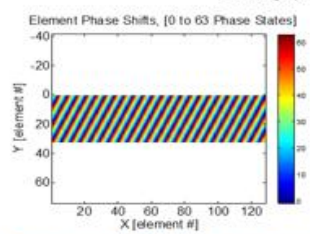
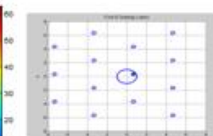
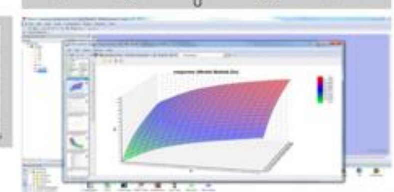




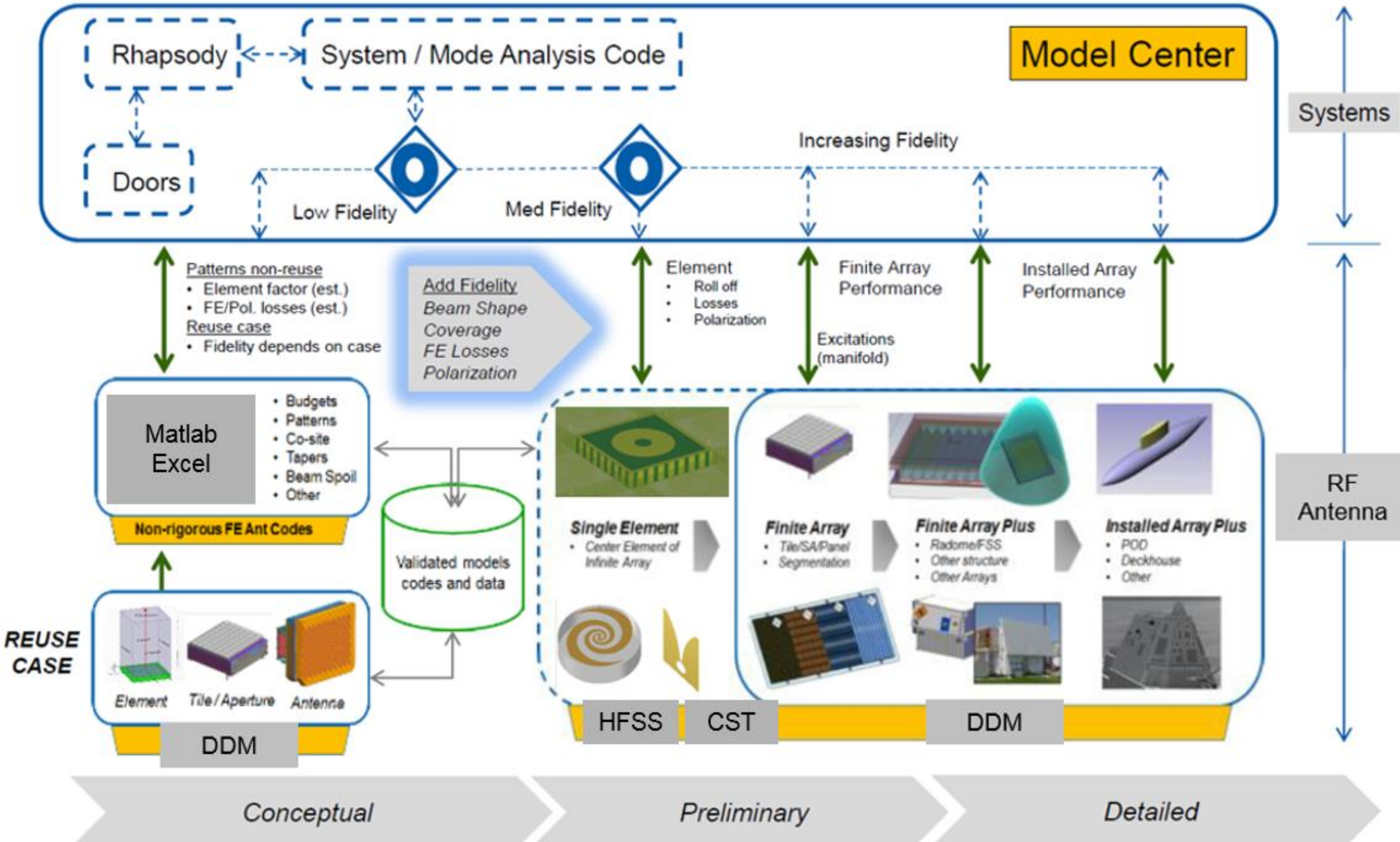






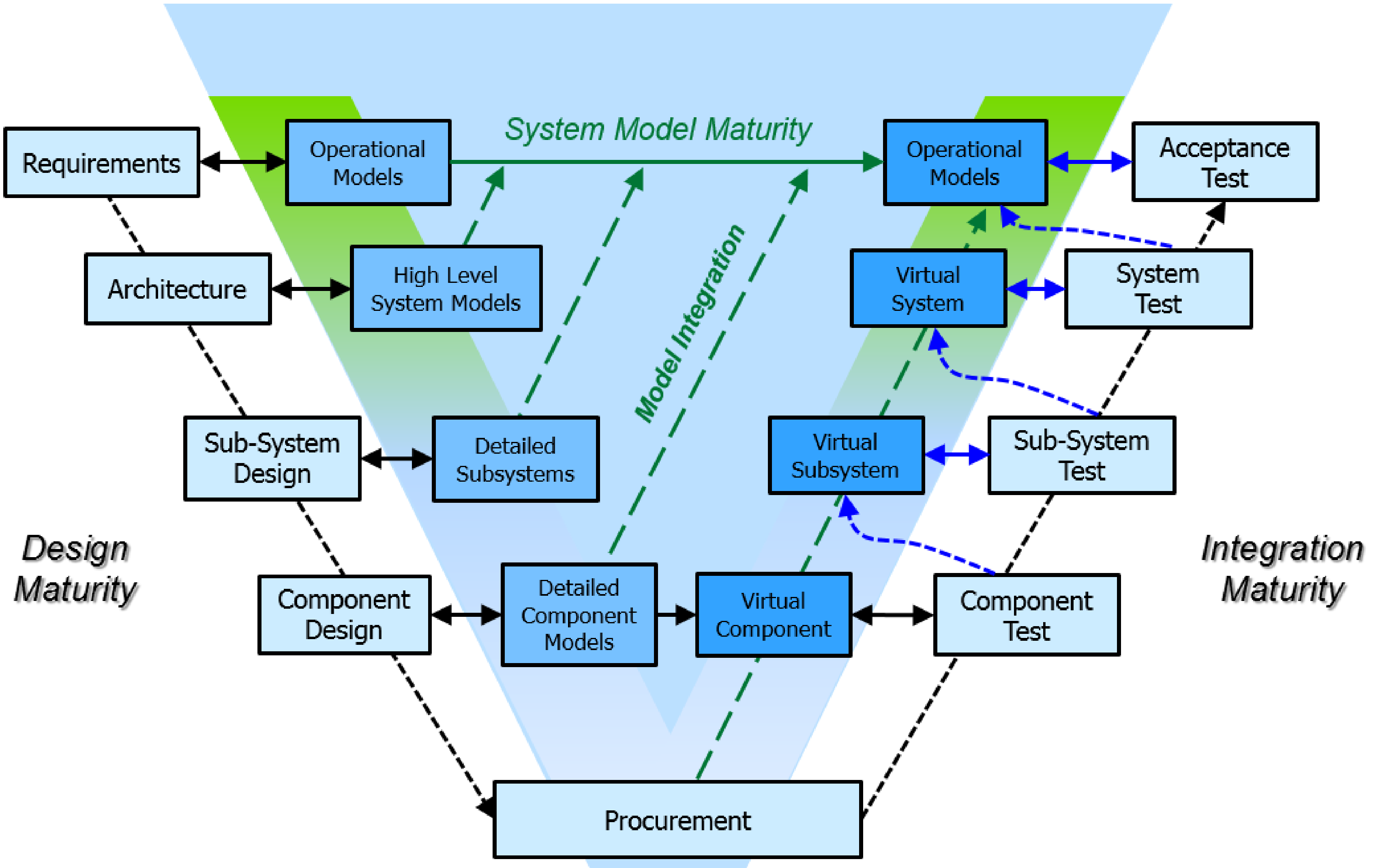
Outputs Trade Analysis, Beam Patterns, Directivity, Element Phasing, Grating Lobes, etc...

Increasing Levels of Fidelity Through the Antenna Design Process



Modeling, Simulations & Analysis

