Using DFSS as an Integrating Framework for MBT&E and DOT&E

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Air Academy Associates

NDIA 2011 Test & Evaluation Conference
Tampa, FL
14 March 2011
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Warm-Up Exercise

• Goal: full concentration on the subject
• Eliminate extraneous issues that could inhibit that
• Write down the top issue on a plain sheet of paper
• Jettison this issue by doing the following:
  - Design a paper airplane that will help you deposit this issue in the waste basket.
  - Launch your paper airplane at the waste basket from your seating area. You may stand or even move around to launch if you wish.
  - Goal is to put the issue in the waste basket, which is obviously symbolic of “putting the issue away.”
Food for Thought .... True or False?

The systems and products that deliver value to our warfighters are perfectly designed to achieve the results we are getting today.
Session Goals and Objectives

1. Know what DFSS is and understand that it is a strategy that uses DOE and other powerful methods to design, develop, and field successful systems.

2. Understand the DFSS process—Identify, Design, Optimize, Validate (IDOV)—and know that it focuses heavily on the Voice of the Warfighter.

3. Know that the DFSS process translates requirements, i.e., task capabilities and system attributes, into measures of effectiveness and measures of performance and then subsequently into design parameters which are then optimized to produce highly capable products and services.

4. Relate to some of the powerful tools that are unique to the DFSS process.

5. Understand what a transfer function is, be able to comprehend its value, and see that it can be used to develop linkages between Critical Operational Issues (COIs) and measures of performance/effectiveness.

6. Comprehend the opportunity for DFSS in your organization with regard to MBT&E and DOT&E.
Agenda

- Introduction and Review

- The Motivation for DFSS

- The DFSS Process: Identify, Design, Optimize, Validate (IDOV)
  - The Identify Phase
    - The DFSS Scorecard
    - Voice of the Customer (VOC)
  - The Design Phase
    - Translating the VOC (Requirements Flowdown)
    - Concept Generation and Selection
    - Transfer Functions
    - Critical Parameter Management
  - The Optimize Phase
    - Multiple Response Optimization
    - Expected Value Analysis Using Monte Carlo Simulation
    - Parameter Design
    - Tolerance Allocation
  - The Validate Phase
    - High Throughput Testing

- Recap of DFSS with MBT&E and Designing the Test and Evaluation

- DFSS Success Stories
Introduction and Review
Performance Improvement Evolution

Interchangeable Parts
Eli Whitney

Assembly Line

Mass Production
Henry Ford

Jidoka
S. Toyoda

Just – In – Time
K. Toyoda

Toyota Production System
T. Ohno

Lean Six Sigma

Interchangeable Parts
Eli Whitney

Standard Costing

Model Variety

Mass / Batch
Alfred P. Sloan

Supermarket Systems

Total Quality
E. Deming, et al

DOE
Taguchi et al

Time & Motion
Division of Labor
F. Taylor

Waste Elimination

System Synchronization

Six Sigma
Motorola

SQC
Shewhart
Western Electric

Supermarket Systems

Lean Six Sigma

*DFSS=Design for Six Sigma
*DFSS=Design for Successful Systems
Graphical Meaning of $\bar{y}$ and $\sigma$

$\bar{y} = \text{Average} = \text{Mean} = \text{Balance Point}$

$\sigma = \text{Standard Deviation}$

\[ \sigma \approx \text{average distance of points from the centerline} \]
Graphical View of Variation

Typical Areas under the Normal Curve

±3σ: Natural Tolerances

-6σ -5σ -4σ -3σ -2σ -1σ 0 +1σ +2σ +3σ +4σ +5σ +6σ

-6σ -5σ -4σ -3σ -2σ -1σ 0 +1σ +2σ +3σ +4σ +5σ +6σ

-6σ -5σ -4σ -3σ -2σ -1σ 0 +1σ +2σ +3σ +4σ +5σ +6σ

68.27%
95.45%
99.73%
99.9937%
99.999943%
99.9999998%

Typical Areas under the Normal Curve

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The Sigma rating/capability of a process performance measure is the result of comparing the 
**Voice of the Process** with the **Voice of the Customer**, and it is defined as follows:

The **number of Sigmas** between the center of a process performance measure’s distribution 
and the nearest specification limit

---

**3σ Process Centered**
- Process is **WIDER** than the specifications, causing waste and cost of poor quality

**6σ Process Centered**
- Process **FITS** well within the specifications, so even if the process shifts, the values fall well within tolerances
**Sigma Ratings Measure Process Capability**

Sigma Capability is a measure of quality. It compares the Voice of the Process with the Voice of the Customer and is correlated to the defect rate. It is computed from DPMO.

Yield is the probability that whatever we are producing (manufactured part, PO, shipped part, etc.) will pass through the entire process without rework and without defects.

<table>
<thead>
<tr>
<th>σ Capability*</th>
<th>DPMO*</th>
<th>RTY</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>308,537</td>
<td>69.1%</td>
</tr>
<tr>
<td>3</td>
<td>66,807</td>
<td>93.3%</td>
</tr>
<tr>
<td>4</td>
<td>6,210</td>
<td>99.4%</td>
</tr>
<tr>
<td>5</td>
<td>233</td>
<td>99.97%</td>
</tr>
<tr>
<td>6</td>
<td>3.4</td>
<td>99.99966%</td>
</tr>
</tbody>
</table>

Yield is the probability that whatever we are producing (manufactured part, PO, shipped part, etc.) will pass through the entire process without rework and without defects.

Six Sigma is a standard of Excellence. It means less than 4 Defects per Million Opportunities.

* Assumes a 1.5 sigma shift in average if the performance measure is normally distributed.
## Relationship Between Lean, Six Sigma and DFSS

### OVERALL YIELD vs SIGMA

(Distribution Shifted ±1.5σ)

<table>
<thead>
<tr>
<th># of Parts (Steps)</th>
<th>±3σ</th>
<th>±4σ</th>
<th>±5σ</th>
<th>±6σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>93.32%</td>
<td>99.379%</td>
<td>99.9767%</td>
<td>99.99966%</td>
</tr>
<tr>
<td>7</td>
<td>61.63</td>
<td>95.733</td>
<td>99.839</td>
<td>99.9976</td>
</tr>
<tr>
<td>10</td>
<td>50.08</td>
<td>93.96</td>
<td>99.768</td>
<td>99.9966</td>
</tr>
<tr>
<td>20</td>
<td>25.08</td>
<td>88.29</td>
<td>99.536</td>
<td>99.9932</td>
</tr>
<tr>
<td>40</td>
<td>6.29</td>
<td>77.94</td>
<td>99.074</td>
<td>99.9864</td>
</tr>
<tr>
<td>60</td>
<td>1.58</td>
<td>68.81</td>
<td>98.614</td>
<td>99.9796</td>
</tr>
<tr>
<td>80</td>
<td>0.40</td>
<td>60.75</td>
<td>98.156</td>
<td>99.9728</td>
</tr>
<tr>
<td>100</td>
<td>0.10</td>
<td>53.64</td>
<td>97.70</td>
<td>99.9666</td>
</tr>
<tr>
<td>150</td>
<td>---</td>
<td>39.36</td>
<td>96.61</td>
<td>99.949</td>
</tr>
<tr>
<td>200</td>
<td>---</td>
<td>28.77</td>
<td>95.45</td>
<td>99.932</td>
</tr>
<tr>
<td>300</td>
<td>---</td>
<td>15.43</td>
<td>93.26</td>
<td>99.898</td>
</tr>
<tr>
<td>400</td>
<td>---</td>
<td>8.28</td>
<td>91.11</td>
<td>99.864</td>
</tr>
<tr>
<td>500</td>
<td>---</td>
<td>4.44</td>
<td>89.02</td>
<td>99.830</td>
</tr>
<tr>
<td>600</td>
<td>---</td>
<td>2.38</td>
<td>86.97</td>
<td>99.796</td>
</tr>
<tr>
<td>700</td>
<td>---</td>
<td>1.28</td>
<td>84.97</td>
<td>99.762</td>
</tr>
<tr>
<td>800</td>
<td>---</td>
<td>0.69</td>
<td>83.02</td>
<td>99.729</td>
</tr>
<tr>
<td>900</td>
<td>---</td>
<td>0.37</td>
<td>81.11</td>
<td>99.695</td>
</tr>
<tr>
<td>1000</td>
<td>---</td>
<td>0.20</td>
<td>79.24</td>
<td>99.661</td>
</tr>
<tr>
<td>1200</td>
<td>---</td>
<td>0.06</td>
<td>75.88</td>
<td>99.593</td>
</tr>
<tr>
<td>3000</td>
<td>---</td>
<td>---</td>
<td>50.15</td>
<td>98.985</td>
</tr>
<tr>
<td>17000</td>
<td>---</td>
<td>---</td>
<td>1.91</td>
<td>94.384</td>
</tr>
<tr>
<td>38000</td>
<td>---</td>
<td>---</td>
<td>0.01</td>
<td>78.820</td>
</tr>
<tr>
<td>700000</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>60.000</td>
</tr>
</tbody>
</table>

Source: Six Sigma RESEARCH INSTITUTE
Motorola University Motorola, Inc.
The Motivation for DFSS
What Have We Learned from LSS (DMAIC)?

