“Customer Success Is Our Mission”

How Rocket Scientists Implement High Maturity

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November, 2009

Case Study by Debra Herrera and Dave Frank
Changing Our Approach

How to take Missile Systems from a Business that...

1. Understands Product Requirements
2. Designs A Product
3. Determines Suppliers
4. Decides Where To Build
5. Evaluate For Affordability
6. Redesigns

To a Business that...

1. Understands The Use Of The Product
2. Makes Requirements Capability Trades Around Affordability
3. Determines A Build Strategy
4. Identifies Where To Buy From
5. Designs To Maximize This Strategy

Design 2010
Why We Need Change

% of Life Cycle Cost Committed

- Concept: 70%
- Development: 15%
- Procurement: 10%
- Op’s and Sup’t: 5%

% of Life Cycle Cost Spent

- Concept: 3%
- Development: 21%
- Procurement: 70%
- Op’s and Sup’t: 6%

- 70% of the cost is determined prior to the start of development
- Yet 76% of the cost is spent post development

Design 2010

- Concept
- Use
- Affordability
- How To Build
- Where to Buy
- How To Design
Understanding What’s Critical to Our Business

The design process drives effective production.

Figure 1. Typical Product Development Cycle

Production Rework Drivers
- Design
- Supplier
- Workmanship
- Test Equipment
- Work Instructions
- Tooling
- NFE/CND
- Process Equip
Profound Shift in Focus

<table>
<thead>
<tr>
<th>Pre-Concept</th>
<th>Development</th>
<th>Production</th>
<th>Field/Maint</th>
</tr>
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<tbody>
<tr>
<td>1st</td>
<td>SW</td>
<td>2nd</td>
<td>1st</td>
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<tr>
<td></td>
<td>SW</td>
<td>2nd</td>
<td>1st</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>HW</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1st SW, SE, HW
Some Uniqueness of RMS

- High Volume Production – focus on full life-cycle costs
  - Small savings per unit >>> Large savings in development
- Families of weapons (missiles, projectiles, etc.) but each with divergent performance objectives

- Some launched from helicopters
- Some launched from airplanes
- Some launched from ships, ground, submarine
- Some with rocket motors
- Some glide
- Some are propelled
- Some are small, some are large
- Some are guided by GPS, IMU, or laser
High Maturity Timeline

1950–1970s

1980s–Present

Pre-Concept    Planning    Development    Production    Field

Statistical techniques

SPC

RMS

Models

Production and Fielded System

Org Objectives

Process

Product

SW/SE

HW
Finding “defects” earlier saves $
Being Predictable Means…

Measuring Design Processes that Accurately Predict Production Yield

Pre-Concept Development Manufacturing Field

*Process Performance Models and Baselines allow predictions to be made throughout the entire product development lifecycle*
Existing Robust Design Methods Support the Transition

Understands The Use Of The Product

Makes Requirements Capability Trades Around Affordability

Determines A Build Strategy

Identifies From Whom To Buy Or Whether To Make

Designs To Maximize This Strategy

Customer relationships
CONOPS
Analysis of Alternatives

Integrated approach
Planned iterations
Reqs. & cost trades

Modern factory & test initiative
Understand variability vs margins

Core competency factory alignment

Key supplier alignment

Design guides
Design for Affordability

Modularity & commonality initiative

Core make/buy strategy

Modeling & Sim
Robust Design - Balancing Performance, Producibility and Affordability in Design

Design For Performance
- Quality Function Deployment
- Parameter Diagrams
- Key Characteristics
- Statistical Design Methods
  - General Orthogonal Solutions
  - Multi-Objective Optimization
  - Sensitivity Analysis
  - Monte Carlo Analysis
  - Requirements Allocation
  - Design of Experiments
  - Data Collection and Analysis
    - Fit Data to PDFs
    - Design of Tests
    - Impact of MSE
    - Analysis of Failed Tests
- Defect Containment Process
- Reliability Prediction

Design For Producibility
- DFMA Workshop
- Producibility Assessments
- Process Capability Analysis
  - PCAT
  - Mechanical Tolerancing
  - GD&T
- Process FMEA
- Process Modeling

Design for Affordability
- Cost as an Independent Variable
  - Acquisition Reform Initiative
  - Warfighter participation
  - Total Ownership Costs
  - The “What” of Affordability
  - Conceptual Trade Studies
- Design to Cost
  - Detailed Design Trade Studies
  - Cost Models and Cost Tracking
  - DTC Metric
- Cost Estimating & Tradeoff Analysis
  - Price H/M/S
  - RPCM & RAYCOST

