“*Customer Success Is Our Mission*”

How Rocket Scientists Implement High Maturity

Tom Lienhard
Thomas_G_Lienhard@Raytheon.com

November, 2009

Case Study by
Debra Herrera and Dave Frank

Raytheon
Missile Systems

Changing Our Approach

How to take Missile Systems from a Business that…

Understands Product Requirements → Designs A Product → Determines Suppliers → Decides Where To Build → Evaluate For Affordability → Redesigns

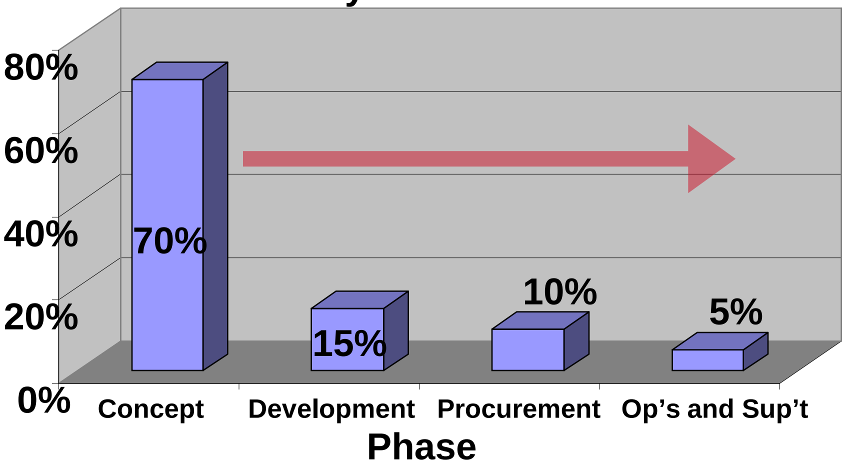
To a Business that

Understands The Use Of The Product → Makes Requirements Capability Trades Around Affordability → Determines A Build Strategy → Identifies Where To Buy From → Designs To Maximize This Strategy

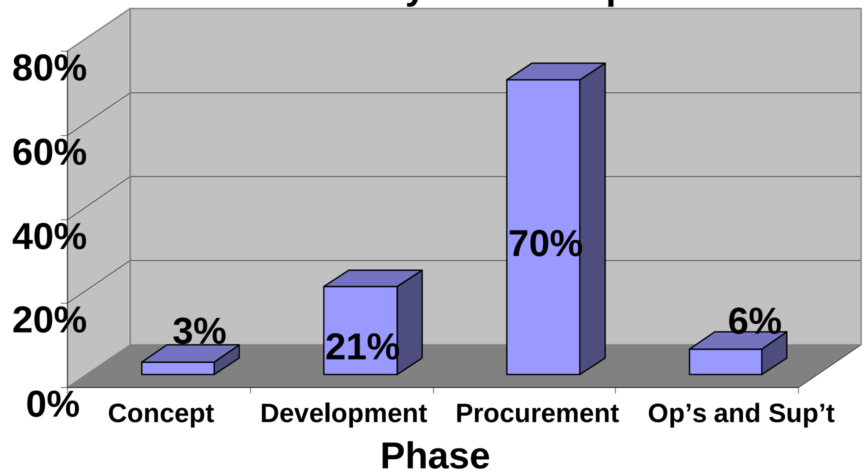
Design 2010

Why We Need Change

% of Life Cycle Cost Committed

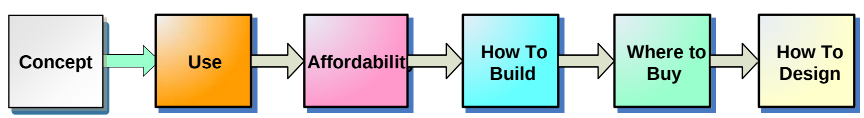


% of Life Cycle Cost Spent



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

Design 2010



Understanding What's Critical to Our Business

Raytheon
Missile Systems

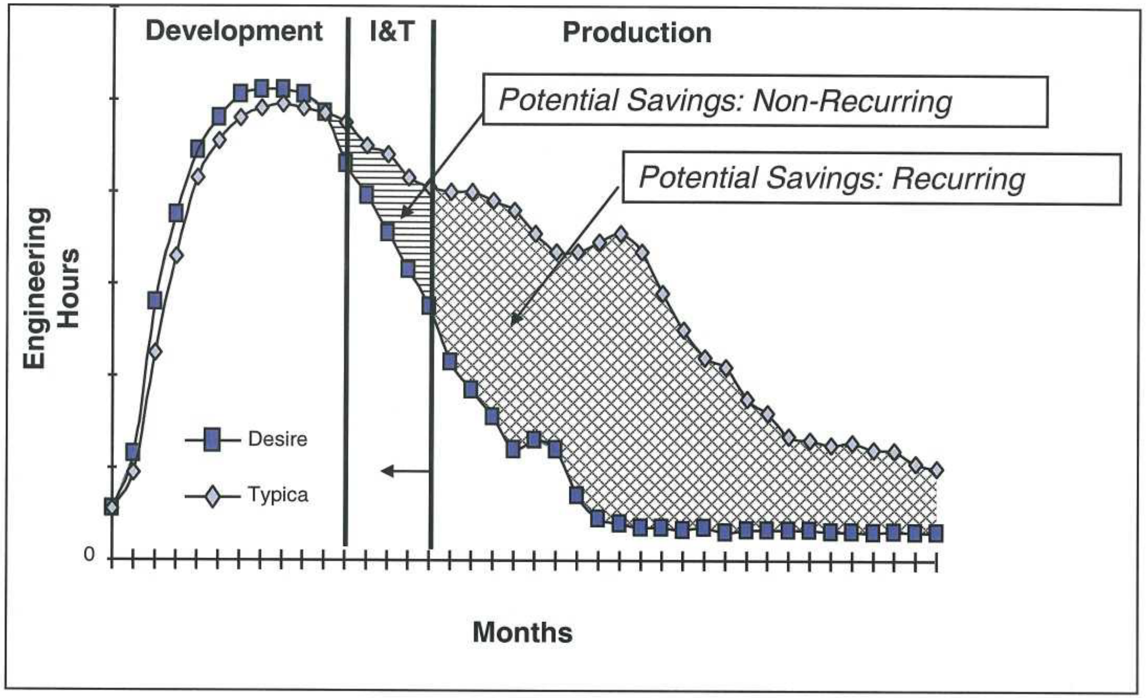
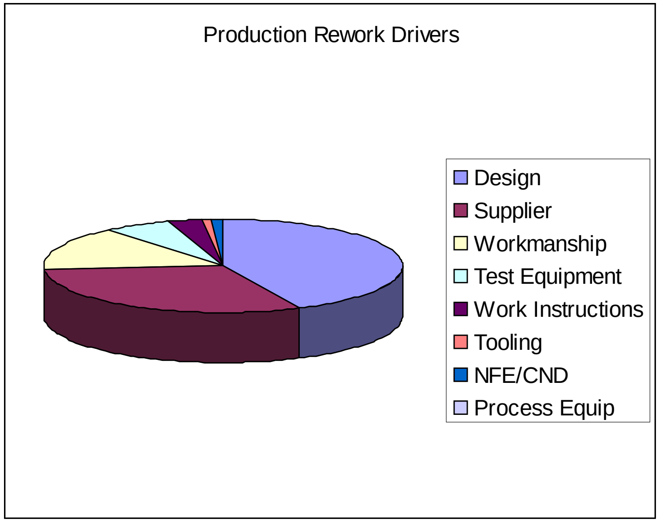


Figure 1. Typical Product Development Cycle



The design process drives effective production

Brain Shift

Raytheon
Missile Systems

SW SE HW

SW SE HW

SW SE HW

SWSEHW

SyDe

SystDeve

System Development

Profound Shift in Focus

Raytheon Missile Systems

Pre-Concept		Development	Production	Field/Maint
1st	SW	2nd 1st	1st	1st
	SE	2nd		
	HW	2nd		