- Total Cost
- Sigma Rating
- Typical Lean Six Sigma Barrier
- Design for Six Sigma
- Optimal Point
DFSS: Getting to the Next Level (the high hanging fruit)
Why DFSS

- Gain knowledge when costs are lowest
- Design in quality right from the start
DFSS Goals

- **Reduce Cycle Time in the Design and Development Process**
- **Reduce the Time to Money (TTM)**
- **Reduce the Cost of Poor Quality**
- **Improve Predictability of QCD (Quality, Cost, Delivery)**
General Electric Testimonial
(Dr. Norm Kuchar*, GECRD, Oct 2011)

- Quality increases of at least $+1\sigma$ at launch over previous designs
- Time to Market decrease by at least 25% over previous launches
- Cost savings due to total resources utilized in the 20-40% range

* Norm was responsible for the worldwide deployment of GE’s DFSS initiative.
The Benefits of DFSS

**DFSS Vision: Predictive Design**
- Early problem identification; solution when costs low
- Faster market entry: earlier revenue stream, longer patent coverage
- Lower total development cost
- Robust product at market entry: delighted customers
- Resources available for next game-changer

**Pre-DFSS: Reactive Design**
- Unhappy customers and employees
- Unplanned resource drain
- Skyrocketing costs
- Next product compromised

• Upfront investment is most effective and efficient
• Show customers highly capable products right from the start
The Vision of DFSS

From
- Evolving design requirements
- Extensive design rework
- Product performance assessed by “build and test”
- Performance and producibility problems fixed after product in use
- Quality “tested in”

To
- Disciplined requirements flowdown
- Controlled design parameters
- Product performance modeled and simulated
- Designed for robust performance and producibility
- Quality “designed in”

- Lean Six Sigma (DMAIC) fixes known problems.
- DFSS prevents unknown problems from occurring.
“As we know, there are known knowns. These are the things we know we know.

We also know there are known unknowns. That is to say we know there are some things we do not know.

But there are also unknown unknowns, the ones we don’t know we don’t know.”

Donald Rumsfeld
Department of Defense news briefing
February 12, 2002
Overview of the DFSS Process
Identify-Design-Optimize-Validate (IDOV*) Model

* The IDOV four-phase DFSS process originated with Dr. Norm Kuchar at GE CRD and is used with permission.

Key Deliverables:

- strategic plan
- benchmarking results
- customer requirements; prioritized, measurable CTCs (HOQ #1)
- Initial performance scorecard
- Design concepts and selection results
- Requirements flowdown
- Prioritized product design characteristics (HOQ #2)
- Design risk assessments
- Transfer functions
- Updated scorecards
- Capability and reliability studies
- X-ability assessment
- Optimized design
- Capability analysis
- Tolerances for key Xs
- Updated scorecards (capability flowup)
- Sensitivity analysis
- Pilots / prototypes and capability analysis
- Validated processes and products
- Updated scorecards
- Control plan
Methods and Tools Used in DFSS

**Identify**
- Project or Study Charter
- Strategic Plan
- Cross-Functional Team
- Voice of the Customer
- Customer Retention Grid
- Benchmarking
- KANO’s Model
- Questionnaires
- Focus Groups
- Interviews
- Internet Search
- Historical Data Analysis
- Design of Experiments
- Quality Function Deployment
- Pairwise Comparison
- **Analytical Hierarchy Process**
- Discrete Event Simulation
- Performance Scorecard
- Flow Charts
- FMEA
- **Visualization**

*Unique to DFSS*

**Design**
- Assign Specifications to CTC’s
- Axiomatic Design
- Critical Parameter Mgt.
- Formulate Design Concepts
- Pugh Concept Generation
- TRIZ
- FMEA
- Fault Tree Analysis
- Brainstorming
- QFD
- Scorecard
- Transfer Function
- Design of Experiments
- Deterministic Simulators
- Confidence Intervals
- Hypothesis Testing
- MSA
- Computer Aided Design
- Computer Aided Engineering

**Optimize**
- Histogram
- Distributional Analysis
- Empirical Data Distribution
- Expected Value Analysis (EVA)
- Adding Noise to EVA
- Non-Normal Output Distributions
- Design of Experiments
- Multiple Response Optimization
- Robust Design Development
- Using S-hat Model
- Using Interaction Plots
- Using Contour Plots
- Parameter Design
- Tolerance Allocation
- Design For Manufacturability and Assembly
- Mistake Proofing
- Product Capability Prediction
- **Part, Process, and SW Scorecard**
- Risk Assessment
- Reliability
- Multidisciplinary Design Optimization (MDO)

**Validate**
- Sensitivity Analysis
- Gap Analysis
- FMEA
- Fault Tree Analysis
- Control Plan
- PF/CE/CNX/SOP
- Run/Control Charts
- Mistake Proofing
- MSA
- Reaction Plan
- High Throughput Testing

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Project Selection: “DMAIC” or “DFSS”?

• In general,

  • “DMAIC” approach and tools work best when goal is to improve an existing product or process, with baseline performance metrics.

  • “DFSS” approach and tools work best when goal is to design a new product or process, with no baseline performance metrics available, or to redesign an existing product or process that is not meeting the performance requirements.

• Many projects contain elements of both; use appropriate tools, without concern about “purity” of approach.
The Identify Phase
The DFSS Process: Identify, Design, Optimize, Validate

– The Identify Phase
  – The DFSS Scorecard
  – Voice of the Customer (VOC)

– The Design Phase
  – Translating the VOC (Requirements Flowdown)
  – Concept Generation and Selection
  – Transfer Functions
  – Critical Parameter Management

– The Optimize Phase
  – Multiple Response Optimization
  – Expected Value Analysis Using Monte Carlo Simulation
  – Parameter Design
  – Tolerance Allocation

– The Validate Phase
  – High Throughput Testing
DFSS Scorecard and its Components

* The DFSS Design scorecard concept originated at Texas Instruments (Defense Systems and Electronics Group) in the early 1990s, and has been adapted and used by DFSS practitioners over the past decade(s).
## Examples of Parts, Process, Performance

<table>
<thead>
<tr>
<th>PARTS</th>
<th>Refrigerator</th>
<th>Engraved Nameplate</th>
<th>Statapult®</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>shelves</td>
<td>metal plate</td>
<td>pull-back arm</td>
</tr>
<tr>
<td></td>
<td>drawers</td>
<td>sealant</td>
<td>pins</td>
</tr>
<tr>
<td></td>
<td>evaporator</td>
<td></td>
<td>cup</td>
</tr>
<tr>
<td></td>
<td>thermostat</td>
<td></td>
<td>rubber band</td>
</tr>
</tbody>
</table>

| PROCESS          | weld sheet metal     | align plate        | attach protractor   |
|                  | attach handle        | engrave            | attach cup          |
|                  | attach handle        | apply sealant      | drill holes         |
|                  | spray protective     |                    | assemble side       |
|                  | coating              |                    | panels to base      |

| PERFORMANCE      | noise level          | plate flatness     | ball/cup fit        |
|                  | cooling speed        | engraving quality  | lateral dispersion  |
### Examples* of Scorecard Entries for MBT&E

<table>
<thead>
<tr>
<th>Task</th>
<th>Measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Employ Lethal Fire Support</td>
<td>Time to Target (&lt; 15 min)</td>
</tr>
<tr>
<td>Conduct Lethal Direct Fires</td>
<td>Positive Control Range (&gt; 50 nm)</td>
</tr>
<tr>
<td></td>
<td>Pssk (&gt; .80)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>System Attribute</th>
<th>Measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aircraft TDL</td>
<td>link range (&gt; 60 nm)</td>
</tr>
<tr>
<td>Provide Lethal Effects</td>
<td>Pk/h (&gt; .95)</td>
</tr>
<tr>
<td>Guide Munition</td>
<td>Ph/s (&gt; .90)</td>
</tr>
</tbody>
</table>

* These examples are taken from Chris Wilcox’s MBT&E Tutorial (page 23) at NDIA T&E 2010.
Scorecard Construction

- The scorecard is broken down into 4 major areas:
  - Parts
  - Process
  - Performance
  - Software

- A total dpu is computed for each of the four areas

- The 4 dpu’s are summed to obtain a total (overall) dpu for the entire product

\[
\text{Part DPU} + \text{Process DPU} + \text{Performance DPU} + \text{Software DPU} = \text{Total DPU}
\]

- First Pass Yield (FPY) is estimated using the approximation:
  \[\text{FPY} = e^{-\text{dpu}}\]
Scorecard Example (Nameplate)

**Part Scorecard**

<table>
<thead>
<tr>
<th>#</th>
<th>Part Name</th>
<th>DPU</th>
<th>Qty</th>
<th>Target</th>
<th>Mean</th>
<th>Std Dev</th>
<th>LSL</th>
<th>USL</th>
<th>UOM</th>
<th>Sample Size Known</th>
<th>ppm Only</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>plate thickness</td>
<td>0.0001083</td>
<td>1</td>
<td>0.0625</td>
<td>0.0614</td>
<td>0.008</td>
<td>0.03125</td>
<td>0.09375</td>
<td>in.</td>
<td>ppm Only</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>plate width</td>
<td>0.0004306</td>
<td>1</td>
<td>1.5</td>
<td>1.51</td>
<td>0.015</td>
<td>1.44</td>
<td>1.56</td>
<td>in.</td>
<td>ppm Only</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>sealant</td>
<td>0.000005</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ppm Only</td>
<td></td>
</tr>
</tbody>
</table>

**Process Scorecard**

<table>
<thead>
<tr>
<th>#</th>
<th>Process Step</th>
<th>DPU</th>
<th>Qty</th>
<th>Opps</th>
<th>Target</th>
<th>Mean</th>
<th>Std Dev</th>
<th>LSL</th>
<th>USL</th>
<th>UOM</th>
<th>Sample Size Known</th>
<th>ppm Only</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>align plate in fixture</td>
<td>0.0005000</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ppm Only</td>
<td>500</td>
</tr>
<tr>
<td>2</td>
<td>engrave</td>
<td>0.0020000</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ppm Only</td>
<td>1500</td>
</tr>
<tr>
<td>3</td>
<td>apply sealant</td>
<td>0.0073333</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ppm Only</td>
<td>1500</td>
</tr>
</tbody>
</table>

**Performance Scorecard**

<table>
<thead>
<tr>
<th>#</th>
<th>Performance</th>
<th>DPU</th>
<th>Qty</th>
<th>Target</th>
<th>Mean</th>
<th>Std Dev</th>
<th>LSL</th>
<th>USL</th>
<th>UOM</th>
<th>Sample Size Known</th>
<th>ppm Only</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>plate flatness</td>
<td>0.0009977</td>
<td>1</td>
<td>0.091</td>
<td>0.011</td>
<td>0.125</td>
<td></td>
<td></td>
<td>in.</td>
<td>ppm Only</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>engraving quality</td>
<td>0.000025</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ppm Only</td>
<td>4000</td>
</tr>
</tbody>
</table>
Scorecard Example (Nameplate, cont.)