From Statistical Design Methods for Engineers Class
Robust Design Methodology

Identify Desired Customer Outcomes / Requirements → Identify Critical Parameters → Identify Noise Factors

Concept and Architecture Development

Develop Transfer Functions for Critical Parameters → Identify Key Characteristics

Design

Perform Trades to Optimize and Balance the Design

Optimize

Verify Design Capability → Establish Controls for Key Characteristics

Verification

Iterate at Each Subassembly and Component Level

Robust Design (Design for Six Sigma – DFSS) embedded in Common Process and Institutionalized at Raytheon Missile Systems
Robust Design Analysis results in...

- A prediction of the Response Statistical Properties
- A prediction of the Probability of Non-Compliance
- An assessment of the Contribution of Parameter Variation to the Response Variation

From Statistical Design Methods for Engineers Class
How do we know when a process is successful?

1. It Meets Spec [✓]
2. It Is Robust To Variation/Unknowns
3. It Is Not Over-Designed

Items 2 & 3 require understanding Margin!
Understanding Design Margins

Adequate Margin
No Risk

Too Much Margin
Opportunity for Improvement
Over Designed – Excessive Material & Process Costs

Not Enough Margin
Significant Risk
Low Yields
Rework & Scrap Costs

From Statistical Design Methods for Engineers Class
Cost Impact of Design Margin

The Advantage of Specifying the Right Amount of Design Margin

Over-Design
- Tighter Tolerances
- Higher Cost Materials
- More Design Iterations
- Diminishing ROI

Under-Design
- Lower Yields
- More Rework/Repair
- Lower Reliability
- Diminishing Product Quality

Sweet Spot

Cost Impact of Design Margin

Expect Relatively Small fluctuations in Cost

Expect Relatively Large fluctuations in Cost

- ← Design Margin → +

From Statistical Design Methods for Engineers Class
Quantitative Measurement of Design Margin

- PNC is the probability of noncompliance
- PNC = 1 – yield
- It is the Probability that a response of interest does not fall within required specification limits
- It is a statistic that allows us predict the achievement of the objectives of any process
- It is one of the most important measurements to evaluate process performance

It is the quantitative measure of design margin

From Statistical Design Methods for Engineers Class
PNC Measures Customer Satisfaction

Customer Satisfaction = Function(Cost, Schedule, Performance, etc.)

- Cost = function (Design Capability, Process Capability(1-PNC))
  - The Base cost of the design is set by the Architecture and CAIV driven changes. It is the accumulated cost of all levels of the design
  - For items that can be reworked: Cost = Base cost + PNC * Rework Cost
  - For items that are scrapped: Cost = Base Cost / (1-PNC)

- Schedule = function (Design Time, Mfg Time, Rework & Repair time)
  - PNC is a measure of how much rework we must perform, and that takes time

- Performance = function (Design, Design Margin (PNC))
  - The PNC on Key Performance Parameters tells us how often the customer requirements are not satisfied

From Statistical Design Methods for Engineers Class
PNC is a prediction of the percent of time that a response of interest will fall outside of its specification limits.

\[ PNC = P(x < LSL) + P(x > USL) \]
Design Margin Measures the Success of the Robust Design Process at any Level


This is Iterative During Development

Voice of the Customer Needs

System Level Requirements

Subsystem Level Requirements

Subassembly Level Requirements

Component ‘Critical to Function’ (CTF) Requirements

Mfg. Process Requirements

Component CTF Specs...

Subassembly CFRs.....

System Level CFRs.....

Mfg. Process CTF Specs

Cpk PNC

Cpk PNC

Cpk PNC

Cpk PNC

From Statistical Design Methods for Engineers Class
Some Tools used at Raytheon Missile Systems for Robust Design

Equation-Based Tolerance Analysis and PNC Prediction

Parameter Allocation

Multi-Objective Optimization for Parameters

RAVE/PEM

JFIT

Input the first four moments of the data set

ErrorChiSquare Results of The Data

Input the Spec Limits

DCAT Example

Data

DCAT

Rolled Yield is the Product of each best yield
DCAT tool also provides a histogram of the data and the curve fitted to the data for PNC calculations.
Antenna Case Study

Debra Herrera
Dave Frank

*All values presented in the case study are fictitious
Program Followed Robust Design Process

