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Application of Design of Experiments in Cost Estimating

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Outline

- Purpose
- Problem Statement
- Objective
- Application
- Design Of Experiments Overview
- Case Study
- Conclusion
- Acknowledgments

Purpose

- Create an awareness of Design of Experiments as another tool for the cost community

Problem Statement

- Background
  - Sheet count method to determine engineering efforts
  - Wide variance between bid and actual
- Supporting Data
  - Design labor hour estimates are low (on the average).
  - The standard deviation of bids ranged from 30-40%. This was the value that the project was being managed.
  - Across the product lines (7) in our division, the hours/sheet (and hours/ft^2) were a factor of 4 from largest to smallest.
    - Complexity is too variable to standardize process across product lines
- In addition to the above challenges, we still had to estimate sheets which is neither supportable nor a consistent process.

Objective

- Develop quick, accurate and reliable cost estimates
  - Simple process
  - Low level of training
  - Consistency
  - Audit trail
- This process will be used by:
  - Project Managers
    - For quick response during proposal efforts
  - Engineers
    - For making design decisions

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Application

- Establish a parametric cost estimating model for budgetary mechanical engineering estimating hours using DOE.

Design Of Experiments Overview

- Design Of Experiments (DOE) Definition
- DOE Process
- DOE Tools / Approaches
- DOE Tool Comparison
- Example Full Factorial Matrix
- DOE Statistical Analysis Overview

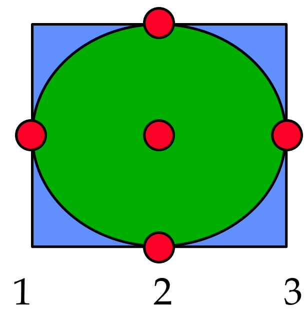
DOE Definition

- DOE organizes the collection of data to determine the most statistically confident relationship between inputs and outputs.
  - Complexity of the relationship is chosen by the user.
- Key terms
  - Variables, inputs, key cost drivers, factors
  - Response, output, results
  - Levels, settings, conditions, limits
  - Equation, relationship, algorithm
  - One Factor at a Time (OFAT)

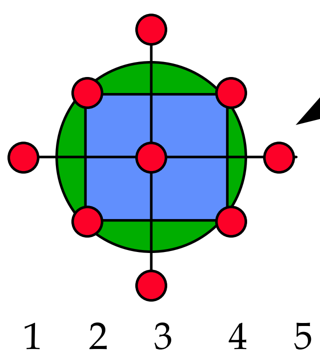
DOE Process

- Define goal - need
- Define response(s) to measure progress to goal
- List all variables and down select to “key” variables using experience
- Select appropriate design matrix - approach
- Select levels for variables
- Address tradeoffs between responses
- Perform test - simulation
- Analyze results
- Discuss next step

DOE Tools / Approaches



- Factorial Designs
  - Full (2^k form)
  - Fractional (2^{k-p} form)
  - Taguchi - maximum assumptions
- Advanced Designs (Response Surface Methods)
  - 3 level (<u>not</u> a 3^k form)
    - Box-Behnken, predictable to limits
  - 5 level (composite with factorial as a basis)
    - Central Composite Design (CCD), predictable in only a portion of limits
  - Optimization
    - Numerical
    - Graphical



Organizing the collection of data to determine the most statistically confident relationship

DOE Tool Comparison

OFAT or Taguchi typical output equation (main effects)

y = z + a*A + b*B + c*C

More information (fine tuning) is achieved as progress to more rigorous tools

Factorial typical output equation (main and interactions)

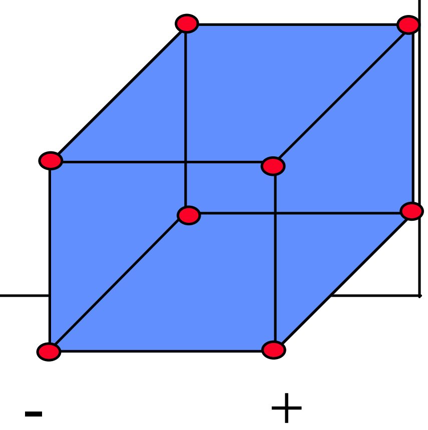
y = z + a*A + b*B + c*C + d*A*B + e*A*C + f*B*C + g*A*B*C