Raytheon
Missile Systems

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 ships, ground, submarine

Some launched from airplanes

Some with rocket motors

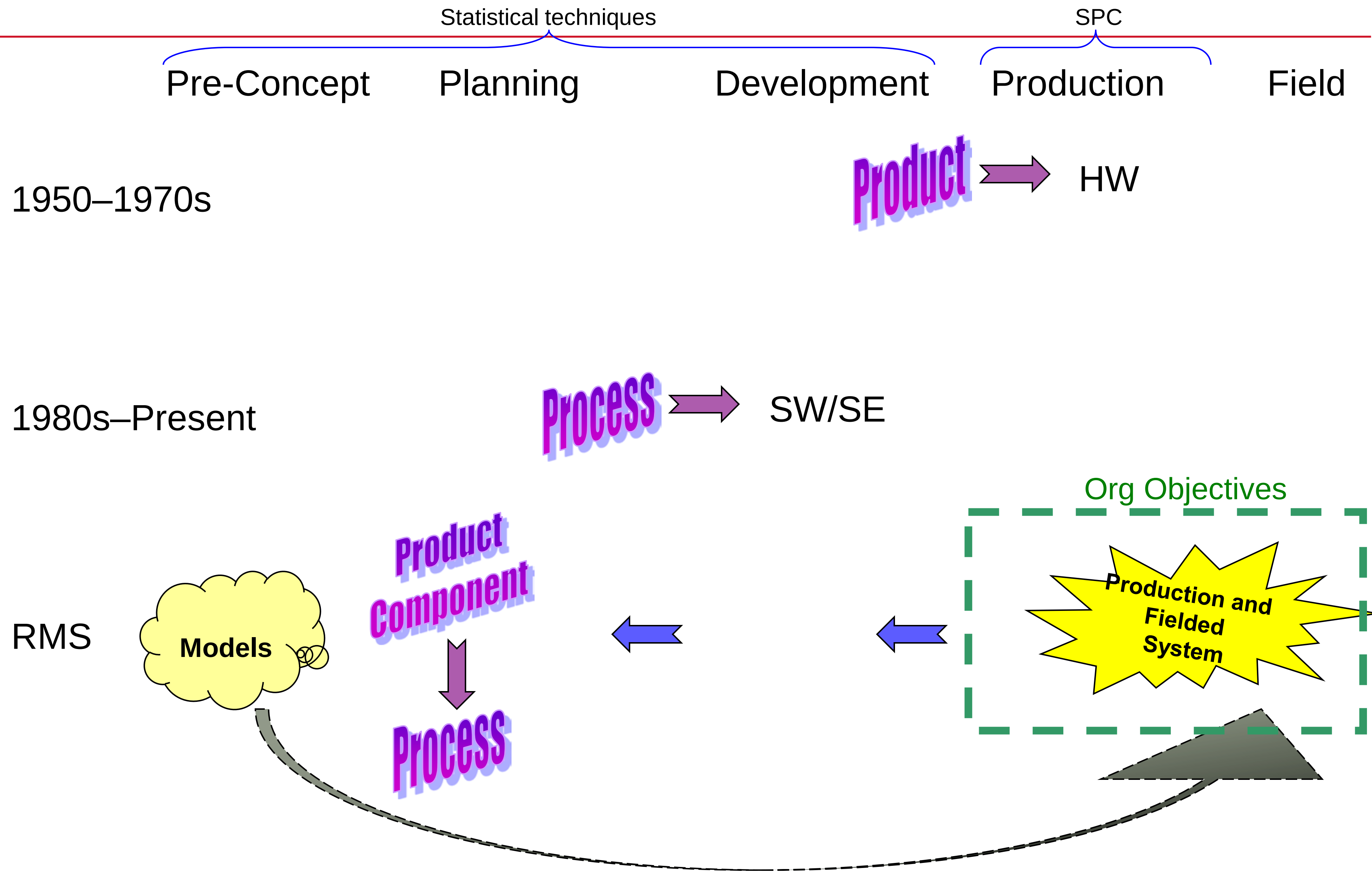
Some glide

Some are propelled

Some are small, some are large

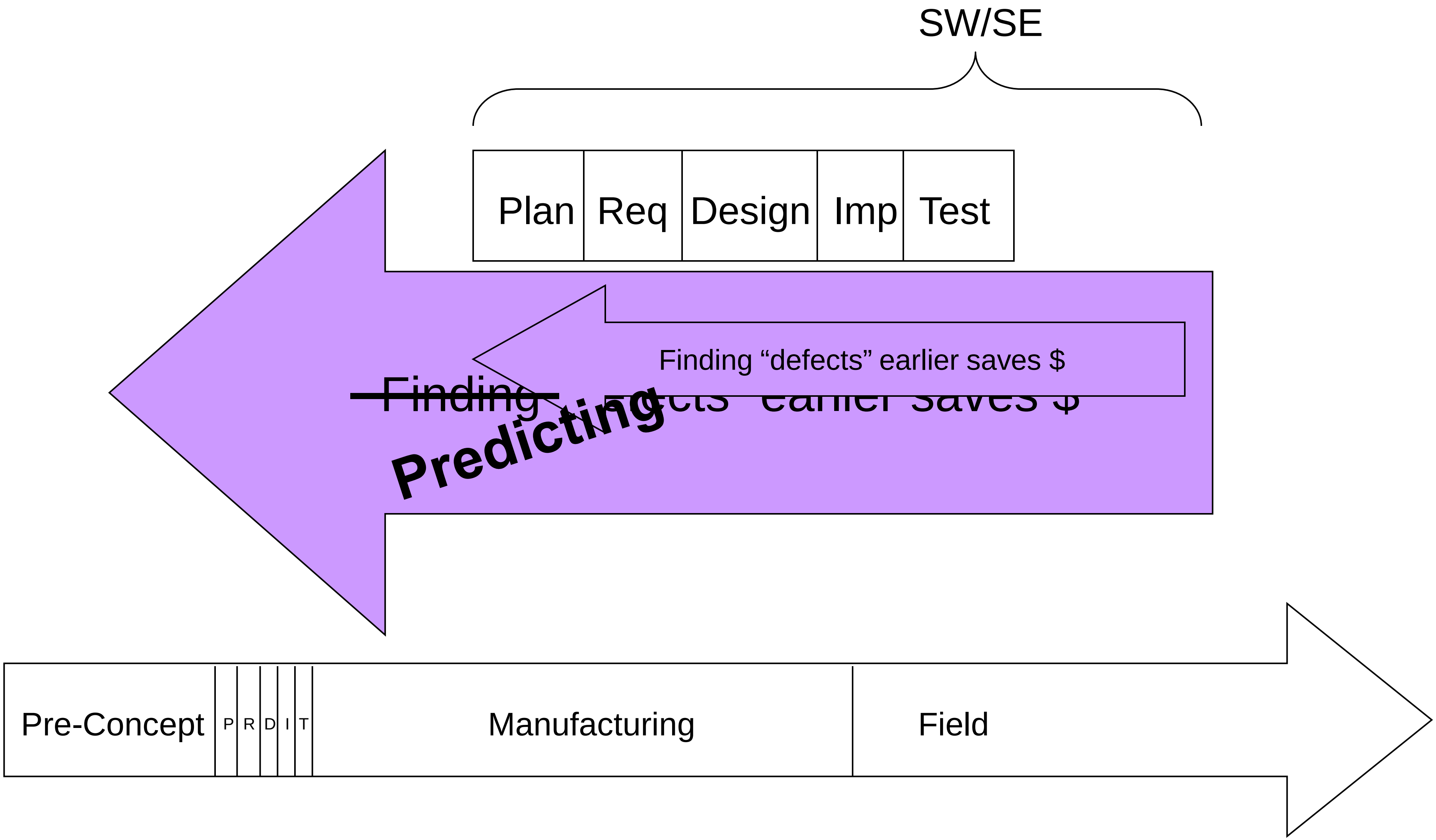
Some are guided by GPS, IMU, or laser

High Maturity Timeline



High Maturity “Epiphany”