Provides Virtual Integration of our Systems for Verification & Validation (V&V)



Using Data Science, Analytics, and Optimization for Trade Space Exploration

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Developed Integrated MBE Antenna System Performance vs. SWaP & Cost Model for MDAO

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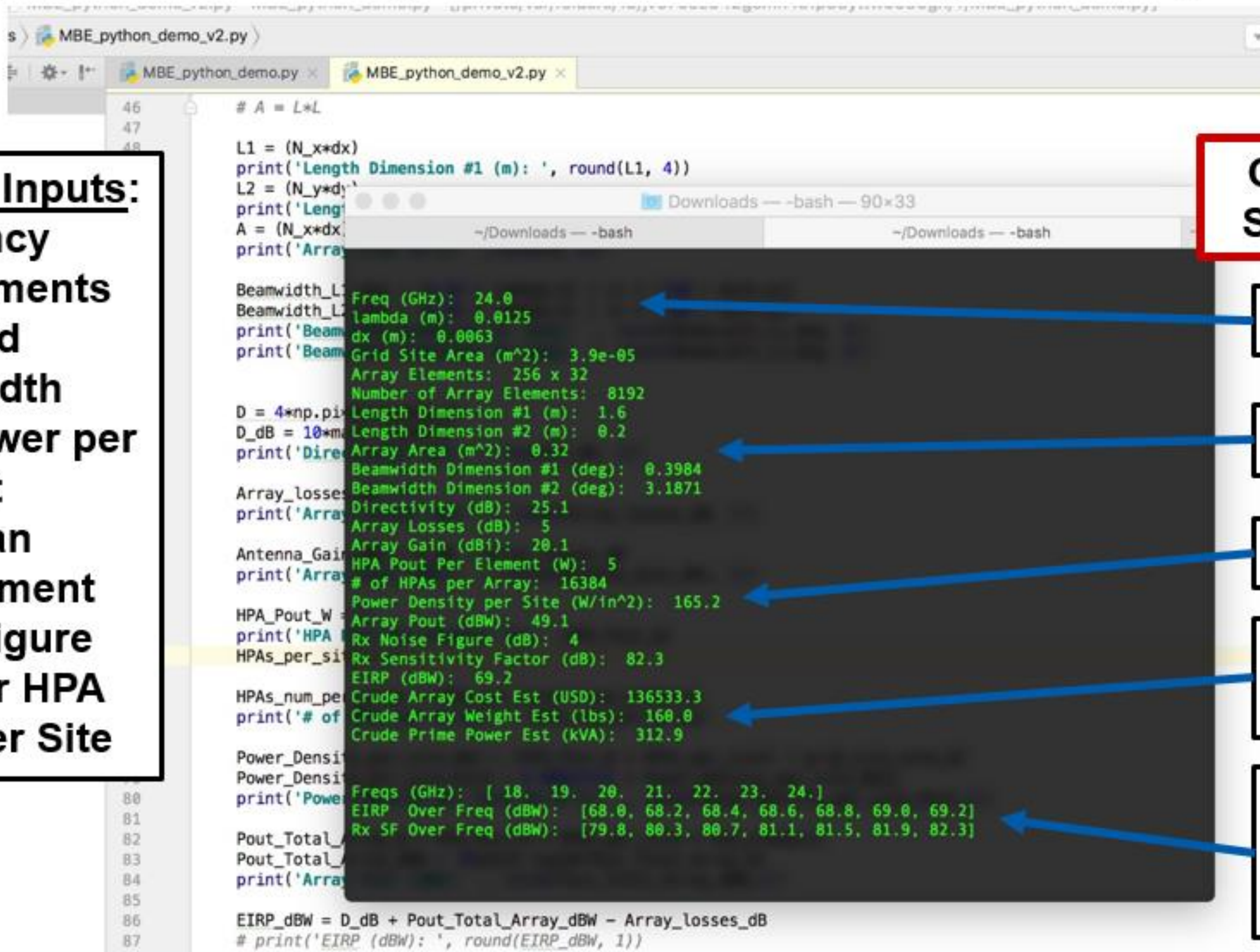
Physics-Based Analytical Model of Phased Array Antenna System