Overall Scorecard (Roll-Up)

<table>
<thead>
<tr>
<th>Part</th>
<th># Steps/Parts</th>
<th>Total dpu</th>
<th>Yield</th>
<th>dpmo</th>
<th>ST Sigma</th>
<th>LT Sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
<td>3</td>
<td>0.000589</td>
<td>99.94%</td>
<td>196.31</td>
<td>5.04</td>
<td>3.54</td>
</tr>
<tr>
<td>Performance</td>
<td>3</td>
<td>0.009833</td>
<td>99.02%</td>
<td>3,277.78</td>
<td>4.22</td>
<td>2.72</td>
</tr>
<tr>
<td>Software</td>
<td>2</td>
<td>0.001248</td>
<td>99.88%</td>
<td>623.86</td>
<td>4.73</td>
<td>3.23</td>
</tr>
<tr>
<td>Total</td>
<td>8</td>
<td>0.011669983</td>
<td>98.84%</td>
<td>1458.748</td>
<td>4.476</td>
<td>2.976</td>
</tr>
</tbody>
</table>

Biggest overall dpu contributor: PROCESS

Areas for Focus: Apply Sealant, Engrave, Plate Flatness
## Statapult Scorecard Summary

### Scorecard Summary

<table>
<thead>
<tr>
<th>Part</th>
<th>Total dpu</th>
<th>Yield</th>
<th>dpmo</th>
<th>ST Sigma</th>
<th>LT Sigma</th>
</tr>
</thead>
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### ppm Only

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### Statapult Scorecard Summary (cont.)

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<th>Opps</th>
<th>Continuous Variable</th>
<th>Sample Size Known</th>
<th>ppm Only</th>
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<table>
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<th>Performance</th>
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<th>Qty</th>
<th>Opps</th>
<th>Continuous Variable</th>
<th>Sample Size Known</th>
<th>ppm Only</th>
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</thead>
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<td></td>
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<td></td>
<td>Sample Size</td>
<td># Defective</td>
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<td>1 4000</td>
<td>2</td>
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</tbody>
</table>
Who is known to have said this?

If we’re not keeping score, we’re only practicing.

Hint: a famous football coach
Suddenly, a heated exchange took place between the king and the moat contractor.

Source: The Far Side
The Far Side Millennium Off-the-Wall Calendar 2000
Far Works, Inc.
Quality Function Deployment (QFD)

Critical to Customer (CTC) Performance Measures

- Task Capabilities and System Attributes
  - In DFSS terms, these are the VOC (Voice of the Customer)

House of Quality #1
- Measures of Effect./Perf.
- Prioritized Req.
- Prioritized MOEs + MOPs

House of Quality #2
- Prod. Design Characteristics
- Prioritized Measures
- Prioritized Design Char’s

House of Quality #3
- Mfg. Process Characteristics
- Prior. Design Characteristics
- Prior. Mfg. Process Char’s

House of Quality #4
- Mfg. Process Control
- Mfg. Process Characteristics

Marketing
- Features
- Quality
- Performance
- Cost

Design Engineering
- Performance
- Reliability
- Cost

Mfg. Engineering
- Manufacturability
- Cost

Manufacturing
- SPC
- Process Capability
Voice of the Customer (Refrigerator)

VOC

- “Want it to be energy efficient”
- “Want it to be quiet”
- “Needs to preserve food”
- “Want to be able to easily reconfigure the shelves”
- “Want to fit large, bulky items”
- “Should last a long time”
- “Would like it to match my kitchen”
Use Pairwise Comparison to Prioritize

Example: “Easy to reconfigure” won 6 times.

Used to set weights for HOQ1
Place Customer Requirements & Rating into HOQ #1 (Refrigerator Example)

<table>
<thead>
<tr>
<th>Grouped customer requirements</th>
<th>Rating</th>
<th>Performance Measures</th>
</tr>
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<tbody>
<tr>
<td>A: energy efficient</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>B: quiet</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>C: preserves food</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>D: easy to reconfigure</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>E: handles large, bulky items</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>F: lasts a long time</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>G: matches kitchen</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

Rating:
- 5: Must have for performance
- 4: Highly desirable feature
- 3: Desirable feature
- 2: Usable feature but not critical
- 1: Nice feature but not critical
Fill in Performance Measures Across Top

<table>
<thead>
<tr>
<th>Peformance Measures (CTCs)</th>
<th>energy efficiency rating</th>
<th>noise level (db)</th>
<th>temperature range</th>
<th>cooling speed (sec per degree)</th>
<th>% adjustable shelves</th>
<th>dis assembled / reassembled time (sec)</th>
<th>shelf depth and width (in.)</th>
<th>mean time to failure (hrs)</th>
<th># available colors</th>
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</thead>
<tbody>
<tr>
<td>A: energy efficient</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B: quiet</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C: preserves food</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D: easy to reconfigure</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E: handles large, bulky items</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>F: lasts a long time</td>
<td>4</td>
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<tr>
<td>G: matches kitchen</td>
<td>1</td>
<td></td>
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</tbody>
</table>
Now, determine the strength of the relationships between the customer requirements and the CTCs. Rate the relationship between each customer requirement and each CTC according to the scale below.

9: Strong Relationship
3: Medium Relationship
1: Weak Relationship
Blank: No Relationship

Compute a Rank-Ordered Sum for each CTC (multiply strength • rating and add)
HOQ # 1 …. Prioritizes the Performance Measures

**CTCs/FPs**  
(Functional Domain)

**VOC**  
(Customer Domain)

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<th>Importance Rating</th>
<th>energy efficiency rating</th>
<th>noise level (db)</th>
<th>temperature range</th>
<th>cooling speed</th>
<th>% adjustable shelves</th>
<th>disassy / reassy time (sec.)</th>
<th>shelf depth and width (in.)</th>
<th>door tray depth (in.)</th>
<th>mean time to failure</th>
<th># available colors</th>
<th>Weighted Sums</th>
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<td>3</td>
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<tr>
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<td>3</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
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</table>

**Task Capabilities and System Attributes are mapped to Performance Measures**
Prioritized Measures Become Side of HOQ # 2

House of Quality # 1
- Measures of Effect./Perf.
- Prioritized Req.
- Prioritized MOEs + MOPs

House of Quality # 2
- Prod. Design Characteristics
- Prioritized Design Char’s

House of Quality # 3
- Mfg. Process Characteristics
- Prior. Mfg. Process Char’s

House of Quality # 4
- Mfg. Process Control

Prioritized Factors/Conditions (MBT&E)

Factors/Conditions that Affect the Performance Measures (MBT&E)

Task Capabilities and System Attributes

Marketing
- Features
- Quality
- Performance
- Cost

Design Engineering
- Performance
- Reliability
- Cost

Mfg. Engineering
- Manufacturability
- Cost

Manufacturing
- SPC
- Process Capability
Case Study: OnTech Self-Heating Container

Key Features (VOC)

- Self-heating
- Activated by button on bottom of can
- Used for hot beverages and soups
- Disposable
- Environmentally compatible
Affinitization of Consumer Appeal

Customer Appeal

CONCEPT
(Packaging)
- “Portable”
- “Self Heating”
- “Easy to Use”
- “Unique”

PRODUCT
(Taste)
- “Not bitter”
- “Fresh”
- “Smooth”
- “Varieties”

Simply...
I want to be able to buy one cup with a button on it, press the button, and it gets hot, and tastes great, then I can throw it away when I’m done.
Pairwise Comparison

Identify VOC Prioritization

<table>
<thead>
<tr>
<th></th>
<th>Portable</th>
<th>Self Heating</th>
<th>Easy to Use</th>
<th>Unique</th>
<th>Not bitter</th>
<th>Fresh</th>
<th>Smooth</th>
<th>Varieties</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>B</td>
<td>B</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>C</td>
<td>A</td>
<td>B</td>
<td></td>
<td></td>
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<td>B</td>
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<tr>
<td>E</td>
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<tr>
<td>F</td>
<td>.</td>
<td></td>
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<tr>
<td>G</td>
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<tr>
<td>H</td>
<td>.</td>
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</tr>
</tbody>
</table>

Example: “Self-Heating” won 5 times.