Response Surface typical output equation (main, interactions, quadratic)

$y = z + a*A + b*B + c*C + d[A]^2 + e[B]^2 + f[C]^2 + g[AB] + h[AC] + i[BC] + j[ABC] + p[A]^3 + q[B]^3 + r[C]^3 + s[A^2B] + t[AB^2] + u[A^2C] + v[AC^2] + w[B^2C] + x[BC^2]$

Example Full Factorial Matrix

Test #	Variable A	Variable B	Variable C	Output 1	Output 2	Output 3	Output 4
1	-	-	-				
2	+	-	-				
3	-	+	-				
4	+	+	-				
5	-	-	+				
6	+	-	+				
7	-	+	+				
8	+	+	+				



Predetermined, organized combinations
to provide resultant equation with reasonably
expected terms - 3 variables at 2 levels: 8 total tests (2^3)

DOE Statistical Analysis Overview

- Purpose is for the user to determine a statistically valid equation for the output
  - F-Test on model
  - R^2 curve fit assessment
  - Prob > |t| for all variable terms
  - t value (outlier t) of test runs
  - Residual Analysis

If these are acceptable to the user, the final equation is valid for predictive usage.

Case Study

- Project Goal
- Response (Output)
- DOE Process Steps
- Cost Driver Identification
- Manufacturing Complexity Case
- Labor Hour Case
- Next Step
- Validation Results
- Result Comparison

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Project Goal

- Perform accurate, consistent and reliable budgetary cost estimating hours in mechanical engineering department
- Utilize DOE as a tool to assist in this process

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Response (Output)

- Mechanical engineering labor hours consists of:
  - Layout and design
  - Analysis
  - Detailing
  - Data package

DOE Process Steps

- Identify cost drivers
- Select appropriate DOE matrix for two cases
  - Case 1. manufacturing complexity
  - Case 2. labor sensitivity analysis
- Collect historic data and identify limits for key cost drivers
- Run the PRICE H model for the established test combinations to obtain the output
- Perform statistical analysis on DOE software

Assumes a calibrated PRICE H model

Cost Driver Identification

- Labor hours
  - Weight, manufacturing complexity, % of new design, design repeat, platform (level of specification), design effort, and engineering experience
  - Manufacturing complexity
  - # of parts, precision, assembly difficulty, process and material type, and platform
- This led to a two-tiered DOE approach
  - One DOE matrix for manufacturing complexity
  - One DOE matrix for labor hours

Manufacturing Complexity Case

- Manufacturing Complexity DOE
- Assembly Difficulty
- Manufacturing Complexity Chart

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Manufacturing Complexity DOE

Cost Driver	Low	Most Likely	High
# of parts	10	45	80
precision	.001	.050	.100
assembly difficulty*	A	B	C
machine / material	titanium	steel	aluminum
platform	com. ground	military ground	air / ground

Incorporate into CCD tool. Has 27 combinations versus the 3125 possible (5^5).

* defined on next page

Precision and assembly difficulty dominate. These replace the complexity term in the labor equation if complexity is significant.