Key Model Inputs:
- Frequency
- # of Elements
- Required Beamwidth
- HPA Power per Element
- Max Scan Requirement
- Noise Figure
- Cost per HPA
- HPAs per Site



Core Antenna System KPPs:
- Frequency
- Size
- Thermal
- Cost & SWaP
- EIRP & Sensitivity Over Freq

Developed Multidisciplinary Phased Array Antenna System Model with Many Interdependencies; Runs in ModelCenter, Matlab, & Python

Evaluate Program-Specific Tradeoffs and View Structure of Data Using Visualization Tools

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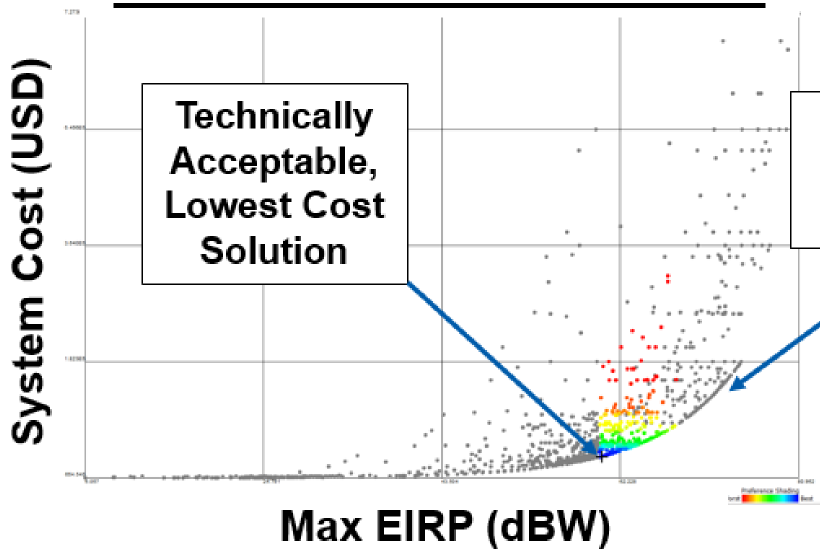
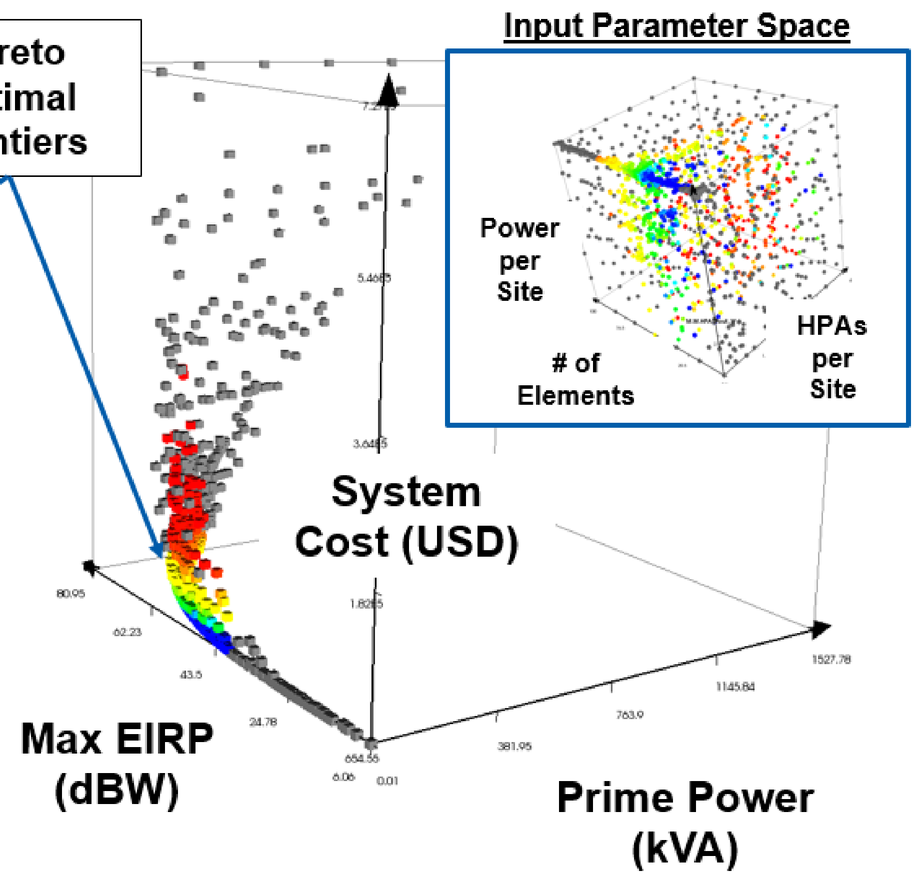
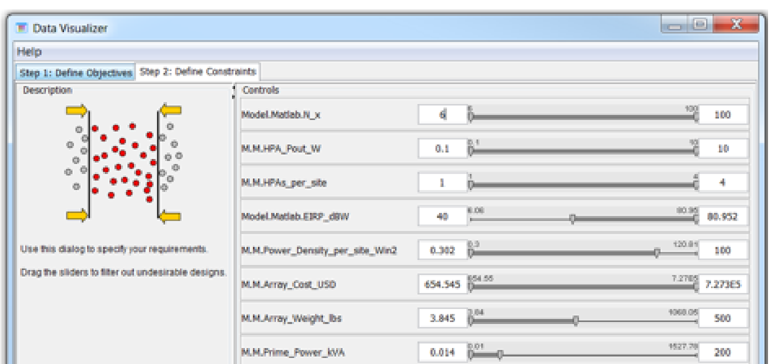
Pareto Front: Max EIRP vs. Cost