Pareto of Pairwise Comparison Results

Used to set weights for HOQ1
VOC ➔ CTCs

Customer Domain Language to Functional Domain Language
### 1st HOQ and Functional Domain

#### Identify

**CTCs/Perf.Measures** (Functional Domain)

**VOC** (Customer Domain)

<table>
<thead>
<tr>
<th></th>
<th>Dimensionality/Shape</th>
<th>Beverage Temperature</th>
<th>Time (sec) to use</th>
<th>Can Temperature</th>
<th>Weight</th>
<th>Taste</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Portable</strong></td>
<td>3</td>
<td>9</td>
<td>3</td>
<td>9</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td><strong>Self Heating</strong></td>
<td>5</td>
<td>3</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td><strong>Easy to Use</strong></td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td><strong>Unique</strong></td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Scores are multiplied by weights and summed below:

| Prioritized CTCs | 54 | 58 | 72 | 66 | 36 | .   | .   |

Voice of the Customer is mapped to Functional or Performance Measures.
The Design Phase
The DFSS Process: Identify, Design, Optimize, Validate

- The **Identify** Phase
  - The DFSS Scorecard
  - Voice of the Customer (VOC)

- **The Design Phase**
  - *Translating the VOC (Requirements Flowdown)*
  - *Concept Generation and Selection*
  - *Transfer Functions*
  - *Critical Parameter Management*

- The **Optimize** Phase
  - Multiple Response Optimization
  - Expected Value Analysis Using Monte Carlo Simulation
  - Parameter Design
  - Tolerance Allocation

- The **Validate** Phase
  - High Throughput Testing
• Complex products may require the "Divide and Conquer" approach.

• Requirements are flowed down, while capabilities are rolled up.

• System Engineers are the masters of the scorecard and make tradeoff decisions.
Requirements Flowdown Using QFD

- **Marketing**
  - Features
  - Quality
  - Performance
  - Cost

- **Design Engineering**
  - Performance
  - Reliability
  - Cost

- **Mfg. Engineering**
  - Manufacturability
  - Cost

- **Manufacturing**
  - SPC
  - Process Capability

- **House of Quality #1**
  - Customer Expectations
  - Functional Req. (CTC’s)
  - Performance CTC’s

- **House of Quality #2**
  - Functional Req. (CTC’s)
  - Prod. Design Characteristics
  - Product Design CTC’s

- **House of Quality #3**
  - Prod. Design Characteristics
  - Mfg. Process Characteristics
  - Process Design CTC’s

- **House of Quality #4**
  - Mfg. Process Characteristics
  - Mfg. Process Control

- **Performance Measures**
Formulate Design Concepts

- Create alternative designs that fulfill CTC’s.
- Compare designs with functional requirements (CTC’s).
- Choose the best design
  - How do we decide which is the best approach?
- Assess risk of chosen design.
- Tools for Concept Generation and Selection
  - Axiomatic Design
  - TRIZ
  - Pugh Concept Selection
Case Study: General Design Concept

- **Beverage**
- **Convection**
- **Energy release**
- **Calcium Oxide (CaO)**
- **Water for reaction**
- **Point of activation**
FAST (Functional Analysis System Technique)

**FAST allows us to quickly design the key functionality of the product (system).**

All of the “hows” and “whys” must be answered (both directions).
### 2nd HOQ: Functional → Physical Domain

#### CTCs (FPs) (Functional Domain)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>wt</th>
<th>Wall thickness</th>
<th>CaO mass</th>
<th>H₂O volume</th>
<th>Button force to activate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Can Temp</td>
<td>4</td>
<td>9</td>
<td>3</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Time to Use</td>
<td>5</td>
<td>3</td>
<td>9</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Dimensionality</td>
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<td>1</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Beverage Temp</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Scores are multiplied by weights and summed below:

| Prioritized DPs | 57 | 75 | 67 | .  | .  | .  |

Functional Parameters are mapped to Design Parameters.
Transfer Function: The Bridge to Innovation

Where does the transfer function come from?

- **Exact transfer function**
- **Approximations**
  - DOE
  - Historical Data Analysis
  - Simulation
Exact Transfer Functions

- Engineering Relationships
  - \( V = I R \)
  - \( F = ma \)

The equation for current \( I \) through this DC circuit is defined by:

\[
I = \frac{V}{R_1 \cdot R_2} = \frac{V(R_1 + R_2)}{R_1 \cdot R_2}
\]

The equation for magnetic force at a distance \( X \) from the center of a solenoid is:

\[
H = \frac{NI}{2\ell} \left[ \frac{.5\ell + x}{\sqrt{r^2 + (.5\ell + x)^2}} + \frac{.5\ell - x}{\sqrt{r^2 + (.5\ell - x)^2}} \right]
\]

Where
- \( N \): total number of turns of wire in the solenoid
- \( I \): current in the wire, in amperes
- \( r \): radius of helix (solenoid), in cm
- \( \ell \): length of the helix (solenoid), in cm
- \( x \): distance from center of helix (solenoid), in cm
- \( H \): magnetizing force, in amperes per centimeter
Hierarchical Transfer Functions

\[ Y = \text{Gross Margin} = \frac{\text{Gross Profit}}{\text{Gross Revenue}} \]

\[ Y = f(y_1, y_2, y_3, y_4, y_5, y_6) \]

\[ y_1 + y_2 + y_3 = (\text{Rev}_{\text{equip}} - \text{COG}) + (\text{Rev}_{\text{post sales}} - \text{Cost}_{\text{post sales}}) + (\text{Rev}_{\text{fin}} - \text{Cost}_{\text{fin}}) \]

\[ y_4 + y_5 + y_6 \]

\[ y_4 \]

\[ \text{Cost}_{\text{post sales}} = f(\text{field cost, remote services, suppliers}) \]

\[ x_1 = f(\text{direct labor, freight, parts, depreciation}) \]
What is a Designed Experiment?

Purposeful changes of the inputs (factors) in order to observe corresponding changes in the output (response).

Inputs

\[ X_1, X_2, X_3, X_4 \]

Outputs

\[ Y_1, Y_2, \ldots \]

\[ \overline{Y}, S_Y \]

<table>
<thead>
<tr>
<th>Run</th>
<th>( X_1 )</th>
<th>( X_2 )</th>
<th>( X_3 )</th>
<th>( X_4 )</th>
<th>( Y_1 )</th>
<th>( Y_2 )</th>
<th>\ldots</th>
<th>( \overline{Y} )</th>
<th>( S_Y )</th>
</tr>
</thead>
<tbody>
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</tr>
</tbody>
</table>
DOE Helps Determine How Inputs Affect Outputs

i) Factor A affects the average of $y$

\[ A_1, A_2 \]

\[ y \]

ii) Factor B affects the standard deviation of $y$

\[ B_1, B_2 \]

\[ y \]

iii) Factor C affects the average and the standard deviation of $y$

\[ C_1, C_2 \]

\[ y \]

iv) Factor D has no effect on $y$

\[ D_1 = D_2 \]

\[ y \]
Catapulting Power into DFSS

Statapult® Catapult
The Theoretical Approach
The Theoretical Approach (cont.)

\[ \dot{\theta} = r_F \sin \theta \cos \phi - (M r_G + m r_B) \sin \theta \]

\[ \frac{1}{2} I_0 \ddot{\theta} = r_F \int_{\theta_0}^{\theta} F(\theta) \sin \theta \cos \phi \, d\theta - (M r_G + m r_B)(\sin \theta - \sin \theta_0) \]

\[ \frac{1}{2} I_0 \ddot{\theta} = r_F \int_{\theta_0}^{\theta_1} F(\theta) \sin \theta \cos \phi \, d\theta - (M r_G + m r_B)(\sin \theta_1 - \sin \theta_0). \]

\[ x = v_B \cos \left( \frac{\pi}{2} - \theta_1 \right) t - \frac{1}{2} r_B \cos \theta_1 \]

\[ y = r_B \sin \theta_1 + v_B \sin \left( \frac{\pi}{2} - \theta_1 \right) t - \frac{1}{2} g t^2. \]

\[ \frac{gl_0}{4 r_B \cos^2 \left( \frac{\pi}{2} - \theta_1 \right)} \left[ r_B \sin \theta_1 + (R + r_B \cos \theta_1) \tan \left( \frac{\pi}{2} - \theta_1 \right) \right] = 0. \]

\[ \theta \sin \theta \sin \phi \]
## Statapult® DOE Demo
(The Empirical Approach)

### Table

<table>
<thead>
<tr>
<th>Run</th>
<th>A</th>
<th>B</th>
<th>Coded Factors</th>
<th>Response Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>144</td>
<td>2</td>
<td>-1 -1 +1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>144</td>
<td>3</td>
<td>-1 +1 -1</td>
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<tr>
<td>3</td>
<td>160</td>
<td>2</td>
<td>+1 -1 -1</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>160</td>
<td>3</td>
<td>+1 +1 +1</td>
<td></td>
</tr>
</tbody>
</table>
What Makes DOE so Powerful?  
(Orthogonality: both vertical and horizontal balance)

A Full Factorial Design for 3 Factors A, B, and C, Each at 2 levels:

<table>
<thead>
<tr>
<th>Run</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>AB</th>
<th>AC</th>
<th>BC</th>
<th>ABC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-</td>
<td>-</td>
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<td>+</td>
<td>+</td>
<td>+</td>
<td>-</td>
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<tr>
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<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>
Value Delivery: Reducing Time to Market for New Technologies

\[ \text{Total # of Combinations} = 3^5 = 243 \]