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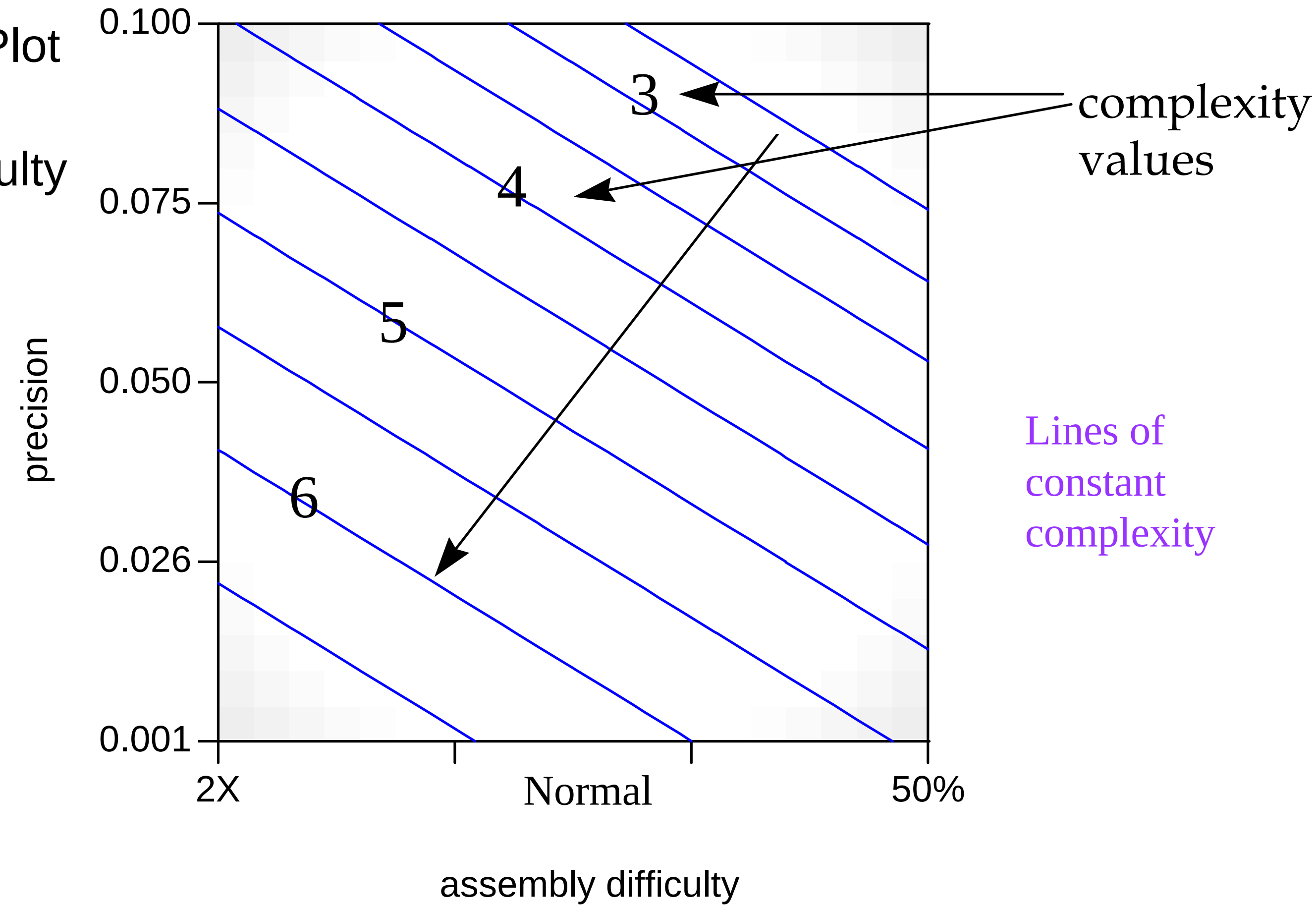
Assembly Difficulty

- A: Assembly tolerance 2 times tougher than part tolerance
- B: Assembly tolerance same as part tolerance, most commonly used
- C: Assembly tolerance 50% less than part tolerance
  - As defined in PRICE-H

Manufacturing Complexity Chart

DESIGN EXPERT Plot

Actual Factors:
X = assembly difficulty
Y = precision



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Labor Hour Case

- Labor Hour DOE
- Design Effort
- Labor Hour DOE Findings
- Response Surface of Labor Hours

Labor Hour DOE

Cost Driver	Low	Most Likely	High
weight	50	525	1000
mfg cplx	4	5	6
% new des	10%	45%	80%
design rep	0%	45%	90%
platform	1.0	1.3	1.6
design effort*	A	B	C
eng exp	extensive	normal	many new

Incorporate into Box-Behnken tool. Has 57 combinations versus 2187 possible (3^7).