Raytheon
Missile Systems



Being Predictable Means…

Raytheon
Missile Systems

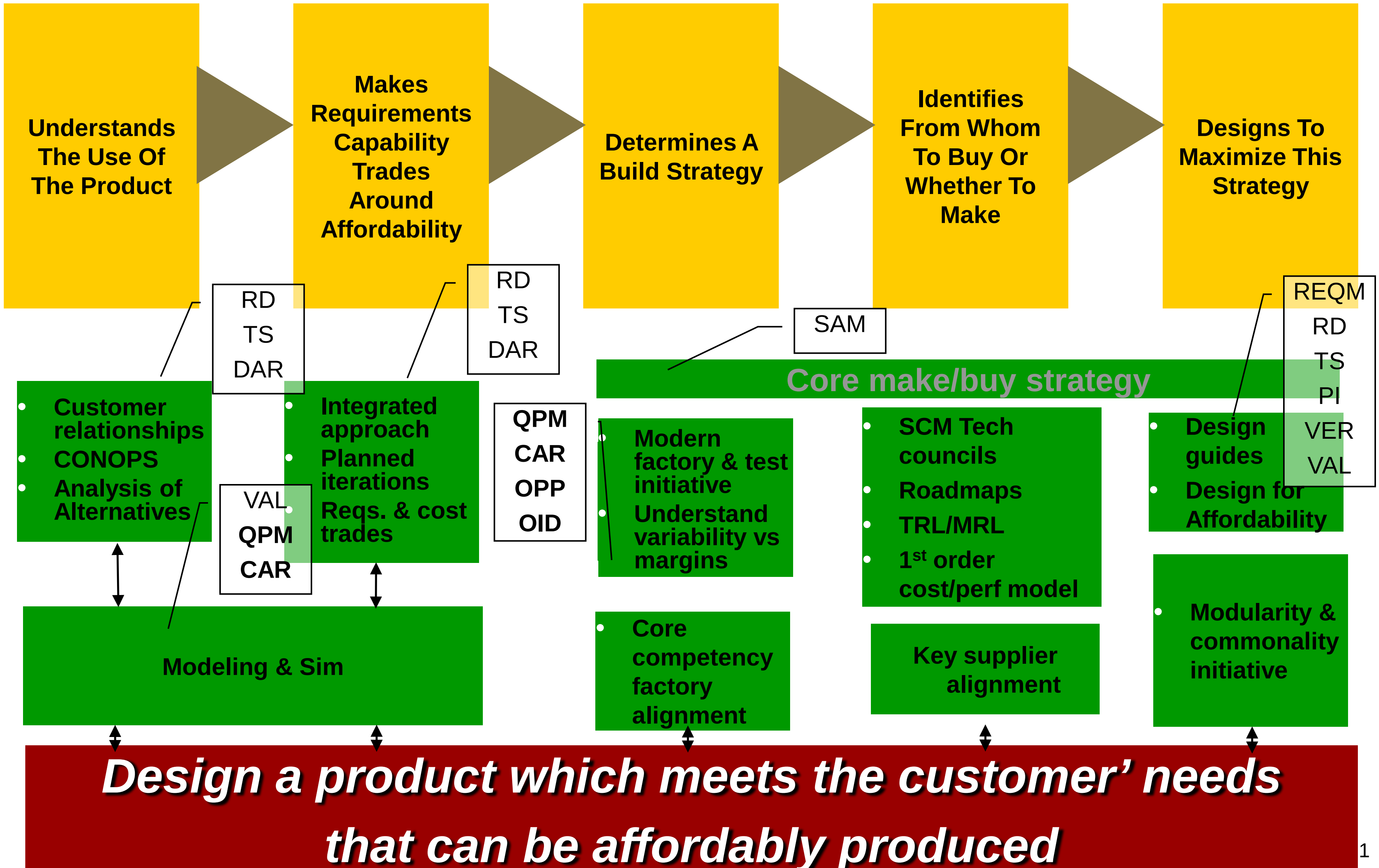
Measuring Design Processes → that → Accurately Predict Production Yield

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

Raytheon
Missile Systems

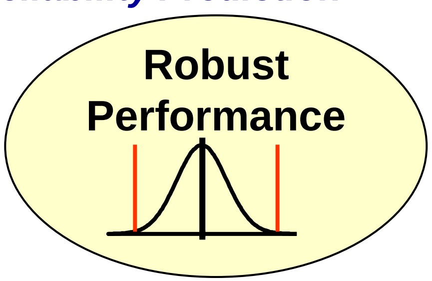


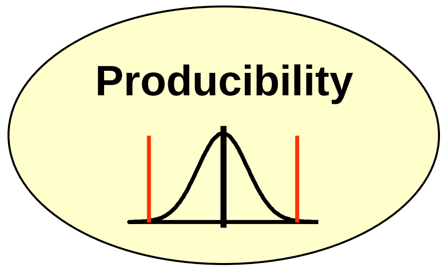
Robust Design - Balancing Performance, Producibility and Affordability in Design

Raytheon Missile Systems

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***



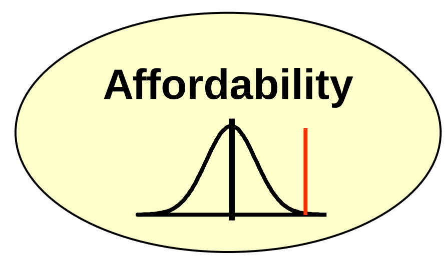


Design For Producibility

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

Design for Affordability

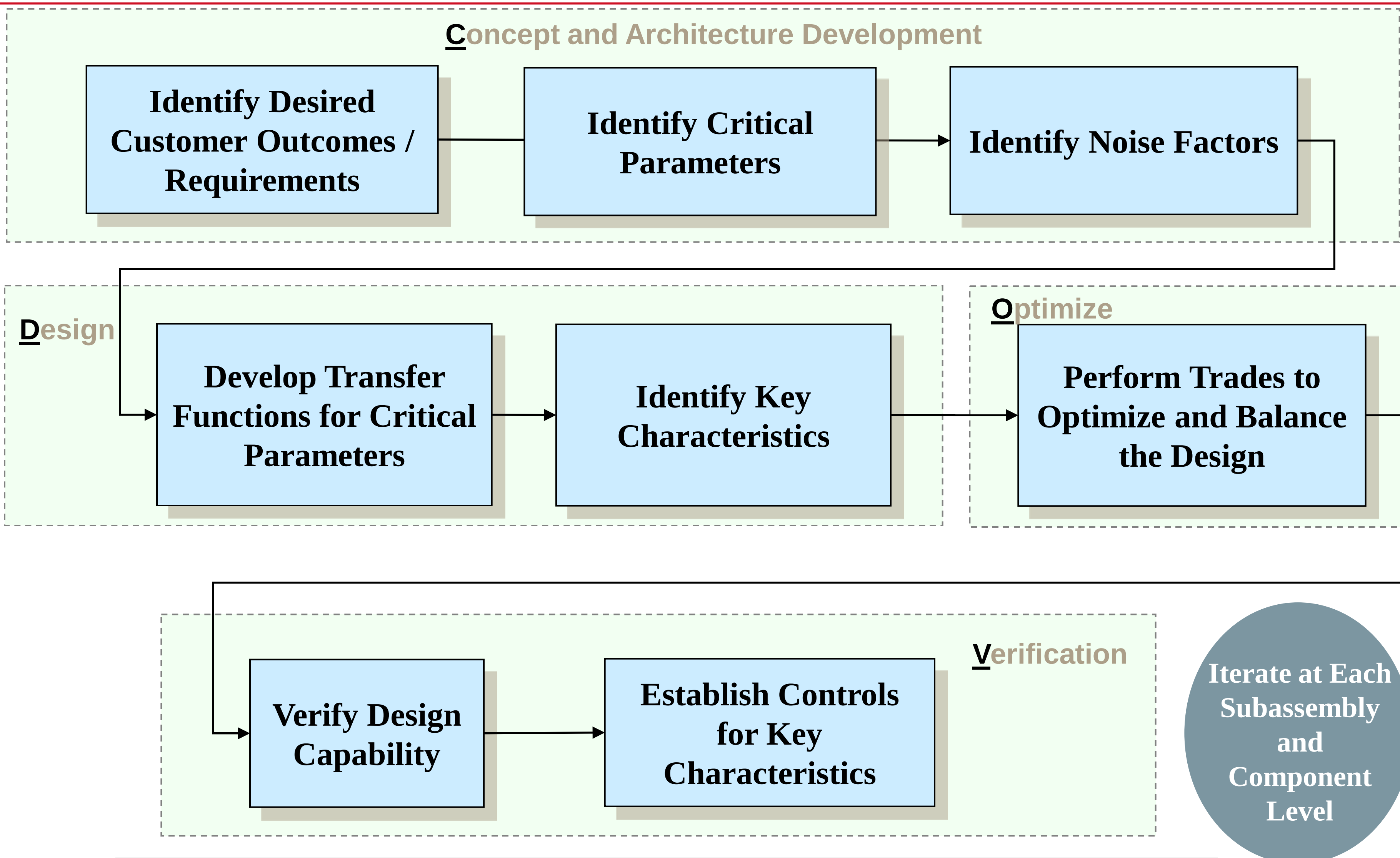
- ***Cost as an Independent Variable***
  - *Acquisition Reform Initiative*
  - *Warfighter participation*
  - *Total Ownership Costs*
  - *The "What" of Affordability*
  - *Conceptual Trade Studies*
- ***Design to Cost***
  - *Detailed Design Trade Studies*
  - *Cost Models and Cost Tracking*
  - *DTC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