3-D Data Manifold of KPP Output Space: Max EIRP vs. Cost vs. Prime Power

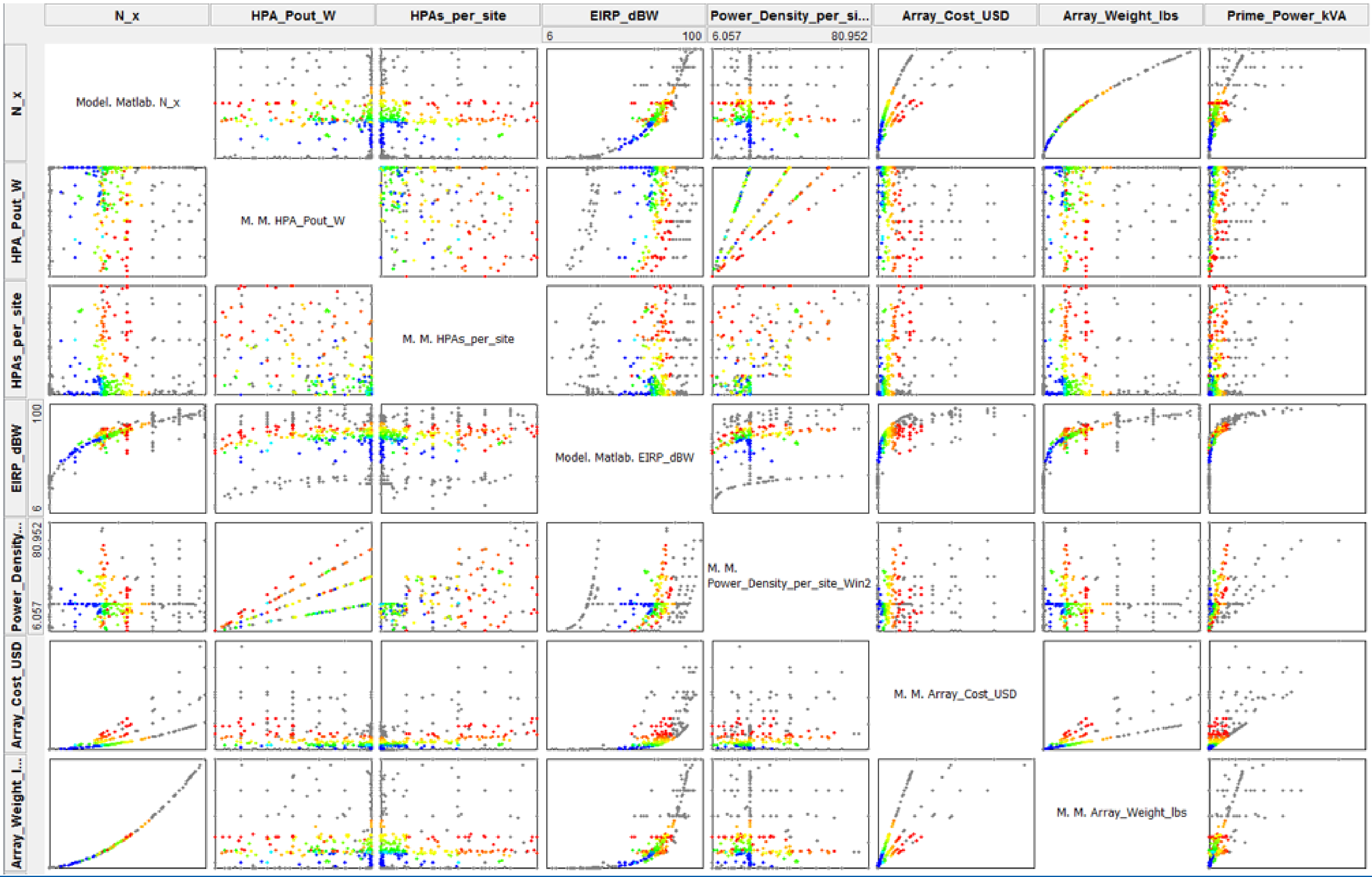


Define Component & SWaP Constraints



Color Shading Design Cases Based on Best (Blue) to Worst (Red); Able to Gray Out Design Cases That Do Not Meet Specified SWaP Constraints

Analyze Performance Relationships Between Input Parameters and System KPPs to Find Optimal Design



Color Shading Design Cases Based on Best (Blue) to Worst (Red); Able to Gray Out Design Cases That Do Not Meet Specified SWaP Constraints

Using Evolutionary Optimization Techniques to Discover Best Solution in Available Trade Space