- **Central Composite Design:** \( n = 30 \)

**Patent Holder:** Dr. Bert Silich
Aircraft Equations

\[ C_L = 0.233 + 0.008(P)^2 + 0.255(P) + 0.012(R) - 0.043(WD1) - 0.117(WD2) + 0.185(WD3) + 0.010(P)(WD3) - 0.042(R)(WD1) + 0.035(R)(WD2) + 0.016(R)(WD3) + 0.010(P)(R) - 0.003(WD1)(WD2) - 0.006(WD1)(WD3) \]

\[ C_D = 0.058 + 0.016(P)^2 + 0.028(P) - 0.004(WD1) - 0.013(WD2) + 0.013(WD3) + 0.002(P)(R) - 0.004(P)(WD1) - 0.009(P)(WD2) + 0.016(P)(WD3) - 0.004(R)(WD1) + 0.003(R)(WD2) + 0.020(WD1)^2 + 0.017(WD2)^2 + 0.021(WD3)^2 \]

\[ C_Y = -0.006(P) - 0.006(R) + 0.169(WD1) - 0.121(WD2) - 0.063(WD3) - 0.004(P)(R) + 0.008(P)(WD1) - 0.006(P)(WD2) - 0.008(P)(WD3) - 0.012(R)(WD1) - 0.029(R)(WD2) + 0.048(R)(WD3) - 0.008(WD1)^2 \]

\[ C_M = 0.023 - 0.008(P)^2 + 0.004(P) - 0.007(R) + 0.024(WD1) + 0.066(WD2) - 0.099(WD3) - 0.006(P)(R) + 0.002(P)(WD2) - 0.005(P)(WD3) + 0.023(R)(WD1) - 0.019(R)(WD2) - 0.007(R)(WD3) + 0.007(WD1)^2 - 0.008(WD2)^2 + 0.002(WD1)(WD2) + 0.002(WD1)(WD3) \]

\[ C_{VM} = 0.001(P) + 0.001(R) - 0.050(WD1) + 0.029(WD2) + 0.012(WD3) + 0.001(P)(R) - 0.005(P)(WD1) - 0.004(P)(WD2) - 0.004(P)(WD3) + 0.003(R)(WD1) + 0.008(R)(WD2) - 0.013(R)(WD3) + 0.004(WD1)^2 + 0.003(WD2)^2 - 0.005(WD3)^2 \]

\[ C_e = 0.003(P) + 0.035(WD1) + 0.048(WD2) + 0.051(WD3) - 0.003(R)(WD3) + 0.003(P)(R) - 0.005(P)(WD1) + 0.005(P)(WD2) + 0.006(P)(WD3) + 0.002(R)(WD1) \]
Fusing Titanium and Cobalt-Chrome

Courtesy Rai Chowdhary
**DOE “Market Research” Example**

Suppose that, in the auto industry, we would like to investigate the following automobile attributes (i.e., factors), along with accompanying levels of those attributes:

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Brand of Auto</td>
<td>-1 = foreign, +1 = domestic</td>
</tr>
<tr>
<td>B: Auto Color</td>
<td>-1 = light, 0 = bright, +1 = dark</td>
</tr>
<tr>
<td>C: Body Style</td>
<td>-1 = 2-door, 0 = 4-door, +1 = sliding door/hatchback</td>
</tr>
<tr>
<td>D: Drive Mechanism</td>
<td>-1 = rear wheel, 0 = front wheel, +1 = 4-wheel</td>
</tr>
<tr>
<td>E: Engine Size</td>
<td>-1 = 4-cylinder, 0 = 6-cylinder, +1 = 8-cylinder</td>
</tr>
<tr>
<td>F: Interior Size</td>
<td>-1 ≤ 2 people, 0 = 3-5 people, +1 ≥ 6 people</td>
</tr>
<tr>
<td>G: Gas Mileage</td>
<td>-1 ≤ 20 mpg, 0 = 20-30 mpg, +1 ≥ 30 mpg</td>
</tr>
<tr>
<td>H: Price</td>
<td>-1 ≤ $20K, 0 = $20-$40K, +1 ≥ $40K</td>
</tr>
</tbody>
</table>

In addition, suppose the respondents chosen to provide their preferences to product profiles are taken based on the following demographic:

<table>
<thead>
<tr>
<th>Demographic</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>J: Age</td>
<td>-1 ≤ 25 years old, +1 ≥ 35 years old</td>
</tr>
<tr>
<td>K: Income</td>
<td>-1 ≤ $30K, +1 ≥ $40K</td>
</tr>
<tr>
<td>L: Education</td>
<td>-1 &lt; BS, +1 ≥ BS</td>
</tr>
</tbody>
</table>
**Question:** Choose the best design for evaluating this scenario

**Answer:** $L_{18}$ design with attributes A - H in the inner array and factors J, K, and L in the outer array, resembling an $L_{18}$ robust design, as shown below:

Segmentation of the population or Respondent Profiles

<table>
<thead>
<tr>
<th>Run*</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>$y_1$</th>
<th>$y_2$</th>
<th>$y_3$</th>
<th>$y_4$</th>
<th>$y_5$</th>
<th>$y_6$</th>
<th>$y_7$</th>
<th>$y_8$</th>
<th>$\bar{y}$</th>
<th>$s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-</td>
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* 18 different product profiles
Modeling The Drivers of Turnover*

1. External Market Factors (Local Labor Market Conditions)
   - Local Unemployment Rate
   - Local Employment Alternatives
   - Company’s Market Share

2. Organizational Characteristics and Practices
   - Supervisor Stability
   - Lateral / Upward Mobility
   - Layoff Climate

3. Employee Attributes
   - Time Since Last Promotion
   - Education Level
   - Job Stability History

*Adapted from Harvard Business Review article on Boston Fleet Bank, April 2004, pp 116-125
The Value of Transfer Functions

- Provide a simple and compact way of understanding relationships between performance measures or response variables (y’s) and the factors (x’s) that influence them.
- Allow for the prediction of the response variable (y), with associated risk levels, before any change in the product or process is made.
- Allow for the assessment of process or product capability in the presence of uncontrolled variation or noise.
- Allow the very quick manipulation of complex systems using Monte Carlo Simulation (i.e., Expected Value Analysis) for the purpose of assessing risk.
- Provide a very easy way to optimize performance via robust or parameter design and tolerance allocation.
- Make sensitivity analysis easy and straightforward.
- Greatly enhance one’s knowledge of a product or process.
- In general, they are the gateway to systematic innovation.
- Provide a meaningful metric for the maturity in DFSS for any organization.
Case Study: Transfer Functions

Example: “Time to use” and “Can temp” as a function of “Wall thickness”, “CaO mass”, and “H₂O volume”

Wall thickness (X1) → Y1=f₁(X1, X2, X3) → Time to use (Y1)
CaO mass (X2) → Y2=f₂(X1, X2, X3) → Can temp (Y2)
H₂O volume (X3) →

How do we find the functions f₁ and f₂?
• First principle equations (Physics / Engineering equations)
• Analytical Models (Simulation and Regression) FEA, CFD, etc.
• Empirical models (Design of Experiments)
Empirical Modeling via DOE

### Design

#### Y-hat Model

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#### Time to use

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#### Max can temp

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<td>H2O Volume</td>
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#### Y-hat Contour Plot of (Time to use) Wall Thickness vs CaO Mass

#### Y-hat Surface Plot of (Time to use) Wall Thickness vs CaO Mass

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Analytical Modeling via FEA/CFD

Finite Element Analysis (FEA) for modeling structural components

Computational Fluid Dynamics (CFD) for modeling temperature (fluid) components
Analytical Modeling with Regression

FEA / CFD Model

Regression Modeling

Predicted results validated in model
Critical Parameter Management and COIs

– A Critical Operational Issue (COI) is linked to operational effectiveness and suitability.

– It is typically phrased as a question, e.g.,

Will the system \textit{detect} the \textit{threat} in a \textit{combat environment} at adequate \textit{range} to allow for successful \textit{engagement}?

\begin{center}
\begin{tikzpicture}
\node (y2) at (0,0) {$y_2$ (engagement)};
\node (y1) at (-2,-1) {$y_1$ (detect)};
\node (x1) at (-4,-2) {$x_1$};
\node (x2) at (-3,-2) {$x_2$};
\node (x3) at (-1,-2) {$x_3$ (ranges)};
\node (x4) at (0,-2) {$x_4$ (threat type)};
\node (x5) at (1,-2) {$x_5$};
\node (x6) at (2,-2) {$x_6$};
\draw (y2) -- (y1);
\draw (y1) -- (x1);
\draw (y1) -- (x2);
\draw (y1) -- (x3);
\draw (y1) -- (x4);
\draw (y1) -- (x5);
\draw (y1) -- (x6);
\end{tikzpicture}
\end{center}
DOE Enables Critical Parameter Management (CPM)

CPM is a systems engineering best practice that is extremely useful in managing, analyzing, and reporting technical product performance. It is also very useful in decomposing COIs and developing linkages between measures and task capabilities/system attributes.
DOE Enables the Composition of Functions

\[ Y = f(A, B, C, D, E, F, ..., M) \]
The Optimize Phase
The DFSS Process: Identify, Design, Optimize, Validate

- The **Identify** Phase
  - The DFSS Scorecard
  - Voice of the Customer (VOC)

- The **Design** Phase
  - Translating the VOC (Requirements Flowdown)
  - Concept Generation and Selection
  - Transfer Functions
  - Critical Parameter Management