From Statistical Design Methods for Engineers Class

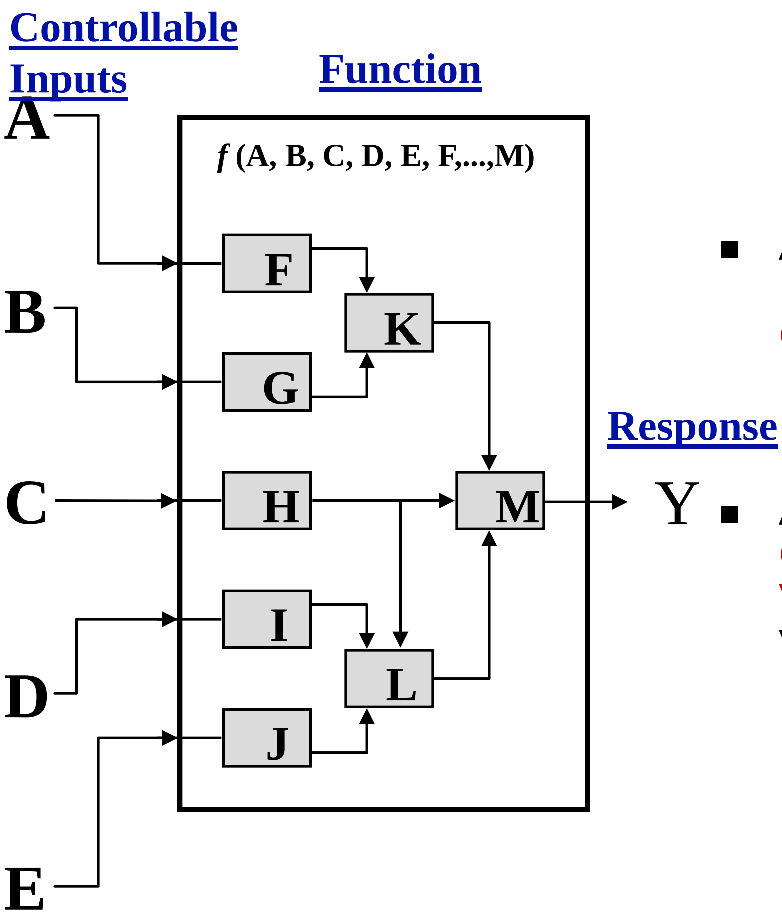
Robust Design Methodology

Raytheon Missile Systems



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

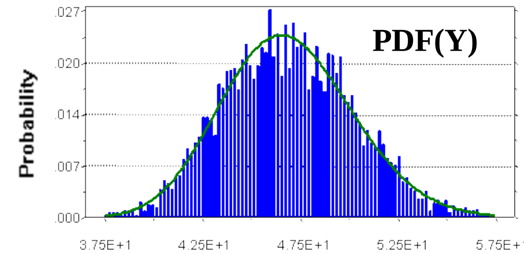
Robust Design Analysis results in...

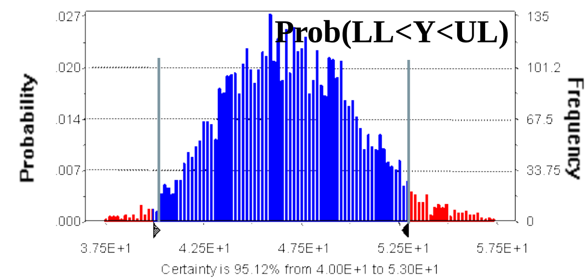


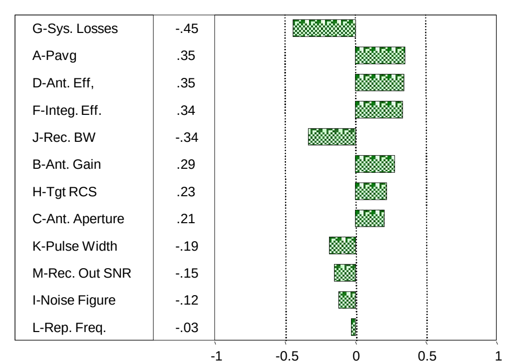
- A prediction of the Response Statistical Properties
- A prediction of the Probability of Non-Compliance
- An assessment of the Contribution of Parameter Variation to the Response Variation