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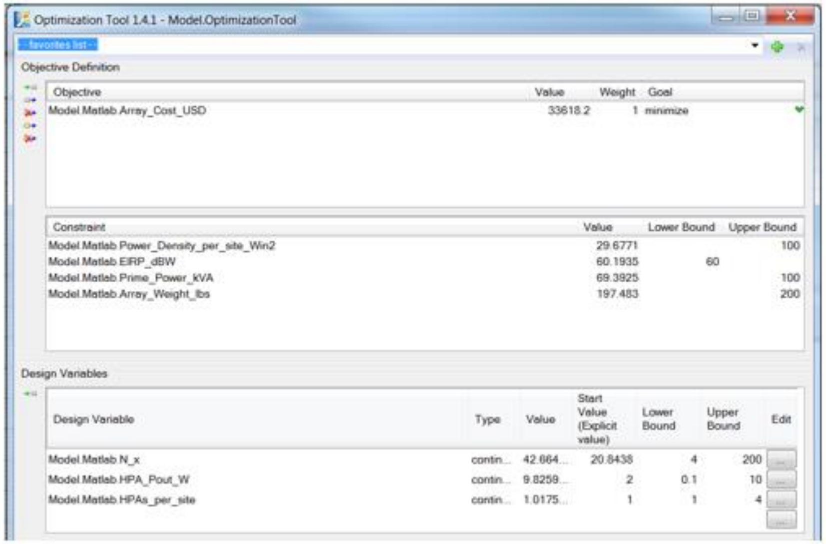
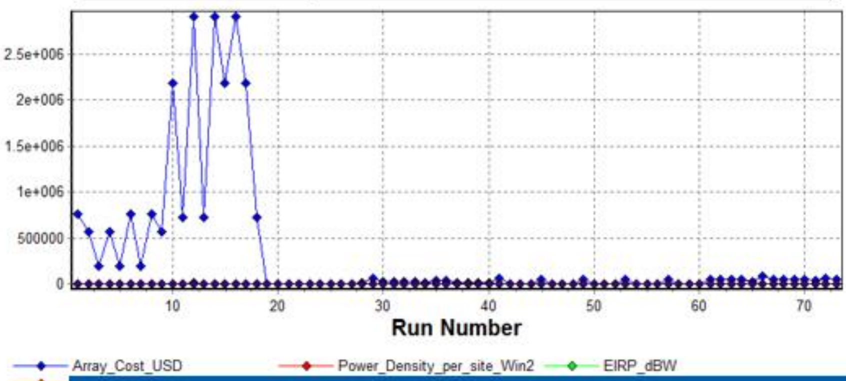
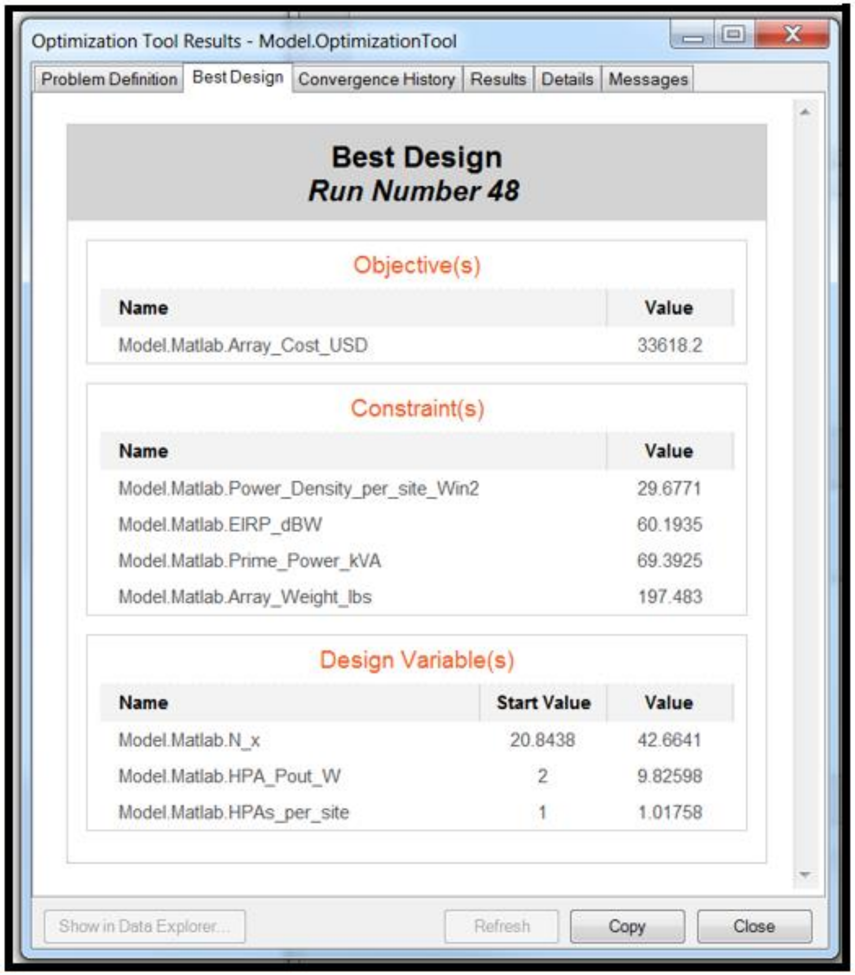
Design System Requirements & Constraints



Minimize Optimization Cost Function



Discover Best Solution in Trade Space



Define Program-Specific Objectives, Constraints, and Input Parameters to Discover Best Trade-Offs and Optimal System Design Solutions

System Trades, Mission Visualization, & Financial Modeling

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System and Mission-Level Modeling: Relating Hardware Performance to Mission Effectiveness

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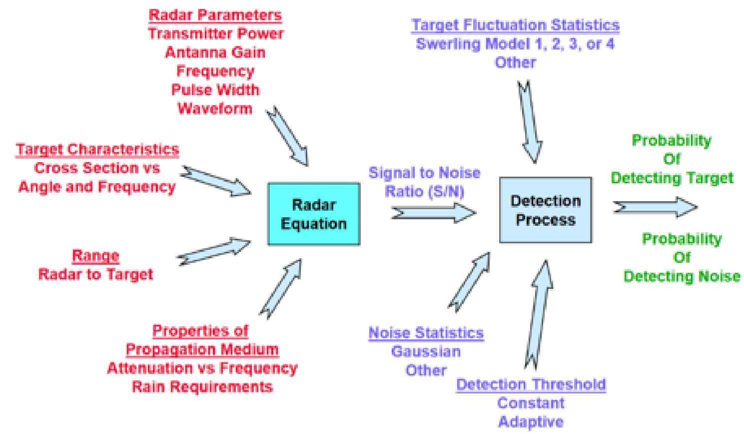
Radar Blake Chart

Radar Performance Blake Chart (Implementing Radar Range Equation):