- Program’s process documented in the DFSS Plan
- A preliminary listing of Key Characteristics was developed based on program objectives and reviewed with the appropriate stakeholders

<table>
<thead>
<tr>
<th>Status</th>
<th>Specification Number</th>
<th>Specification Description</th>
<th>Paragraph Number</th>
<th>Paragraph Description</th>
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<tr>
<td>KPC</td>
<td>4482922-906RV3</td>
<td>CIDS Antenna Sub Assembly</td>
<td>5.5.8.9.4.2-4</td>
<td>Peak Sidelobe</td>
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<td>Boresight Alignment</td>
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<td>CIDS Antenna Sub Assembly</td>
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<td>CIDS Antenna Sub Assembly</td>
<td>5.5.8.12.3</td>
<td>Band Aid Coverage</td>
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<td>KPC</td>
<td>4482922-906RV3</td>
<td>CIDS Antenna Sub Assembly</td>
<td>5.5.8.11.7</td>
<td>Band Guard Coverage</td>
</tr>
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</table>

- The antenna design process was chosen as one of the key processes (subprocess) to apply statistical design methods due to sensitivity of seeker performance to variation and the low capabilities of past antenna designs

*All values presented in the case study are fictitious*
Team Started With the Prototype Missile Seeker Antenna Design

- Requirements were allocated to sub-components
  - Those directly related to Key Performance Parameters were set with “challenge” limits
  - Sub-component model predictions met allocated antenna requirements
    - However, initial prototype antenna model lacked resolution to predict resulting system-level sensitivities to known manufacturing tolerances
- Data was collected from Proof of Design (PoD) and Proof of Manufacturing (PoM) units
- Multiple deficiencies and inconsistencies in early units’ performance
- Customer / Program Office expecting completed design
  - $XM Award Fee tied to exhibiting sufficiency of design
- DCAT (Design Capability Analysis Tool) was selected to analyze performance and design margin

Fig. 1: Block Diagram of a Canonical Missile Seeker Antenna Sector
Data Analyzed to Measure Design Margin via PNC

- **Data Conversion**
  - Data put into Excel format and converted to linear terms
  - PNC calculations performed by the Data Collection Analysis Tool (DCAT)

### DCAT

<table>
<thead>
<tr>
<th>TEST DESCRIPTION</th>
<th>UNITS</th>
<th>LOWER LIMIT</th>
<th>UPPER LIMIT</th>
<th>EXCLU DE?</th>
<th>TEST AVG</th>
<th>TEST II</th>
<th>Cpk</th>
<th>Cpk lower</th>
<th>PNC Observed</th>
<th>Rolled Yield</th>
<th>DATA PTS</th>
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<tbody>
<tr>
<td>R1 - Frequency 10</td>
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<td>-3.241</td>
<td>1.651</td>
<td>0.000</td>
<td>1.000</td>
<td>0.815</td>
<td>0.550</td>
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<td>6.767E-03</td>
<td>2.453E-03</td>
<td>9.221E-03</td>
<td>0.991</td>
</tr>
</tbody>
</table>

DCAT tool also provides a histogram of the data and the curve fitted to the data for PNC calculations.

*All values presented in the case study are fictitious*

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**Rolled Yield:** 0.9444  
**PNC:** 0.056  
**DATE:** 3/25/2008

**DCAT Takes You Beyond Stoplight (Qualitative) Performance Charts**
Reviewing the Antenna Data

- PNC threshold established
  - Based on number of problem parameters and program objectives
  - Measurement capability revisited to insure we are not chasing test problems

- Rolled yield
  - Focus on the element contributors driving cost and performance
  - Use Yield prediction to support ROI for investigations/improvement

\[ \text{ScrapCost} = \text{UnitCost} \times \text{PNC} \times \text{NumUnits} \]

<table>
<thead>
<tr>
<th>Requirement</th>
<th>PNC</th>
<th>Yield</th>
<th>Possible Contributors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Sidelobe Level</td>
<td>39.7%</td>
<td>60.3%</td>
<td>Circulator, Power Source</td>
</tr>
<tr>
<td>Boresight Alignment</td>
<td>44.2%</td>
<td>55.8%</td>
<td>Filter, Sector Feed</td>
</tr>
<tr>
<td>Pattern Gains</td>
<td>37.3%</td>
<td>62.7%</td>
<td>Sector Feed, Filter</td>
</tr>
<tr>
<td>Return Loss</td>
<td>22.1%</td>
<td>77.9%</td>
<td>Radiating Element, Power Source</td>
</tr>
<tr>
<td>Insertion Loss</td>
<td>11.6%</td>
<td>88.4%</td>
<td>Power Source, Sector Feed</td>
</tr>
<tr>
<td><strong>Rolled Yield</strong></td>
<td></td>
<td>28.0%</td>
<td></td>
</tr>
</tbody>
</table>