- **The Optimize Phase**
  - *Multiple Response Optimization*
  - *Expected Value Analysis (Monte Carlo Simulation)*
  - *Parameter (Robust) Design*
  - *Tolerance Allocation*

- The **Validate** Phase
  - High Throughput Testing
Multiple Response Optimization Simulation* Example

Cross Support Diameter (2-4)

Vertical Support Diameter (2-4)

Box Diameter (2-4)

Beam Angle (35-60)

Design Cost (≤ 300)

Rib Compression (≤ 11)

Triaxial Acceleration (≤ 15)

Vehicle Impact Safety Process

* From SimWare Pro by Philip Mayfield and Digital Computations
Multiple Response Optimization (cont.)
Capability Prior to Optimization

Input Controls

Control Set 1

Cross Support Diameter (2 to 4)
Vertical Support Diameter (2 to 4)
Box Diameter (2 to 4)
Beam Angle (35 to 60)
Multiple Response Optimization (cont.)
Capability After Optimization

Input Controls

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<tr>
<td>Cross Support Diameter (2 to 4)</td>
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<td>2.270</td>
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</table>
DFSS with Monte Carlo Simulation

- Expected Value Analysis
- Robust (Parameter) Design
- Tolerance Allocation
Expected Value Analysis (EVA)

EVA is the technique used to determine the characteristics of the output distribution (mean, standard deviation, and shape) when we have knowledge of (1) the input variable distributions and (2) the transfer functions.

\[
\begin{align*}
X_1 & \\
X_2 & \\
X_3 & \\
\end{align*}
\]

\[
\begin{align*}
y_1 &= f_1(X_1, X_2, X_3) \\
y_2 &= f_2(X_1, X_2, X_3)
\end{align*}
\]

\[
\begin{align*}
\text{Distribution of } X_1 & \\
\text{Distribution of } X_2 & \\
\text{Distribution of } X_3 & \\
\end{align*}
\]

\[
\begin{align*}
\text{Distribution of } y_1 & \\
\text{Distribution of } y_2 & \\
\end{align*}
\]
Expected Value Analysis Example

What is the mean or expected value of the y distribution?

What is the shape of the y distribution?
Parameter Design (Robust Design)

Process of finding the optimal mean settings of the input variables to minimize the resulting dpm.
Parameter Design (Robust Design)

If you’re the designer, which setting for X do you prefer?

Changing the mean of an input may possibly reduce the output variation!
Robust (Parameter) Design Simulation* Example

Nuclear Reservoir Level Control Process

- Plug Pressure (20-50)
- Bellow Pressure (10-20)
- Ball Valve Pressure (100-200)
- Water Temp (70-100)

Reservoir Level (700-900)

* From SimWare Pro by Philip Mayfield and Digital Computations
Tolerance Allocation

Which input standard deviations have the biggest effect on the output variation?
Which resistor’s standard deviation has the greater impact on the capability of $I$?

$$I = \frac{9(R_1 + R_2)}{R_1 \cdot R_2}$$

$\text{LSL} = .255$

$\text{USL} = .285$
A reduction in $R_1$'s standard deviation (sigma) significantly reduces the dpm while a reduction in $R_2$'s standard deviation has a smaller effect.

A reduction in $R_1$'s standard deviation by 50% (from 2 ohms to 1 ohm) combined with an increase in $R_2$'s standard deviation by 25% (from 4 ohms to 5 ohms) results in a dpm = 9,743.

(This result is not shown in the table.)
Case Study: Optimization Strategy

Wall thickness (X1) → Y1=f₁(X1, X2, X3) → Time to use (Y1)
CaO mass (X2) → Y2=f₂(X1, X2, X3) → Can temp (Y2)
H₂O volume (X3)

How do we best set X1, X2, X3 to optimize Y1 and Y2?

- Expected Value Analysis (EVA) - a form of Monte Carlo simulation
- Robust Design methods - including computer-based Parameter Design
- Tolerance Allocation - via computer-based tolerance analysis
EVA – Monte Carlo Simulation

### Process Inputs

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### Expected Value Analysis

#### Process Inputs

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<tr>
<td>Noise_Mc Normal</td>
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<td>0.29626055</td>
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#### Process Outputs

- **Time to use**
  - 1,000,000
- **Max can temp**
  - 1,000,000

#### Normal Distro Statistics

- KS Test p-Value (Normal): 0.211
- dpm: 530,572,305
- Cpk: -0.026
- Cpk: -0.077
- Sigma Level: -0.077
- Sigma Capability: 0.238
Parameter (Robust) Design

Parameter Ranges

Select the range for each input parameter

Wall Thickness Mean From 1 to 1
CaO Mass Mean From -1 to 1
H2O Volume Mean From -1 to 1
Noise, Time to use Mean From 0 to 0
Noise, Max can Mean From 0 to 0

Expected Value Analysis

Process Inputs

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Process Outputs

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Optimize

Computing Optimal Parameters

Calculating

Total Weight = 100.

Inputs

Wall Thickness = 0.0
CaO Mass = 0.9999
H2O Volume = 0.99978
Noise, Time to use = 0.0
Noise, Max can temp = 0.0

Outputs

Time to use = 4.589 dpm
Max can temp = 8.834 dpm
# Tolerance Allocation

## Tolerance Allocation Table

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<tr>
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<td>H2O Volu Normal</td>
<td>-0.9340357</td>
<td>0.14123</td>
</tr>
<tr>
<td>Noise Tim Normal</td>
<td>0</td>
<td>0.5507544</td>
</tr>
<tr>
<td>Noise Max Normal</td>
<td>0</td>
<td>0.2935261</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>N = 1,000,000 (in dpm)</th>
<th>Time to use Table (Normal dpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall Thickness</td>
<td>CaO Mass</td>
</tr>
<tr>
<td>90% Sigma</td>
<td>1.416</td>
</tr>
<tr>
<td>75% Sigma</td>
<td>1.023</td>
</tr>
<tr>
<td>50% Sigma</td>
<td>3.26</td>
</tr>
<tr>
<td>Nominal</td>
<td>7.048</td>
</tr>
<tr>
<td>-10% Sigma</td>
<td>14.48</td>
</tr>
<tr>
<td>-25% Sigma</td>
<td>40.3</td>
</tr>
<tr>
<td>-50% Sigma</td>
<td>171.0</td>
</tr>
</tbody>
</table>

## Expected Value Analysis

Optimize

By variance reduction

### Process Inputs

<table>
<thead>
<tr>
<th>Factor</th>
<th>Distro</th>
<th>First Parameter</th>
<th>Second Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall Thick Normal</td>
<td>-1</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>CaO Mass Normal</td>
<td>-0.9599782</td>
<td>0.0000000</td>
<td></td>
</tr>
<tr>
<td>H2O Volu Normal</td>
<td>-0.9340357</td>
<td>0.14123</td>
<td></td>
</tr>
<tr>
<td>Noise Tim Normal</td>
<td>0</td>
<td>0.5507544</td>
<td></td>
</tr>
<tr>
<td>Noise Max Normal</td>
<td>0</td>
<td>0.2935261</td>
<td></td>
</tr>
</tbody>
</table>

### Process Outputs

<table>
<thead>
<tr>
<th>Time to use</th>
<th>Max can temp</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,000,000</td>
<td>1,000,000</td>
</tr>
<tr>
<td>13.9396</td>
<td>105.0247</td>
</tr>
<tr>
<td>0.6279</td>
<td>0.3578</td>
</tr>
<tr>
<td>17</td>
<td>107</td>
</tr>
</tbody>
</table>

### Normal Distro Statistics

<table>
<thead>
<tr>
<th>KS Test p-Value (Normal)</th>
<th>dpm</th>
<th>Cpk</th>
<th>Cp</th>
<th>Sigma Level</th>
<th>Sigma Capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.012</td>
<td>0.0</td>
<td>546</td>
<td>.17</td>
<td>1.625</td>
<td>5.521</td>
</tr>
<tr>
<td>1.84</td>
<td>5.621</td>
<td>5.621</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The Validate Phase
The DFSS Process: Identify, Design, Optimize, Validate

- The **Identify** Phase
  - The DFSS Scorecard
  - Voice of the Customer (VOC)

- The **Design** Phase
  - Translating the VOC (Requirements Flowdown)
  - Concept Generation and Selection
  - Transfer Functions
  - Critical Parameter Management

- The **Optimize** Phase
  - Multiple Response Optimization
  - Expected Value Analysis Using Monte Carlo Simulation
  - Parameter Design
  - Tolerance Allocation

- The **Validate Phase**
  - High Throughput Testing
The Validate Phase

- Validating performance
- Performing sensitivity analysis
- Comparing Predicted capability with actual
- Gap analysis (reasons for lack of confirmation)
- Updating scorecards
Critical parameters are validated against predictions from models.