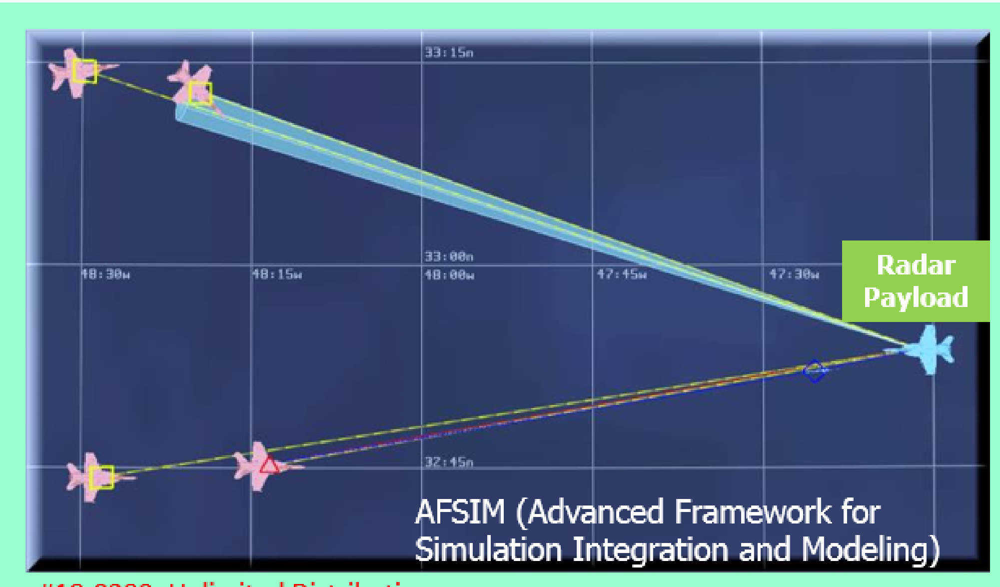
Numerator					
Quantity	Unit	Linear	dB - Gain	dB - Losses	
Pt	W	800000	59.0		
Gt	dBi		38.0		
Gr	dBi		38.0		
lambda^2	m^2	0.01	-20.0		
RCS	m^2	6	7.8		
# of Pulses		10	10.0		
Denominator					
(4*pi)^3		1984.40171		33.0	
k	w/Hz*K	1.38E-23		-228.6	
To	K	290		24.6	
B	Hz	7.50E+05		58.8	
NF	dB			6.0	
Ls	dB			13.0	
L_Tx_Ant	dB			2.0	
SNR	dB			8.2	
Totals			132.8	-83.1	
R^4 (dB)					215.9

R^4 (m^4)	3.85721E+21
Range (m)	249211.6
Range (km)	249.2
Range (Nm)	134.6
Range (miles)	154.9

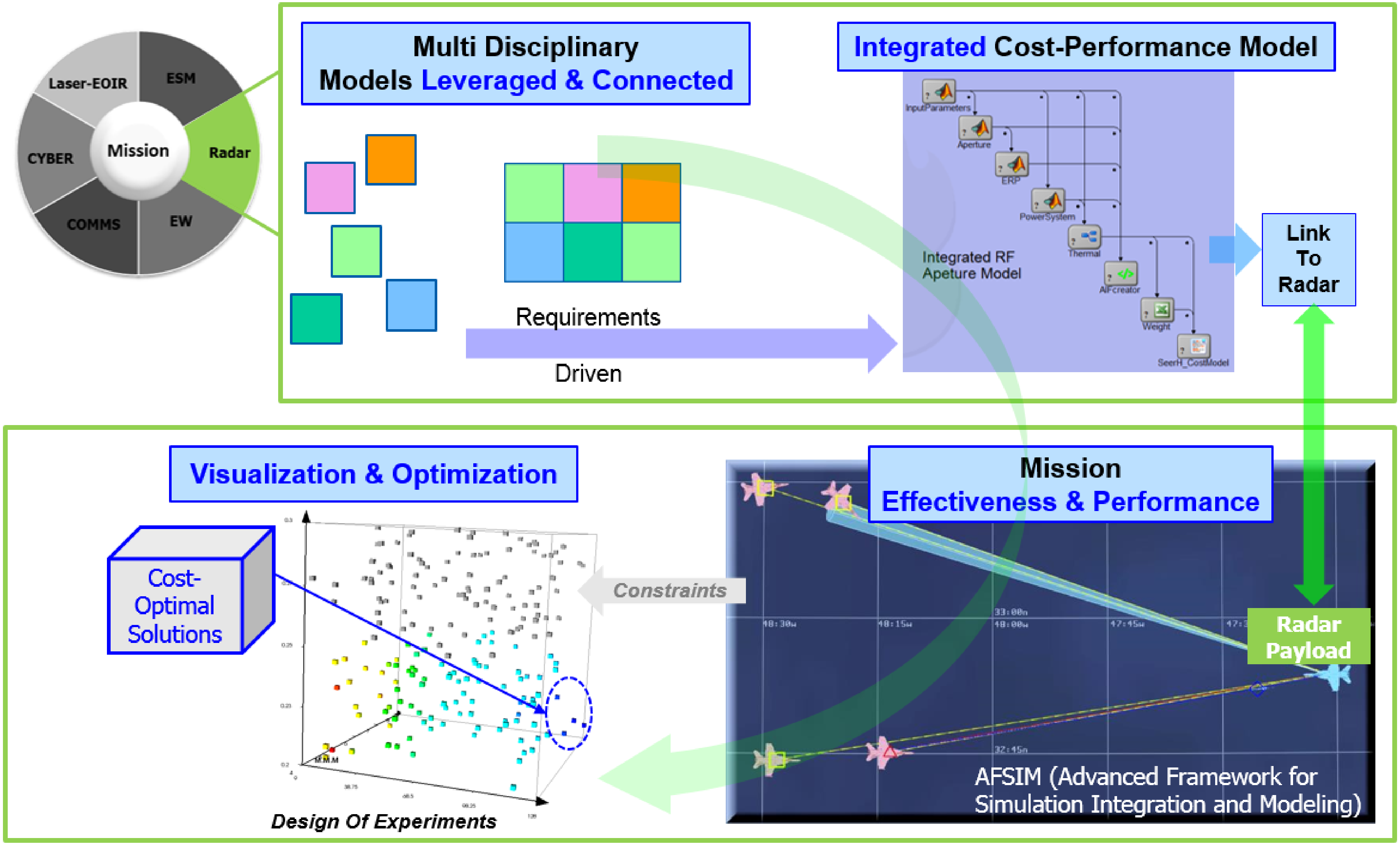
Radar Detection Models



Mission Scenario Simulation



Components, Sub-System & System Analytical Models- Integrated and Linked to the Mission