*All values presented in the case study are fictitious
Performance, Producibility and Cost Issues Identified

- Due to excessive variation in the predicted performance of the design, the yield was calculated to be only X% (WAY lower than the goal)

- The antenna design was already well over the cost objective, and no acceptable rework procedure is authorized
  - For each acceptable antenna that could be integrated into the next assembly level, 3 to 4 other antennas would be scrapped which would prevent the program from achieving its producibility and affordability goals

It was predicted that we could not produce the product at a price the customer could afford
Causal Analysis & Resolution Plan

Action Plan:
- Revise and reallocate requirements where possible to meet the antenna design process capability and know manufacturing capability
- Improve the antenna design process by reducing variation of lower level KPCs
- Choose an improved supplier process to better match the antenna performance requirements

Initially, Systems Engineering did not want to revise and reallocate the antenna requirements since this would require a change to their systems design process
- Quantifying design margin in PNC and showing the cost impact of $$ for dBs made the Chief Engineer champion the robust design process
- Providing Systems Engineering a quantitative impact to their “challenge” performance requirements enabled more productive “dB for dollars” trade decisions
Process Changes Made to Match Design Capabilities

- **Systems Engineering**
  - Initial systems design process did not have robust models for many antenna performance parameters
  - 6DOF simulation based on extremely conservative cases and “tribal knowledge”
  - Adjusted systems design process to cases observed in field testing (data-driven) – 6DOF models adjusted to new data / knowledge
  - Result: Some of the antenna requirements were relaxed and reallocated based on a $$ for dB trade study

- **Antenna Design**
  - Antenna design identified the key variation drivers and susceptibilities in the antenna
  - Adjusted design process and brought in supplier manufacturing engineers who worked with the team to match both the design process and the manufacturing process to the desired performance capabilities
Results / Future Activities

- Predicted yield increased from X% to over 4X%
  - Unit costs reduced over 40%
- Cost avoidance of over $XM
- $XM Award Fee criteria met 3 months ahead of schedule – Award Fee won
- Enhanced Antenna Modeling
  - Parameterized full-wave EM sub-component models cascaded to create full-antenna model capable of predicting physical geometry effects on gain/pattern and S-parameter performance
  - Tools are in place to accurately predict performance of combined elements
- Design to Cost
  - PNC simplifies cost calculations on parts
  - Goal is to provide PM cost data for making effective ROI decisions
- Critical Parameter Management
  - PNC calculations on POD/POM hardware will be compared with prediction and tracked
- Customer Understood and Accepted Design Maturity

From Customer’s Technical Representative: “I wish all of our technology developers would use this approach for predicting manufacturing maturity.”
Questions
That’s All Folks

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Raytheon Missile Systems Achieves CMMI Level 5 + IPPD

CMMI Lead Appraiser Comments

- Unique high maturity approach
  - Not many other organizations have achieved level 5 + IPPD (industry-wide)
  - No others like this - Business driven vs. CMMI model driven level 5 (Design 2010)
  - Covers complete product life cycle

- Promote RMS high maturity approach to be the gold standard across Raytheon and Industry
  - Increase sales (Put RMS on the map)
  - Be the supplier of choice

- Leverage your process strengths, which includes high maturity, for use in proposals

- The organization is confident in its process usage; however, is open to constructive feedback.

CMMI Level 5 + IPPD - Global Strengths Identified by the Appraisal Team

- The organization’s statistical understanding and modeling begins with the pre-concept phase and continues through operational and technical simulations as well as production. RMS models not only fielded system performance, but development and manufacturing processes as well.

- The organization uses process performance models and process performance baselines during pre-concept, proposal, requirements analysis and design, implementation, proof of design, proof of manufacturing, low rate initial production, and production.

- The projects’ process composition is a result of an extensive suite of models which statistically predict schedule, producibility, affordability, and technical robustness.

- The Probability of Non-Compliance (PNC) metric allows a program to quantify, in terms of cost, the probability of meeting its objectives and reduce risk of execution.