Methods may include
• Prototypes
• Lab scale production
• Test-fixturing of subassemblies

If validation is poor .......... gap analysis!
Introduction to High Throughput Testing (HTT)

- A recently developed technique based on combinatorics
- Used to test myriad combinations of many factors (typically qualitative) where the factors could have many levels
- Uses a minimum number of runs or combinations to do this
- Software (e.g., ProTest) is needed to select the minimal subset of all possible combinations to be tested so that all 2-way combinations are tested.
- HTT is not a DOE technique, although the terminology is similar
- A run or row in an HTT matrix is, like DOE, a combination of different factor levels which, after being tested, will result in a successful or failed run
- HTT has its origins in the pharmaceutical business where in drug discovery many chemical compounds are combined together (combinatorial chemistry) at many different strengths to try to produce a reaction.
- Other industries are now using HTT, e.g., software testing, materials discovery, integration and functionality testing (see example on next page).
Submarine Threat Detection Example

Suppose we want to perform a verification test with the following 7 input factors (with their respective settings):

- Submarine Type (S1, S2, S3)
- Ocean Depth (Shallow, Deep, Very Deep)
- Sonar Type (Active, Passive)
- Target Depth (Surface, Shallow, Deep, Very Deep)
- Sea Bottom (Rock, Sand, Mud)
- Control Mode (Autonomous, Manual)
- Ocean Current (Strong, Moderate, Minimal)

All possible combinations would involve how many runs in the test?

If we were interested in testing all pairs only, how many runs would be in the test? Pro Test generated the following test matrix.
Submarine Threat Detection Example (cont.)

The following 15 test cases will test all pairwise combinations.

<table>
<thead>
<tr>
<th>Factor Name</th>
<th>Factor_A</th>
<th>Factor_B</th>
<th>Factor_C</th>
<th>Factor_D</th>
<th>Factor_E</th>
<th>Factor_F</th>
<th>Factor_G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>S3</td>
<td>Deep</td>
<td>Passive</td>
<td>Very Deep</td>
<td>Mud</td>
<td>Manual</td>
<td>Minimal</td>
</tr>
<tr>
<td>Case 2</td>
<td>S1</td>
<td>Very Deep</td>
<td>Passive</td>
<td>Surface</td>
<td>Rock</td>
<td>Autonomous</td>
<td>Strong</td>
</tr>
<tr>
<td>Case 3</td>
<td>S2</td>
<td>Shallow</td>
<td>Active</td>
<td>Shallow</td>
<td>Rock</td>
<td>Manual</td>
<td>Moderate</td>
</tr>
<tr>
<td>Case 4</td>
<td>S2</td>
<td>Deep</td>
<td>Passive</td>
<td>Deep</td>
<td>Sand</td>
<td>Autonomous</td>
<td>Moderate</td>
</tr>
<tr>
<td>Case 5</td>
<td>S1</td>
<td>Shallow</td>
<td>Active</td>
<td>Surface</td>
<td>Sand</td>
<td>Manual</td>
<td>Minimal</td>
</tr>
<tr>
<td>Case 6</td>
<td>S1</td>
<td>Very Deep</td>
<td>Passive</td>
<td>Shallow</td>
<td>Mud</td>
<td>Autonomous</td>
<td>Minimal</td>
</tr>
<tr>
<td>Case 7</td>
<td>S3</td>
<td>Very Deep</td>
<td>Active</td>
<td>Deep</td>
<td>Mud</td>
<td>Manual</td>
<td>Strong</td>
</tr>
<tr>
<td>Case 8</td>
<td>S2</td>
<td>Very Deep</td>
<td>Active</td>
<td>Deep</td>
<td>Sand</td>
<td>Autonomous</td>
<td>Strong</td>
</tr>
<tr>
<td>Case 9</td>
<td>S3</td>
<td>Shallow</td>
<td>Passive</td>
<td>Shallow</td>
<td>Mud</td>
<td>Autonomous</td>
<td>Strong</td>
</tr>
<tr>
<td>Case 10</td>
<td>S3</td>
<td>Deep</td>
<td>Active</td>
<td>Surface</td>
<td>Rock</td>
<td>Manual</td>
<td>Moderate</td>
</tr>
<tr>
<td>Case 11</td>
<td>S1</td>
<td>Shallow</td>
<td>Active</td>
<td>Deep</td>
<td>Rock</td>
<td>Autonomous</td>
<td>Minimal</td>
</tr>
<tr>
<td>Case 12</td>
<td>S1</td>
<td>Deep</td>
<td>Passive</td>
<td>Very Deep</td>
<td>Rock</td>
<td>Manual</td>
<td>Moderate</td>
</tr>
<tr>
<td>Case 13</td>
<td>S2</td>
<td>Very Deep</td>
<td>Active</td>
<td>Surface</td>
<td>Mud</td>
<td>Autonomous</td>
<td>Moderate</td>
</tr>
<tr>
<td>Case 14</td>
<td>S3</td>
<td>Deep</td>
<td>Active</td>
<td>Shallow</td>
<td>Sand</td>
<td>Manual</td>
<td>Strong</td>
</tr>
<tr>
<td>Case 15</td>
<td>S2</td>
<td>Shallow</td>
<td>Active</td>
<td>Very Deep</td>
<td>Rock</td>
<td>Manual</td>
<td>Minimal</td>
</tr>
</tbody>
</table>
HTT Applications

• Reducing the cost and time of testing while maintaining adequate test coverage

• Integration and functionality testing

• Creating a test plan to stress a product and discover problems

• Prescreening before a large DOE to ensure all 2-way combinations are feasible before discovering, midway through an experiment, that certain combinations are not feasible

• Developing an “outer array” of noise combinations to use in a robust design DOE when the number of noise factors and settings is large
Requirements Flowdown Using QFD

Customer Expectations

House of Quality # 1
- Functional Req (CTC's)
- Performance CTC's

House of Quality # 2
- Functional Req (CTC's)
- Prod. Design Characteristics
- Product Design CTC's

House of Quality # 3
- Prod. Design Characteristics
- Mfg. Process Characteristics
- Process Design CTC's

House of Quality # 4
- Mfg. Process Control

Marketing
- Features
- Quality
- Performance
- Cost

Design Engineering
- Performance
- Reliability
- Cost

Mfg. Engineering
- Manufacturability
- Cost

Manufacturing
- SPC
- Process Capability
Case Study: Validation

Critical parameters are validated against predictions from models.

Methods may include

- Prototypes
- Lab scale production
- Test-fixturing of sub-assemblies
### 3rd HOQ: Physical Domain → Process Domain

#### Design Parameters (Physical Domain) → Process Parameters (Process Domain)

<table>
<thead>
<tr>
<th>Design Parameter</th>
<th>Mold Temp</th>
<th>Injection Speed</th>
<th>Clamp Force</th>
<th>Injection Pressure</th>
<th>Seamer roll force</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall thickness</td>
<td>3</td>
<td>9</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>CaO mass</td>
<td>5</td>
<td>3</td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H2O volume</td>
<td>4</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Button force</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Design Parameters are mapped to Process Parameters

| Prioritized PPs | 75 | 69 | 50 | 62 | 17 | .   |

**Validate**
### 4th HOQ: Process Domain → Process Control

**Process Control**

<table>
<thead>
<tr>
<th>PP (Process Domain)</th>
<th>Process Parameters are mapped to Process Controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mold Temp</td>
<td>5</td>
</tr>
<tr>
<td>Injection Speed</td>
<td>4</td>
</tr>
<tr>
<td>Clamp Force</td>
<td>2</td>
</tr>
<tr>
<td>Injection Pressure</td>
<td>3</td>
</tr>
<tr>
<td>Seamer roll force</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Prioritized PCs</th>
<th>Machine 1 SOP</th>
<th>Machine 2 SOP</th>
<th>Force IMR Chart</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>67</td>
<td>71</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>67</td>
<td></td>
</tr>
</tbody>
</table>

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## Methods & Tools Used in Case Study

<table>
<thead>
<tr>
<th>Identify</th>
<th>Design</th>
<th>Optimize</th>
<th>Validate</th>
<th>Mfg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>QFD</td>
<td>Axiomatic Design</td>
<td>TRIZ</td>
<td>Analytical Modeling &amp; Simulation</td>
<td>LSS/DFSS</td>
</tr>
<tr>
<td>VOC</td>
<td>CUSTOMER DOMAIN</td>
<td>8 PATTERNS</td>
<td>SURVEYS INTERVIEWS FOCUS GROUPS PAIRWISE COMPARISON BASES</td>
<td></td>
</tr>
<tr>
<td>HOQ1</td>
<td>FUNCTIONAL DOMAIN</td>
<td>SYSTEMS VIEW</td>
<td>Functional Analysis System Technique (FAST)</td>
<td></td>
</tr>
<tr>
<td>CTCs (FPs)</td>
<td>FUNCTIONAL DOMAIN</td>
<td>INDEPENDENCE &amp; INFORMATION OPTIMIZATION (DECOUPLING)</td>
<td>DOE / EVA MONTE CARLO / DS PARAMETER DESIGN TOLERANCING</td>
<td></td>
</tr>
<tr>
<td>HOQ2</td>
<td>PHYSICAL DOMAIN</td>
<td>FUNCTIONAL MODEL TC &amp; PC ALGORITHMS RESOURCES</td>
<td>FEA, CFD: ANSYS FLUENT COSMOS</td>
<td></td>
</tr>
<tr>
<td>CTCs (FPs)</td>
<td>(VIA AXIOMATIC DESIGN)</td>
<td>(DECOUPLING)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DPs</td>
<td>PHYSICAL DOMAIN</td>
<td>FUNCTIONAL MODEL TC &amp; PC ALGORITHMS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HOQ3</td>
<td>PROCESS DOMAIN</td>
<td>TC &amp; PC ALGORITHMS CONFIRMATION</td>
<td>HYPOTHESIS TESTS CONFIRMATION</td>
<td></td>
</tr>
<tr>
<td>DPs</td>
<td>PROCESS DOMAIN</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HOQ4</td>
<td>PROCESS CONTROL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PPs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Methods & Tools

- **QFD**
  - VOC
  - HOQ1
  - CTCs (FPs)