Results from Crystal Ball® Monte Carlo SW

$\mu_y, \sigma_y, \beta_{1y}, \beta_{2y}$





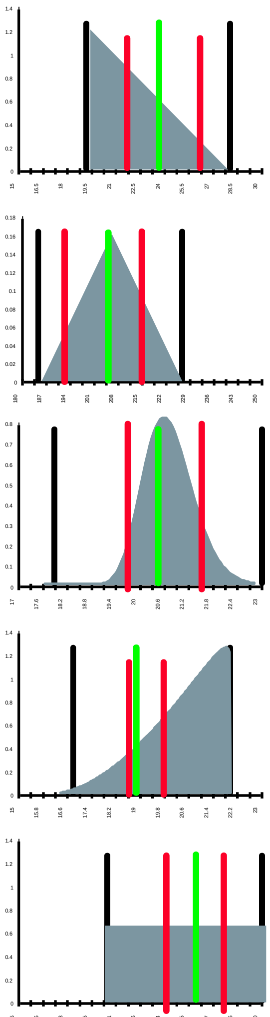


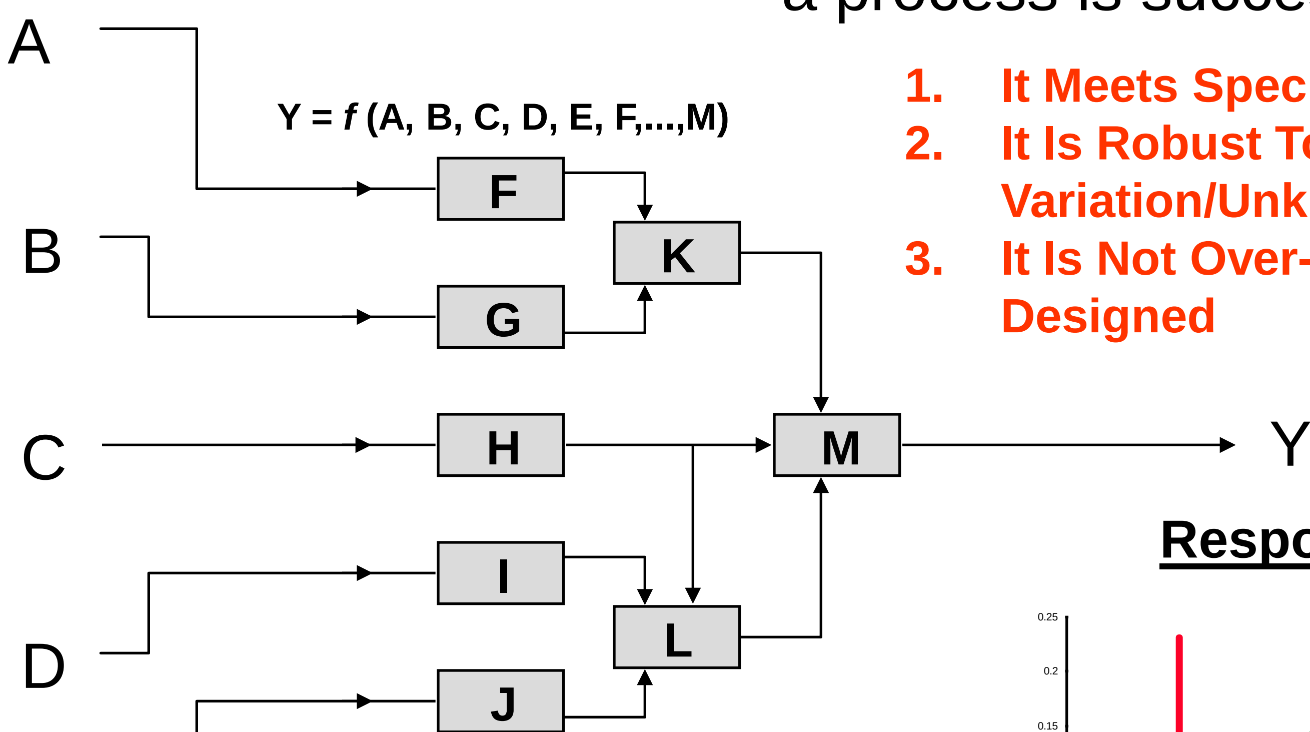
From Statistical Design Methods for Engineers Class

Understanding Process From a Mathematical Perspective

Raytheon
Missile Systems

Controllable Inputs

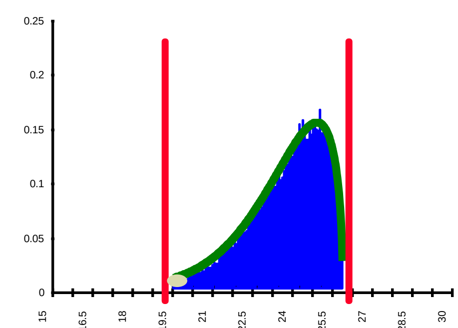




How do we know when a process is successful?

1. **It Meets Spec √**
2. **It Is Robust To Variation/Unknowns**
3. **It Is Not Over-Designed**

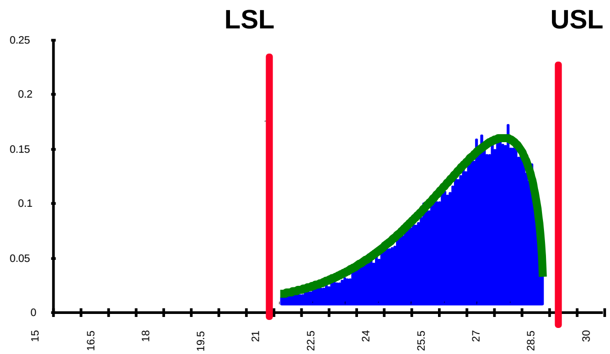
Response



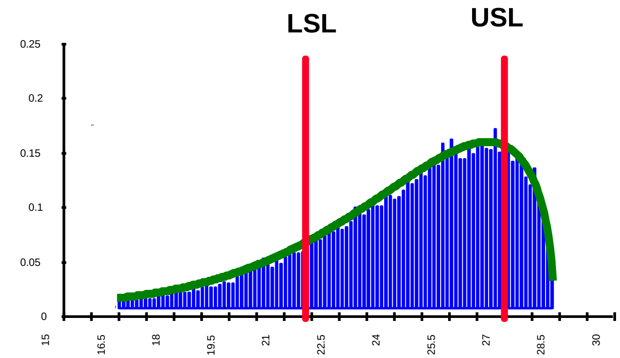
Items 2 &3 require understanding Margin!

From Statistical Design Methods for Engineers Class

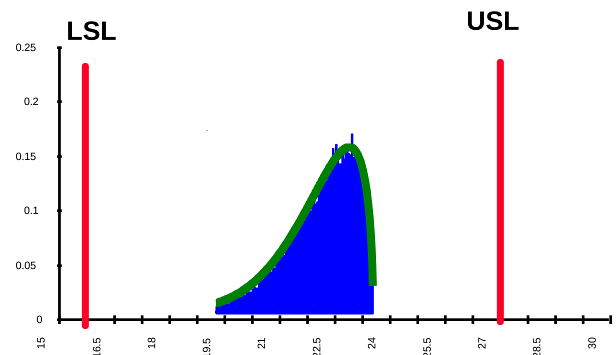
Understanding Design Margins



Adequate Margin
No Risk



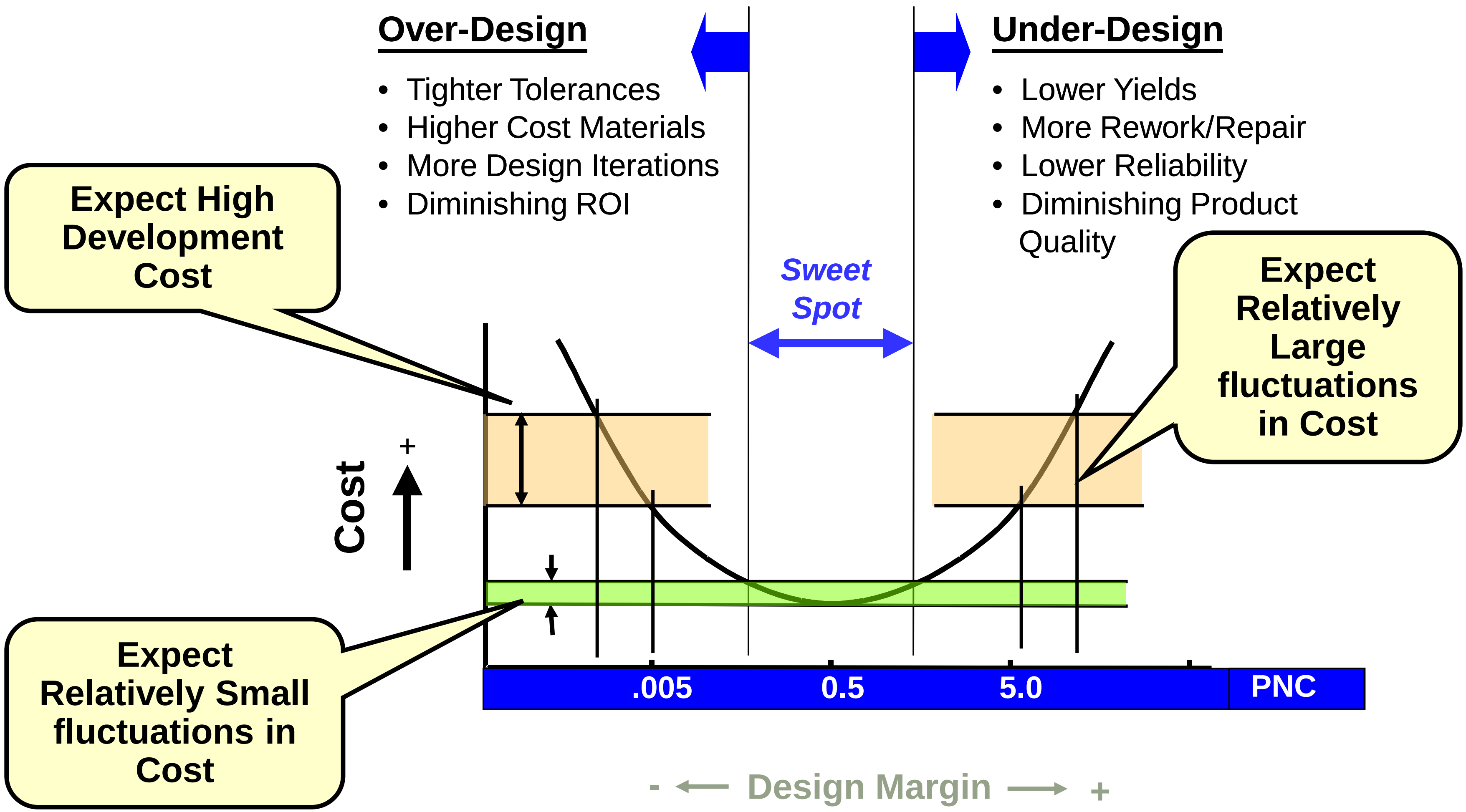
Not Enough Margin
Significant Risk
Low Yields
Rework & Scrap Costs