* defined on next page

All important - quadratic terms and interactions exist

Design Effort

- A - extensive mod to existing design
- B - new design within established product line: existing state of the art
- C - new design different from established product line: must develop new technology or material
  - As defined in PRICE-H

Labor Hour DOE Findings

- All variables (cost drivers) are statistically significant
- Labor Hours = f(Weight^2, New design^2, Design effort^2)
- Weight interacts (has synergy) with
  - All cost drivers except engineering experience
- Manufacturing complexity interacts (has synergy) with
  - New design, design repeat, platform and design effort
- New design interacts (has synergy) with
  - Design repeat, platform and design effort

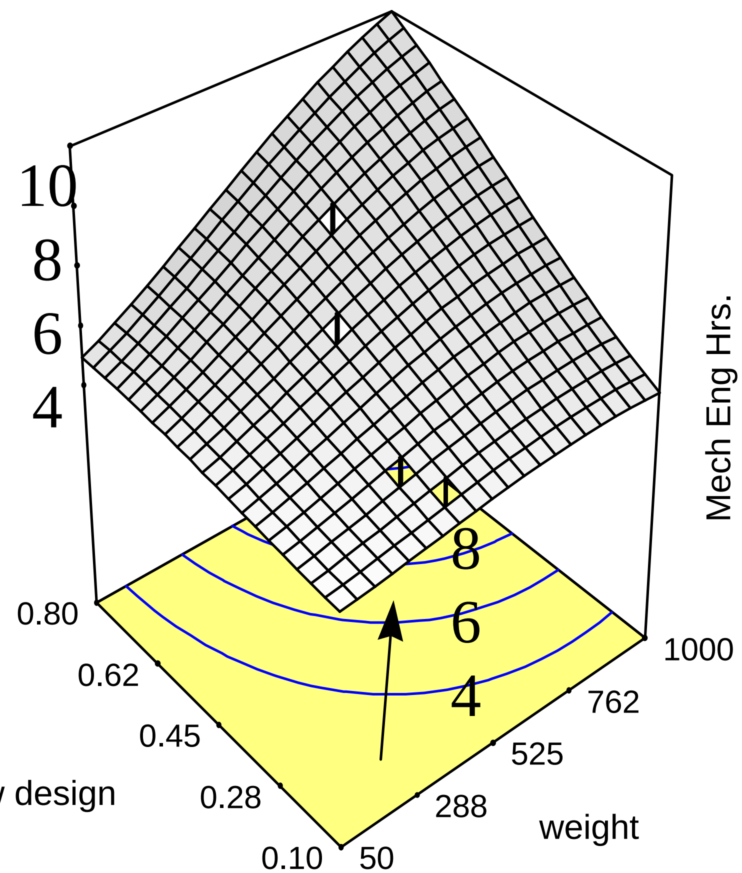
Together these items create
the final equation for hours.

Response Surface of Labor Hours

DESIGN EXPERT Plot

Actual Factors:
X = weight
Y = % new design

Actual Constants:
mfg cmplx = 5.0
design repeat = 0.45
platform = 1.3
design eff = 3.5
eng exper = 0



3D and 2D view shown on same chart

Proprietary data removed.