- **Axiomatic Design**
  - CUSTOMER DOMAIN
  - FUNCTIONAL DOMAIN
  - PHYSICAL DOMAIN
  - INDEPENDENCE & INFORMATION OPTIMIZATION (DECOUPLING)

- **TRIZ**
  - FUNCTIONAL MODEL TC & PC ALGORITHMS RESOURCES

- **Analytical Modeling & Simulation**
  - TC & PC ALGORITHMS CONFIRMATION
  - TC & PC ALGORITHMS

- **LSS/DFSS**
  - SURVEYS INTERVIEWS FOCUS GROUPS PAIRWISE COMPARISON BASES
  - Functional Analysis System Technique (FAST)
  - DOE / EVA MONTE CARLO / DS PARAMETER DESIGN TOLERANCING
  - HYPOTHESIS TESTS CONFIRMATION

- **Methods**
  - SURVEYS
  - INTERVIEWS
  - FOCUS GROUPS
  - PAIRWISE COMPARISON BASES
  - HYPOTHESIS TESTS
  - CONFIRMATION

- **Tools**
  - DOE / EVA
  - MONTE CARLO / DS PARAMETER DESIGN TOLERANCING
The Original DFSS (Design for Six Sigma)

Identify

- HOQ1
  - Customer Requirements
  - Functional Requirements

Design

- HOQ2
  - Design Parameters

Optimize

- HOQ3
  - Design Parameters
  - Manufacturing Parameters

Validate

- HOQ4
  - Manufacturing Parameters
  - Process Control Parameters
Design for Successful Systems (DFSS_о+DFR)

- In DFSS_о we use HOQ1-4
- In DFR we add HOQ5 & HOQ6
  - In **HOQ5** we list and prioritize Reliability Tests which address each Functional Requirement.
  - In **HOQ6** we list and prioritize Test Procedures which address each Reliability Test.
Evolution of Design for Successful Systems
(DFSS* + DFR + FAST/FMEA)

CUSTOMER REQUIREMENTS

FUNCTIONAL REQUIREMENTS

HOQ1

FUNCTIONAL REQUIREMENTS

DESIGN PARAMETERS

HOQ2

DESIGN PARAMETERS

MANUFACTURING PARAMETERS

HOQ3

MANUFACTURING PARAMETERS

PROCESS CONTROL PARAMETERS

HOQ4

RELIABILITY TESTS

FUNCTIONAL REQUIREMENTS

HOQ5

TEST PROCEDURES

RELIABILITY TESTS

FUNCTIONAL REQUIREMENTS

HOQ6

DFR

F.A.S.T. /FMEA

DFSS*
Use these matrices of DFSS for Designing the T&E (see next page)
Steps for Designing the Test and Evaluation*

Tools and Methods from DFSS that can help accomplish these steps are in parentheses:

- Develop the measures of effectiveness from the task capabilities and the measures of performance from the system attributes. (HOQ 1)
- Determine the operational factors and conditions. (HOQ 2)
- Develop linkages between measures and COIs. (CPM)
- Complete linkages from measure-to-system-to-task. (CPM)
- Assign one or more data sources to each evaluation measure. (HOQ 5)
- Determine the operational conditions that can or cannot be addressed by the identified data sources. (HOQ 2, CPM, and HOQ 5)
- Develop detailed measure design. (HOQ 6)
- Develop design of experiments. (HOQ 2, CPM, HOQ 5, HOQ 6)

* These steps are taken from Chris Wilcox’s MBT&E Tutorial (page 25) at NDIA T&E 2010.
DFSS Success Stories
Partial Listing of Who Has Used Our DFSS Process and Tools

- Xerox
- Gates Rubber Company
- Hyundai
- Timken
- GE Medical Systems
- Medtronic
- St. Jude Medical
- Sony
- John Deere
- Delphi
- Sensis
- Nokia
- Bose Corporation
- PerkinElmer
- Samsung
- ATMI
- Pollak Industries
- Sandia National Laboratory
- Abbott Laboratory Diagnostics
- GlaxoSmithKline
- General Dynamics Land Systems
GEMS LightSpeed™ CT Scanner

GE's First DFSS System ('98): Full Use of Six Sigma/DFSS Tools

- Key customer CTQs identified
  - Image quality
  - Speed
  - Software reliability
  - Patient comfort
- Disciplined systems approach: 90 system CTQs
- 33 Six Sigma (DMAIC) or DFSS projects/studies
- Scorecard-driven
- Part CTQs verified before systems integration

Leading-Edge Technology

- World's first 16-row CT detector
- Multi-slice data acquisition
- 64-bit RISC computer architecture
- Long-life Performix™ tube

Results

Better image quality
- Earlier, more reliable diagnoses
- New applications: vascular imaging, pulmonary embolism, multi-phase liver studies,…
- Much faster scanning:
  - Head: from 1 min to 19 sec (9 million/yr)
  - Chest/abdomen: from 3 min to 17 sec (4 million/yr)
- Clinical productivity up 50%
- 10x improvement in software reliability
- Patient comfort improved – shorter exam time
- Development time shortened by 2 years
- High market share; significant margin increase

"Biggest breakthrough in CT in a decade," Gary Glazer, Stanford
GE’s Six Sigma/DFSS Financial Benefits: ‘96 - ‘00

- Major impact on the bottom line
- Significant benefits from customer delight, including DFSS

Margin on revenue growth from customer delight, including DFSS products, ~ $1000M
Xerox has invented an environmentally friendly copy paper that costs less. The new cut-sheet “High-Yield Business Paper” requires half as many trees, fewer chemicals and less energy to manufacture and it weights less, reducing postage and trucking costs. Merilyn Dunn of InofTrends suggests the paper will be used for transactions such as invoices and phone bills where people don’t care about long-term archiving of documents. Xerox and others have tried to use cheap newsprint in copiers and laser printers in the past, but “you always had catastrophically bad results related to the curl in a digital printer,” said Steve Simpson, Xerox’s vice president in charge of paper and supplies. Bruce Katz, a paper technologist in Xerox’s research facility in Webster, said he was able to overcome the curling problem by figuring out how to make cellulose fibers in the paper line up evenly, so they would shrink at the same rate when the toner fusing process took place.

Note: Bruce Katz, a Xerox DFLSS GB, used the DesIgNNOVATION™ methods to accomplish this.
The Xerox Corp. designs, manufactures and markets iGen3, a color printer that can produce photo-quality prints at 110 pages per minute. When the current iGen3 was to be modified, the engineering team was tasked with redesigning the belt tensioning mechanism on the photoreceptor into a smaller package without adjusting the length of the belt. The redesign had to take several noise factors into account. The outcome of the project was a design that met the constraints placed on it by the system. This IDOV project is a practical example of how Design for Lean Six Sigma (DFLSS) can bring about the best option available in a constrained design.

Please see the referenced article for a detailed presentation of this case study.
Some Results From Other DFSS Studies

Accelerated Testing of a Proprietary Product
- Time to qualify process changes reduced from a year to 5 weeks – 860% test cost reduction
  - 5 years benefit of $48.5M based on accelerated placement of lower cost units

Regression Analysis to Predict Life of a Proprietary Product
- $2M ΔNPV Improvement
  - 24 hours to develop right material
- Overall length of project: 3 months (vs. 2 years using traditional approach)
  - Life expectancy improvement: over 4x!

Modeling to Reduce Development Costs and Improve TTM
- Matured the new design to last for >5 Million cycles in 6 months
- Demonstrated that following DFSS can accelerate Time to Market
- Established the importance that all QMS parts go through the DFSS process

Identifying Critical Parameters
- 25% cost reduction of part: $3M savings
- Leveraged the new accurate measuring process across product lines
  - Short term solution in two months, long term took a year

Supply Problem Resolution Using Simple Hypothesis Testing
- $2M immediate savings and saved the product from being withdrawn from field
  - Took just four months to resolve a problem that had lingered for 10 years
  - Gained control of infant mortality (i.e., failures within first 6 months)
Using DFSS to Improve Reliability Growth

**FEF = Fix Effectiveness Factor**

Historical data from reliability growth models indicates an overall average of .7  
(Source: Larry Crow’s RAMS 2011 presentation, page 68)

Using a DFSS FEF of at least .9, we can see that the number of iterations can be reduced substantially to achieve the same goal.

<table>
<thead>
<tr>
<th>Iteration</th>
<th>FEF = .7</th>
<th>FEF = .9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start</td>
<td>1,000,000</td>
<td>1,000,000</td>
</tr>
<tr>
<td>After 1st Iter.</td>
<td>300,000</td>
<td>100,000</td>
</tr>
<tr>
<td>After 2nd Iter.</td>
<td>90,000</td>
<td>10,000</td>
</tr>
<tr>
<td>After 3rd Iter.</td>
<td>27,000</td>
<td>1,000</td>
</tr>
<tr>
<td>After 4th Iter.</td>
<td>8,100</td>
<td>100</td>
</tr>
<tr>
<td>After 5th Iter.</td>
<td>2,430</td>
<td>10</td>
</tr>
<tr>
<td>After 6th Iter.</td>
<td>729</td>
<td>1</td>
</tr>
<tr>
<td>After 7th Iter.</td>
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<td>.1</td>
</tr>
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<td>After 8th Iter.</td>
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<td>.01</td>
</tr>
<tr>
<td>After 9th Iter.</td>
<td>20</td>
<td>.001</td>
</tr>
</tbody>
</table>
For More Information, Please Contact

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