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

Cost Impact of Design Margin

The Advantage of Specifying the Right Amount of Design Margin



Quantitative Measurement of Design Margin

Raytheon Missile Systems

- 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

PNC Measures Customer Satisfaction

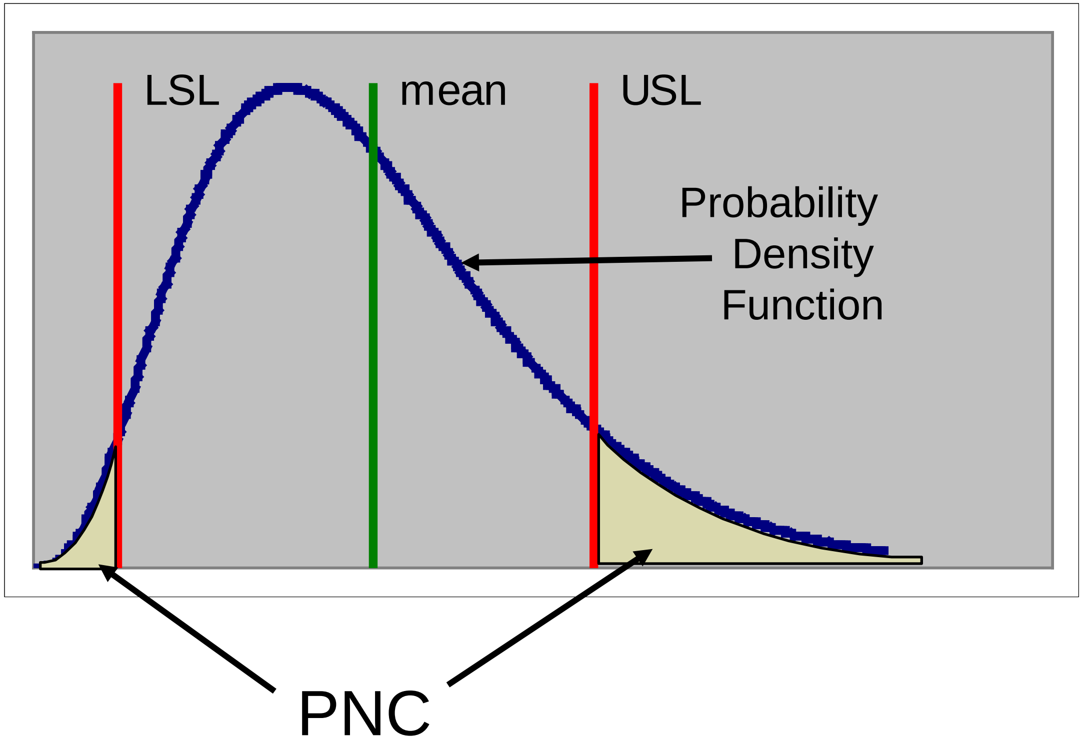
Raytheon Missile Systems

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**

Graphic Representation PNC

- PNC is a prediction of the percent of time that a response of interest will fall outside of its specification limits



PNC is calculated by integrating the PDF (probability density function) to find the area above or below any points of interest