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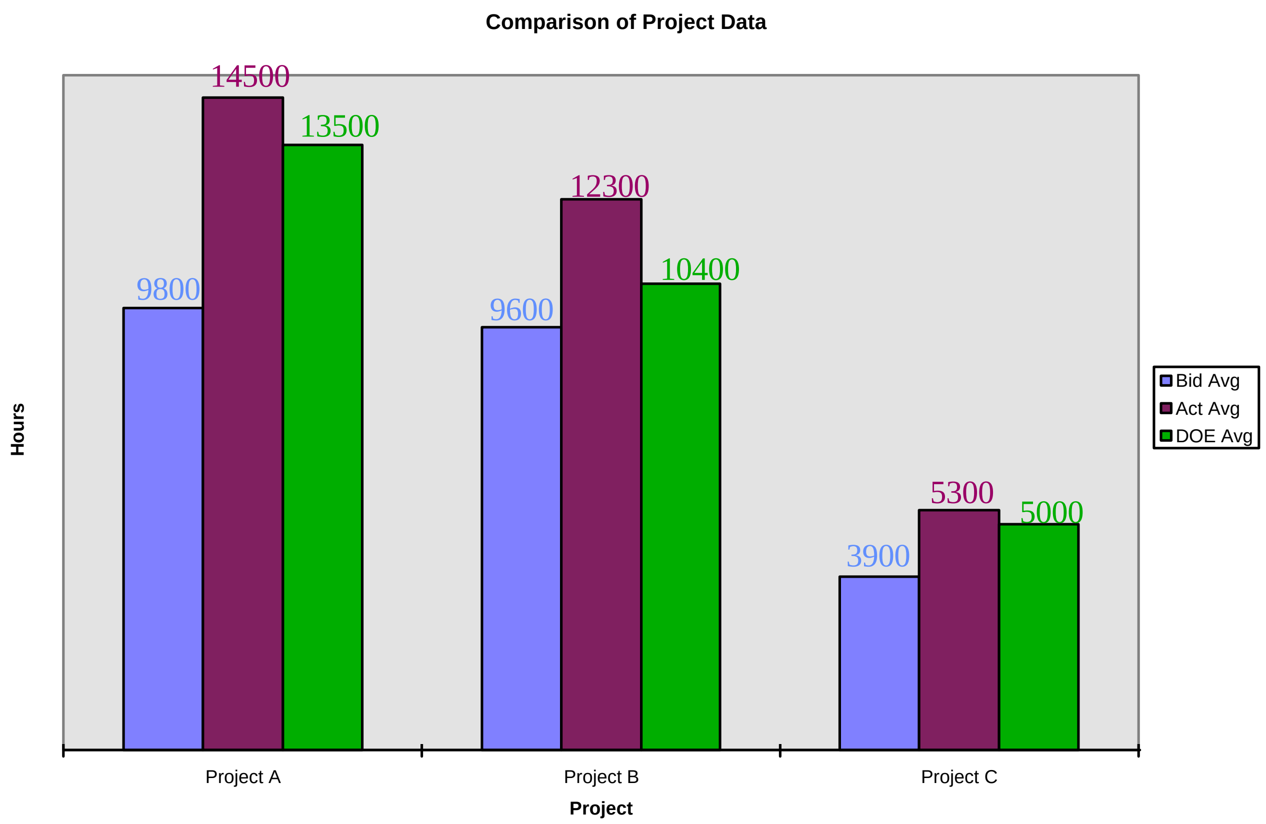
Next Step

- The final equations are statistically valid.
- Create instructions to clearly define the process
- Validate DOE model with actual project data
  - Compare with PRICE H as a sanity check

Validation Results

- The DOE model followed the PRICE H runs (design and drafting hours) within a reasonable percentage (roughly 4%)
- Thus far, the DOE model follows the actual data rather well. When combining several estimates together, the comparison to actual was very close (within 7%).
- The standard deviation for the DOE model versus actuals is similar to the sheet count method.
- The validation effort is still in process.

Result Comparison



Project B has very small sample size

Conclusion

- Initial results show methodology works well after comparing to actuals from a few projects
- Will be folded into a larger mechanical engineering cost estimating process
- DOE analysis will be repeated periodically. This will update for the full PRICE H model calibrations.
- DOE is an applicable tool and is available for use.

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Acknowledgments

- PRICE-H user manual
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