SEER-H Parametric Cost Estimation Tool: Bringing Cost Into the Design Optimization Loop

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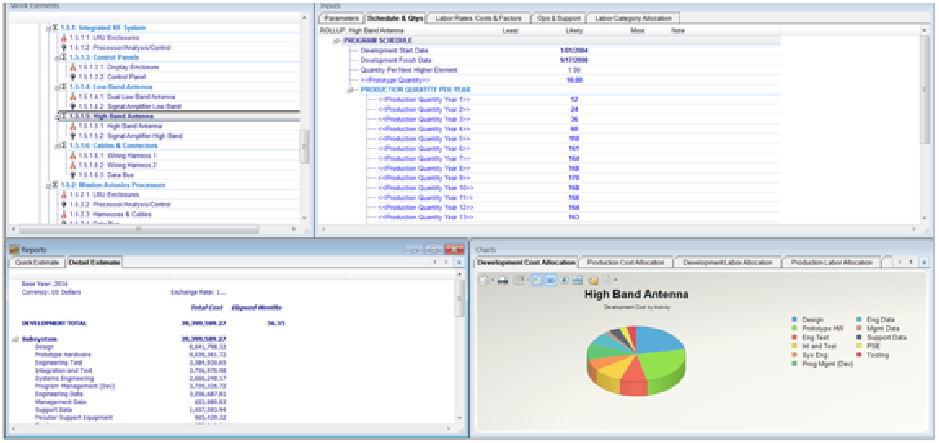
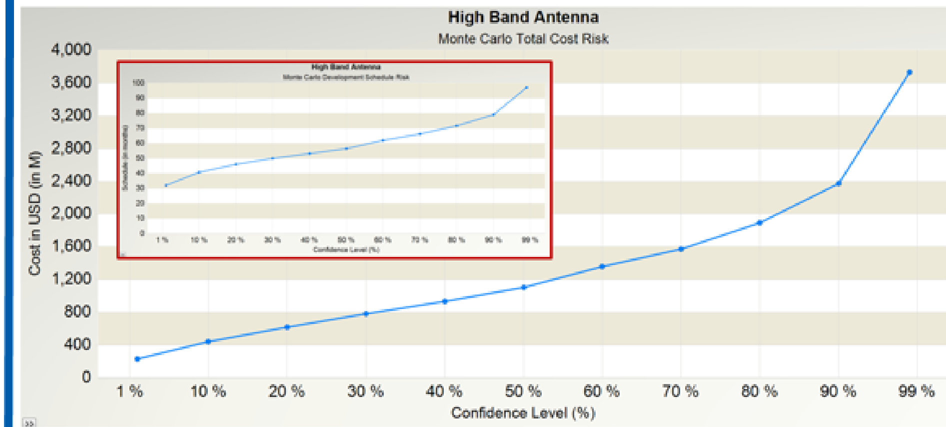
Component Cost Breakdown



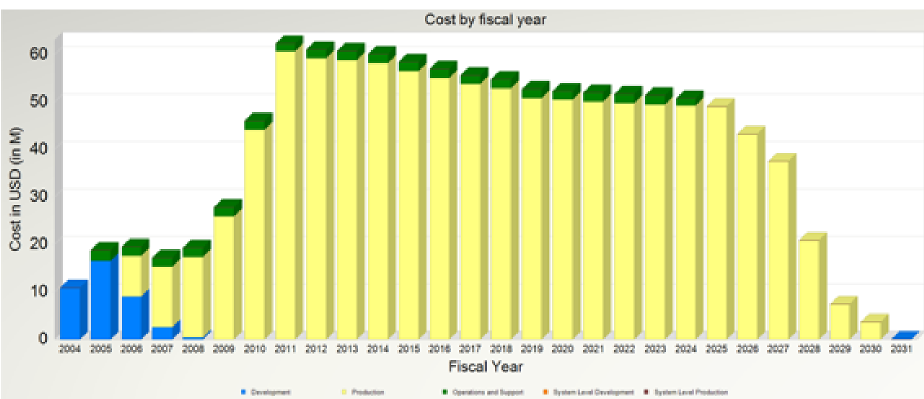
*Note: Generic cost model example. Numbers do not reflect Northrop Grumman actuals.

Cost & Schedule Risk Estimates

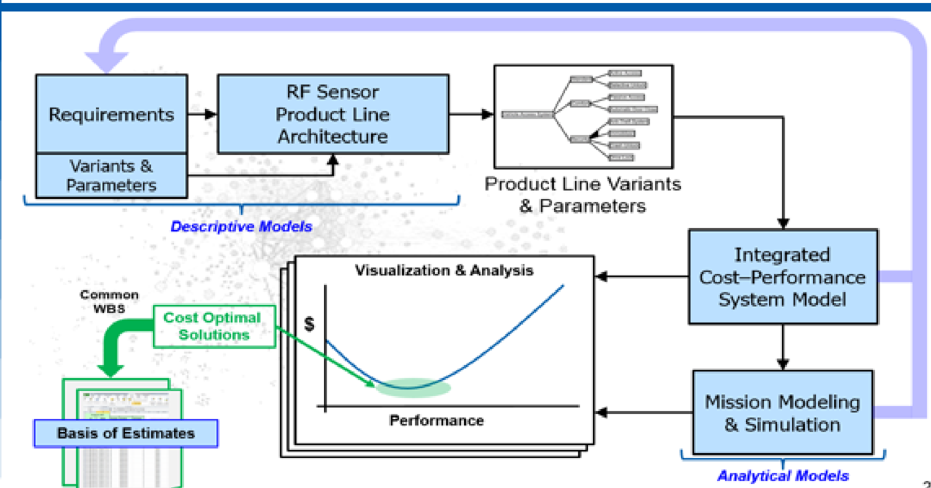


*Note: Generic cost model example. Numbers do not reflect Northrop Grumman actuals.