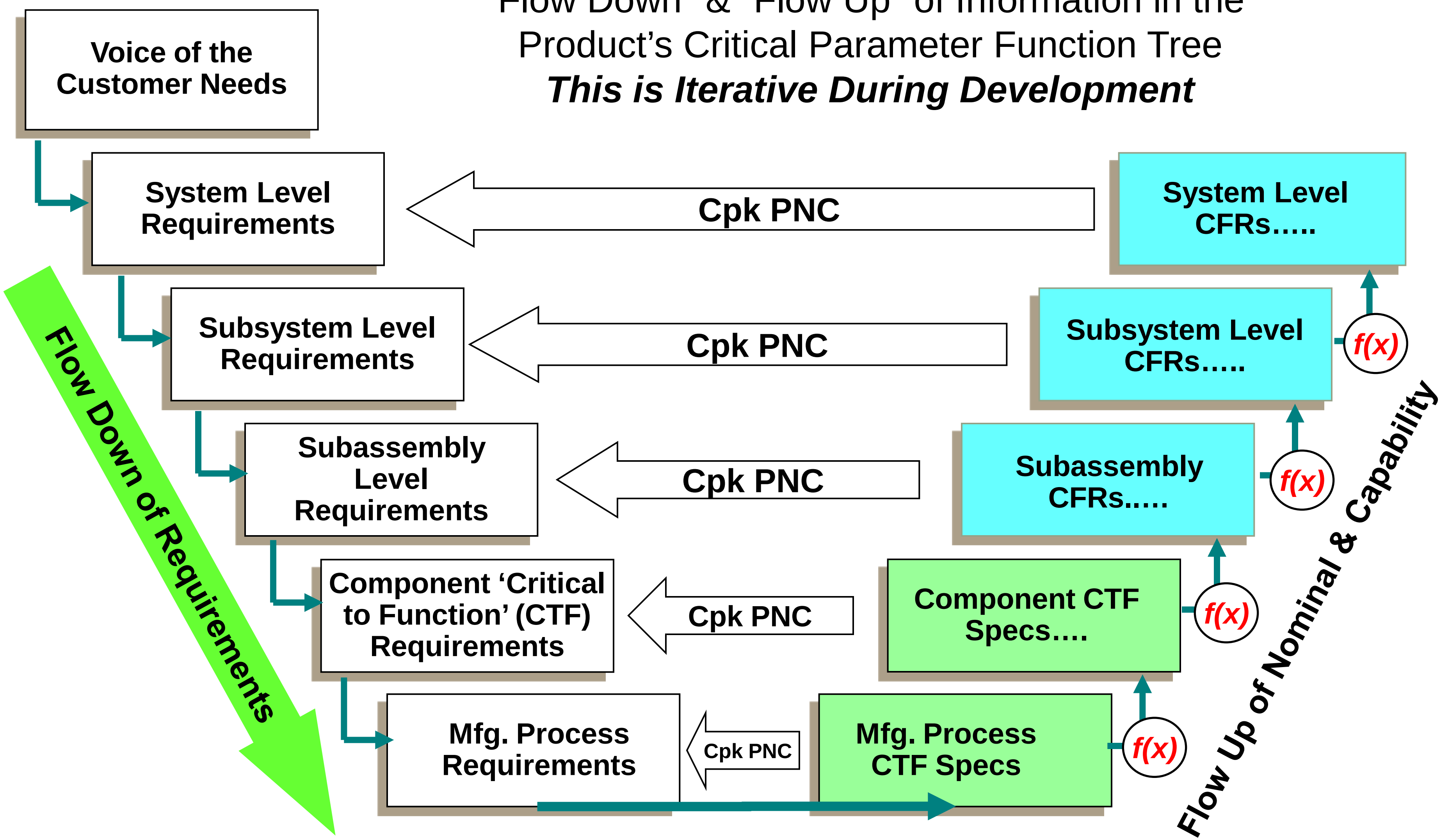
$$PNC = P(x < LSL) + P(x > USL)$$

From Statistical Design Methods for Engineers Class

Design Margin Measures the Success of the Robust Design Process at any Level

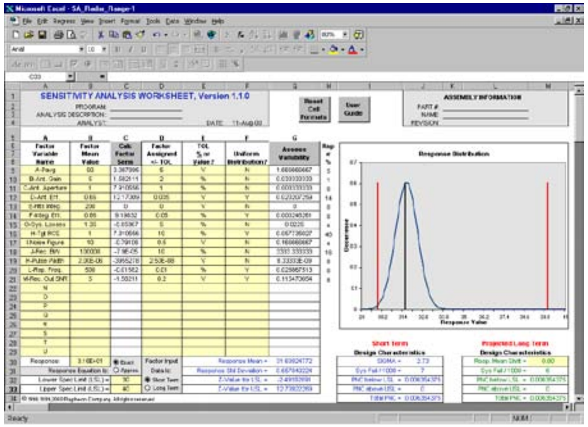
"Flow Down" & "Flow Up" of Information in the Product's Critical Parameter Function Tree

This is Iterative During Development

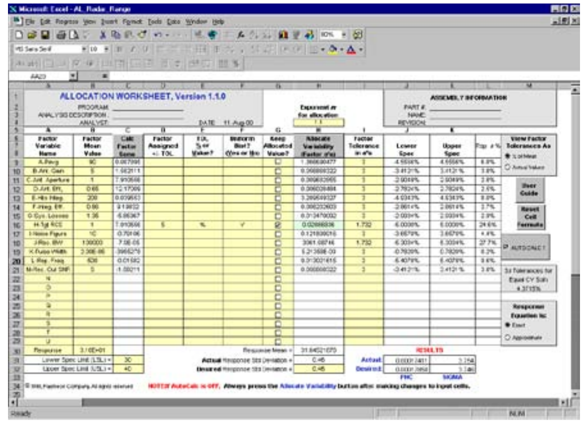


Some Tools used at Raytheon Missile Systems for Robust Design

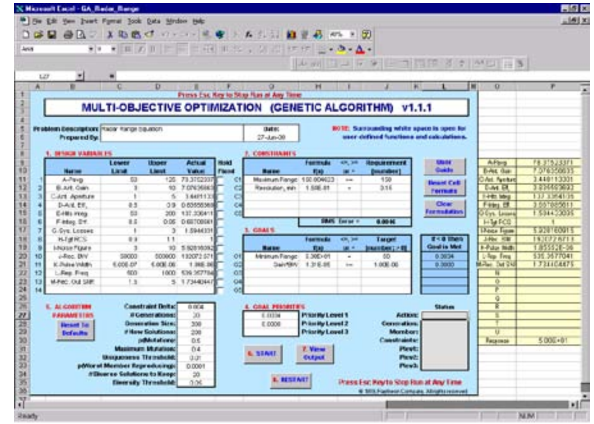
Raytheon Missile Systems



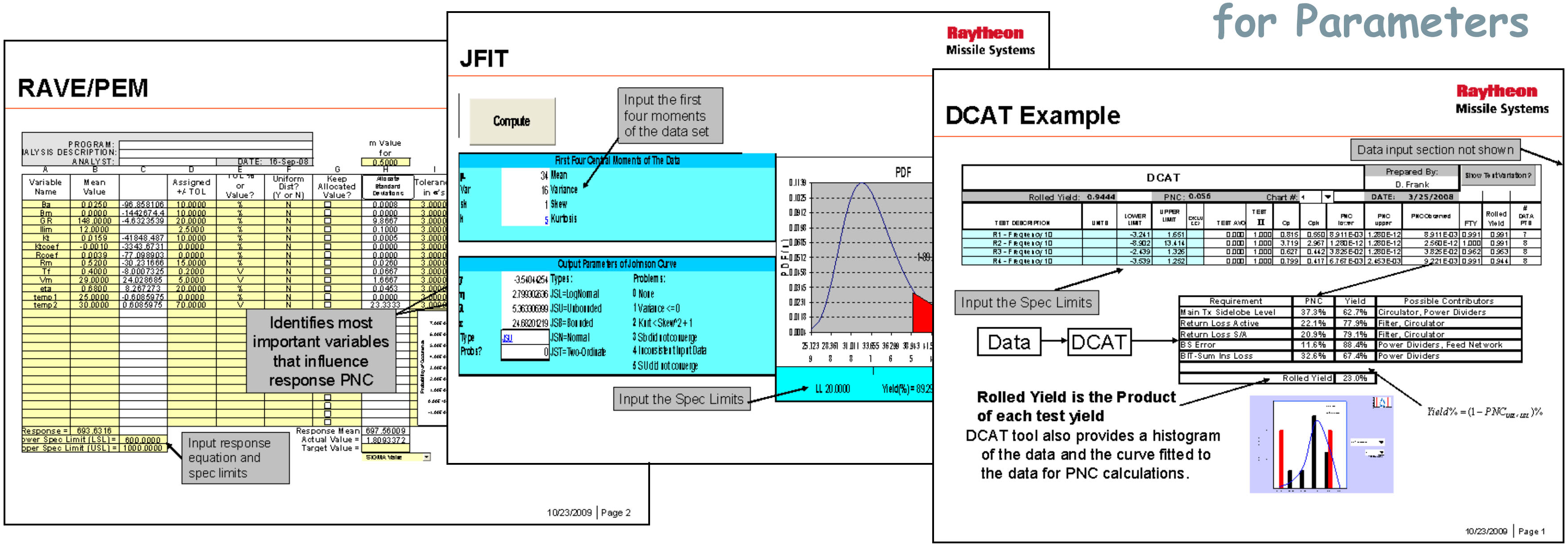
Equation-Based Tolerance Analysis and PNC Prediction



Parameter Allocation



Multi-Objective Optimization for Parameters



Antenna Case Study

Debra Herrera
Dave Frank

*All values presented in the case study are fictitious

Program Followed Robust Design Process

Raytheon
Missile Systems

- 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

Status	Specification Number	Specification Description	Paragraph Number	Paragraph Description
KPC	4482922-906RV3	CIDS Antenna Sub Assembly	5.5.8.9.4.2-4	Peak Sidelobe
KPC	4482922-906RV3	CIDS Antenna Sub Assembly	5.5.8.9.7.2-3	Boresight Alignment
KPC	4482922-906RV3	CIDS Antenna Sub Assembly	5.5.8.0.6	Pattern Gains
KPC	4482922-906RV3	CIDS Antenna Sub Assembly	5.5.8.0.6	Auxiliary Pattern Gains
KPC	4482922-906RV3	CIDS Antenna Sub Assembly	5.5.8.7	Return Loss
KPC	4482922-906RV3	CIDS Antenna Sub Assembly	5.5.8.7	Insertion Loss
KPC	4482922-906RV3	CIDS Antenna Sub Assembly	5.5.8.12.3	Band Aid Coverage
KPC	4482922-906RV3	CIDS Antenna Sub Assembly	5.5.8.11.7	Band Guard Coverage

- 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

Raytheon Missile Systems

- 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

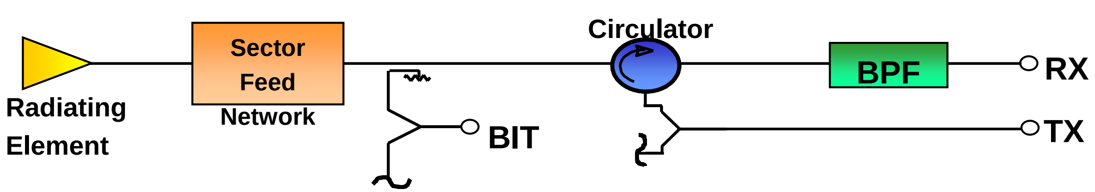


Fig. 1: Block Diagram of a Canonical Missile Seeker Antenna Sector

Data Analyzed to Measure Design Margin via PNC

Raytheon
Missile Systems

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

DCAT

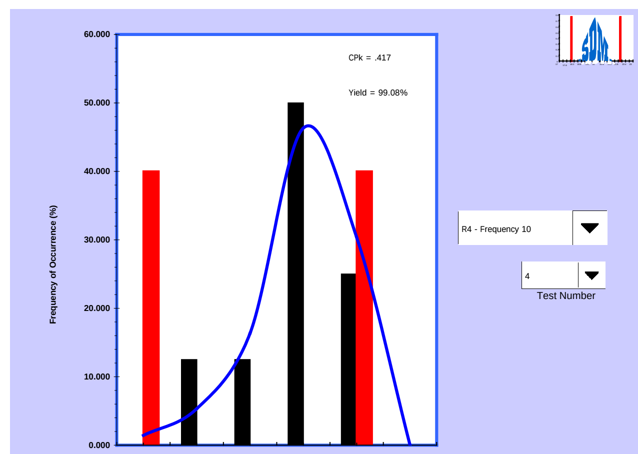
Prepared By: D. Frank

Show Test Variation ?

Rolled Yield: 0.9444 | **PNC: 0.056** | **Chart #:** 4 | **DATE: 3/25/2008**

TEST DESCRIPTION	UNITS	LOWER LIMIT	UPPER LIMIT	EXCLUDE?	TEST AVG	TEST Π	Cp	Cpk	PNC lower	PNC upper	PNC Observed	FTY	Rolled Yield	# DATA PTS
R1 - Frequency 10		-3.241	1.651		0.000	1.000	0.815	0.550	8.911E-03	1.280E-12	8.911E-03	0.991	0.991	7
R2 - Frequency 10		-8.902	13.414		0.000	1.000	3.719	2.967	1.280E-12	1.280E-12	2.560E-12	1.000	0.991	8
R3 - Frequency 10		-2.439	1.326		0.000	1.000	0.627	0.442	3.825E-02	1.280E-12	3.825E-02	0.962	0.953	8
R4 - Frequency 10		-3.539	1.252		0.000	1.000	0.799	0.417	6.767E-03	2.453E-03	9.221E-03	0.991	0.944	8

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

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

$$ScrapCost = UnitCost * PNC * NumUnits$$

Data → DCAT →

Requirement	PNC	Yield	Possible Contributors
Peak Sidelobe Level	39.7%	60.3%	Circulator, Power Source
Boresight Alignment	44.2%	55.8%	Filter, Sector Feed
Pattern Gains	37.3%	62.7%	Sector Feed, Filter
Return Loss	22.1%	77.9%	Radiating Element, Power Source
Insertion Loss	11.6%	88.4%	Power Source, Sector Feed
	Rolled Yield	28.0%	

*All values presented in the case study are fictitious

PNC Simplifies Cost Calculations – Measures Affordability

Performance, Producibility and Cost Issues Identified

Raytheon
Missile Systems

- 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

Raytheon Missile Systems

- 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

Raytheon Missile Systems

- 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

Raytheon
Missile Systems

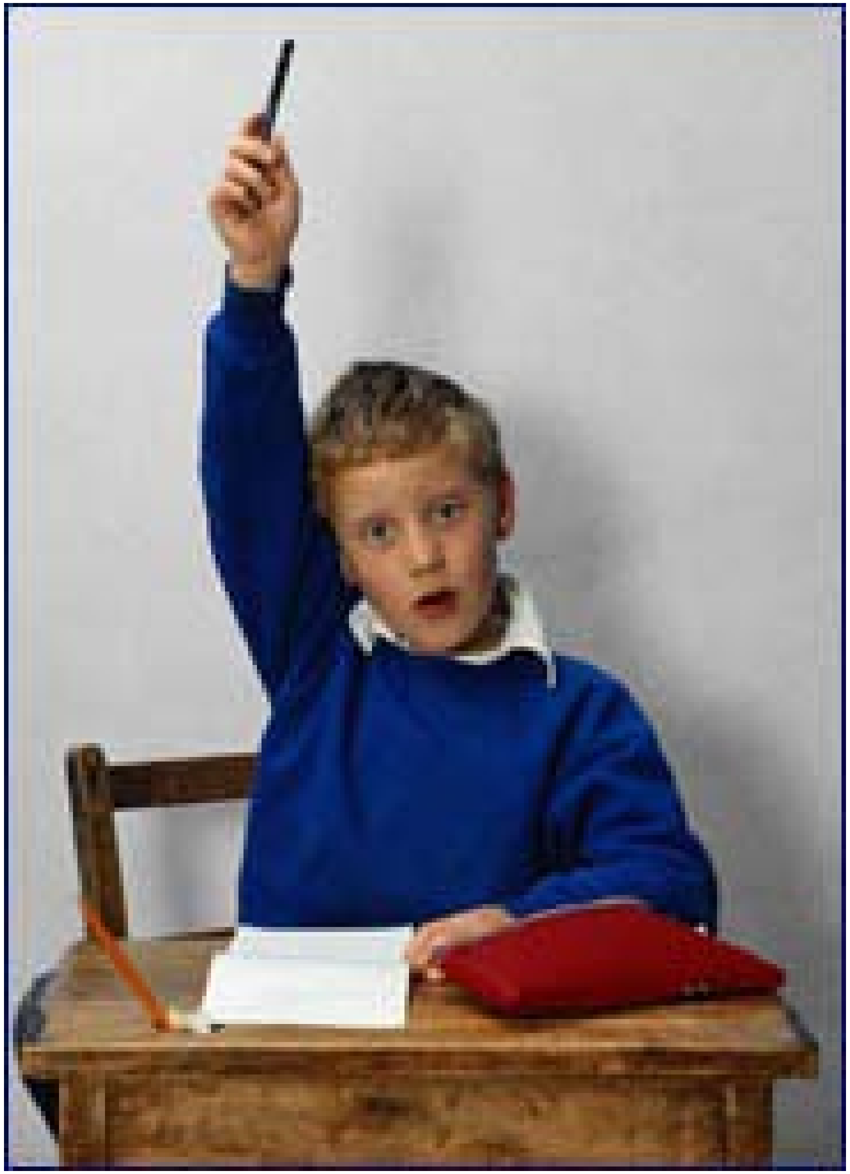
Results / Future Activities

- 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

Raytheon
Missile Systems



That's All Folks

Raytheon
Missile Systems

Tom Lienhard

Thomas_G_Lienhard@Raytheon.com

(520) 794-2989

Raytheon Missile Systems Achieves CMMI Level 5 + IPPD

Raytheon
Missile Systems

CMMI Lead Appraiser Comments

Raytheon
Missile Systems

- 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.

8/13/2009 | Page 2

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

Raytheon
Missile Systems

- 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.*

8/13/2009 | Page 1

CMMI Level 5 + IPPD Results Validate Design 2010