Fiscal Year Projections



*Note



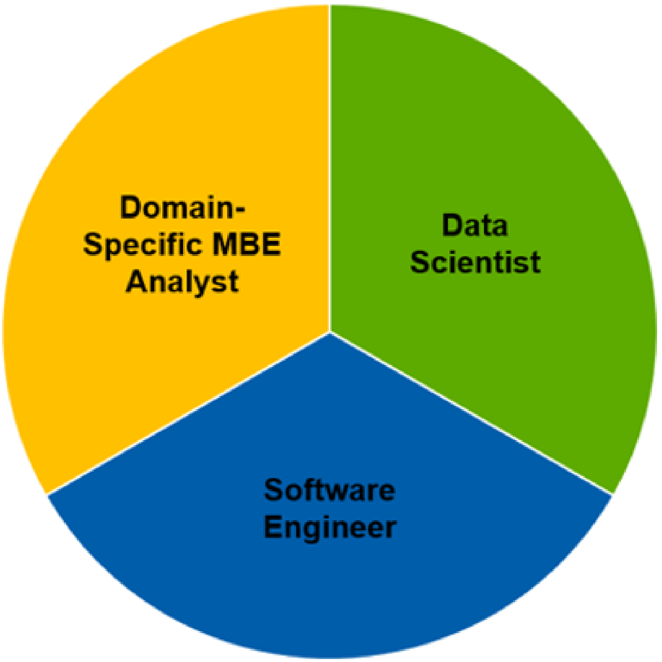
Using Cost History Data to Estimate Detailed Development, Production, and Life-Cycle Costs of Future Antenna Systems

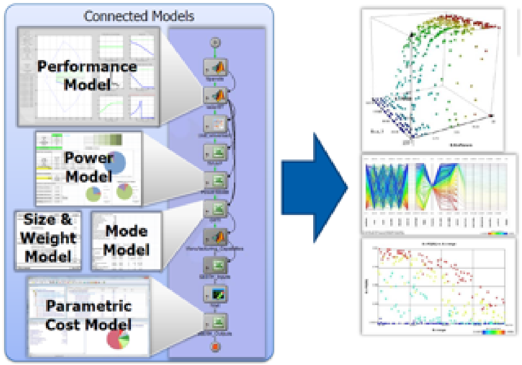
MBE Analytical Services: An Idea to Expand MBE Analytics

What is Required for a Successful MBE Analytics Team?

- **Domain-Specific MBE Analyst:**
  - Work with program leads to identify & prioritize the problems worth solving and develop a program-specific MBE strategy
  - Work with software engineer to create technical MBE solution
  - Work with data scientist to communicate program needs and trade study results
- **Data Scientist:** Use connected MBE models to analyze program data, run trade studies for program, and create innovative data visualizations
- **Software Engineer:** Create technical MBE software product for program and integrate program's engineering models

Proposed Team Member Roles





Digital Platform: Model Aggregation & Integration with MBE Creates Network Effects

Suppliers: Model Creators

Aggregator: Model-Based Engineering (MBE)

Users: Programs

Once an aggregator has gained some number of end users, more suppliers will come onto the aggregator's platform.

Virtuous Growth Cycle

Additional suppliers then make the aggregator more attractive to more users, which in turn draws more suppliers, in a virtuous cycle.

More data and more models integrated on the MBE platform lead to more accurate predictions which attracts more programs and in turn more model development

Conclusions & Next Steps

Conclusions

- Increasing system complexity is straining traditional engineering and design techniques for phased array antenna, radar, and multi-function RF systems

- Integrated MBE modeling techniques are needed to manage system complexity, improve technical communication, and create cost-optimal solutions

- Customers are beginning to expect model integration from hardware to system to mission-level and throughout the entire system design lifecycle

- Our implementation an integrated antenna and radar system model consisting of disparate hardware and subsystem models provides a blueprint for future antenna system designs and cost-performance trades

- Large-scale multi-disciplinary design, analysis, and optimization (MDAO) techniques coupled with mission effectiveness simulations will result in better customer solutions, reduced risk, and more efficient RF and radar system design

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Multidisciplinary System Design Optimization Using Model-Based Engineering to Support Phased Array Antenna Architectural Trades

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The typical challenge in RF sensor system design is to meet the customer's specified mission or system performance needs while fitting within the cost, size, weight, and power (SWaP) constraints. Traditional design methods using non-connected models often fail to capture complex system interactions and make system optimization for all constraints difficult, time consuming, and error prone. Given the increasing complexity of RF sensor systems, a digitally integrated & connected analytical modeling solution is needed to identify system configurations that meet challenging mission requirements and provide the best cost, performance, & risk trade.

This work, utilizing ModelCenter, overviews how the Model-Based Engineering (MBE) Integrated Antenna Model has been leveraged to support radar and electronic warfare (EW) trade studies by integrating performance, SWaP, and cost models to explore design trades and optimization. Model-Based Systems Engineering (MBSE) and Multidisciplinary System Design Optimization (MSDO) techniques are combined to perform rigorous quantitative and analytical modeling of a phased array antenna system. The author has built a MBE metamodel to accurately and quickly explore trades; predicting performance (such as effective isotropic radiated power (EIRP), # of simultaneous beams, frequency, and spatial coverage), SWaP, and cost to find an optimal solution set. This work integrates subsystem and component models into a unified metamodel that is integrated with system-level EIRP models, a SEER-H cost model, and a mission-level simulation. Subsystems and components modeled include the transmit module, power system, antenna radiator, antenna system, thermal, and pod weight. The models are integrated using Matlab and ModelCenter for analysis and multi-objective optimization. MBE has enabled the design team to evaluate the EIRP trade space against requirements more thoroughly and in significantly less time.

A major benefit of MBE is the flexibility and agility of the integrated model toolset that allows the user to rapidly modify underlying components and design parameters in the model and produce decision-quality visualization charts to meet the needs of internal & external customers. As the design matures, the metamodel can be quickly updated to iterate options. A MBE Integrated Antenna Model can be used for initial design exploration (pre-program trade studies), and then be leveraged throughout the system design & development lifecycle. This presentation will demonstrate a framework for how analytical MBE can be adopted by more phased array design programs and capture efforts to support technical & strategic decision making.