Reflections on Statistical Engineering and Its Application

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Outline

• Overview of Statistical Engineering
• Initial Thoughts on “Building Blocks”
• Initial Thoughts on “Statistical Engineering Principles”
• NASA Example
• Impact on the DoD, NASA, and the National Labs
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Overview of Statistical Engineering

- Future focus: Large, unstructured, complex problems!
- Solutions require collaboration among high profile interdisciplinary teams!
- Problems cut across the organization
Overview of Statistical Engineering

• Building upon Six Sigma
  • Good strategic structure
  • Need for something tactical in between
  • How do we deploy our tools?
• Success requires new tools and mindset
• Need to ask how we can generalize solution tactics to solve future problems
Overview of Statistical Engineering

• One pathway: Statistical Engineering
• Goal: Develop appropriate theory
  • to apply known statistical principles and tools
  • to solve high impact problems
  • for the benefit of humanity.
• Minimize “one-off” solutions
Overview of Statistical Engineering

• The heart of Statistical Engineering is the scientific method.

• Most theories underlying statistical engineering involve strategic application of the scientific method.
  • Deming-Shewhart PDCA (Plan, Do, Check, Act)
  • DMAIC (Define, Measure, Analyze, Improve, Control)
Initial Thoughts on the Building Blocks

• The Scientific Method Is a Fundamental Approach for Discovery and Problem Solving
• Statistical Thinking Is Essential Developing Solutions
• Success Requires Teams that Function Well
  • Subject Matter Expertise
  • Statistical/Analytical Expertise
• “All Models Are Wrong; Some Are Useful”
Initial Thoughts on the Building Blocks

- Probability is the basic language for quantifying uncertainty.
- All probability statements are subjective, depending on critical assumptions (beliefs!).
- Statistical methods must be as robust as possible to assumptions and models.
- Other people must be able to duplicate results.
SE Principle 1

• Proper Data Collection, Analysis, and Interpretation Are Essential for the Scientific Method
  • Dependence on the proper question of interest
  • Impact of restrictions on data collection
  • Proper consideration of constraints on factors/ regressors
  • Must avoid error of the third kind!
  • In early phases, data include expert opinion.
SE Principle 2

• All Data Collection, Especially Experimentation, Must Be Sequential
  • Iterative procedure
    • Adaptive
    • Able to mitigate problems
  • Each phase targets different questions
  • Final Phase: Data must dominate opinion to extent possible.
SE Principle 3

• All Data Collection Must Recognize Sources of Variability
  • Local control of error (blocking, co-variates)
  • Basis to minimize biases, understand true precision
  • Understanding sources necessary for variation reduction
  • More complicated the problem, the more sources of variability!
SE Principle 4

• Approximate Models that Include Uncertainty Are Fundamental to Analysis
  • At least two sources of error:
    • Model: over- or under-specified; linear or non-linear
    • Background noise – Often combination of several sources!
  • Important to understand error propagation, especially as the system becomes more complex
SE Principle 5

• Analyses Require Clear Statements about All Modeling Assumptions
  • Essential for other researchers to duplicate
  • States and justifies the beliefs of the research team
    • Subject matter experts
    • Analysis
  • Essential for both Bayesian and Frequentist Analysis!
SE Principle 6

• All Analyses Require the Proper Use of Data to Assess Assumptions
  • Residual analysis typically essential
    • Raw residuals never appropriate!
    • Must standardize as closely as possible to appropriate distribution
    • Translate residual to subject matter language/understanding
  • Reserve data for model validation/confirmation
SE Principle 7

• Difference between Data Cleansing and Data Manipulation
  • Data cleansing: Identifying and correcting bad data
  • Data manipulation: throwing away data not consistent with assumed model (original beliefs of the research team)
  • Outliers often are the most interesting data points!
  • Cannot discard data without proper assignable cause!
SE Principle 8

• Analyses Must Take into Proper Account the Sources of Variability
  • Informal: Database records for check “interesting” cases
  • Formal:
    • Blocking
    • Variance component estimation
    • Including covariates in formal model
SE Principle 9

• Complex Systems of Systems
  • Require combination of subject matter expert first principles/physics and statistical/empirical models
  • Outputs from subsystems become inputs to assemblies
  • Proper propagation of error models essential
  • Empirical confirmation of models
    • Generally easier at the simplest subsystems
    • Often, limited opportunities for complex assemblies
SE Principle 9 - Continued

• Belief Networks Can Provide Basis to Combine Information from Subsystems into Assemblies
  • Combination of subject matter opinion and frequentist model outputs
  • Formal Bayesian with strong prior distributions
  • Require clearly stated and vetted assumptions
  • Empirical confirmation highly desired but impossible in certain cases
  • Common limitation: focus on probability of an event (0/1 data)
SE Principle 10

• Interactions Often Are More Important than Main Effects
  • Operational-Developmental Testing
  • Insights from Robust Parameter Design
    • System robustness to environmental conditions
    • Proper mitigation strategies for operating system
NASA Example - COPVs

• Relatively Small Statistical Engineering Project
• Overarching Question of Interest: Reliability of COPVs at Use Conditions for Expected Life of Mission
• Issues:
  • Many different types of COPVs used in spacecraft
  • Vessel tests are very expensive: money and time
• NASA Engineering Safety Center (NESC) Project
COPVs

• The Core NESC Analytics Team:
  • Reliability Engineers:
    • JPL
    • Langley Research Center
    • Glenn Research Center
  • Statisticians:
    • Marshall Space Flight Center
    • Virginia Tech
COPVs

- NASA Team’s Approach: Focus on Strands Used to Wrap Vessels
  - Less expensive
  - Can have many more experimental units than for vessels
- Still Issue with Time to Test
- Problem: How Do Strands Predict Vessel Behavior?
COPVs

• Initial Study: Previous Strand and Vessel Tests
  • Relevant strand study conducted at a national lab:
    • 57 strands at high loads for 10 years
    • Net information learned: Strands either fail very early or last more than 10 years
  • Vessel studies:
    • Also 10 years
    • Weibull model parameters seem similar to strand studies
COPVs

- Team’s Initial Concept
  - Much larger study
  - Censor very early
    - Reduces time
    - Allows the larger study in a practical amount of time
- Proceed in phases
- Have detailed data records to track any problems
COPVs

• Phase A: Conducted During Shake-Out of Equipment
  • Small study (although bigger than the national lab study!)
  • Statistical goal: Determine if the parameters from the national lab study are valid as the basis for planning the larger study!
  • Note: Phase A gave the team an opportunity to re-plan the larger experiment, if necessary!
COPVs

• Phase B: “Gold Standard” Experiment
  • Planned time required: 1 year
  • Used 4 “blocks” of equal numbers of strands
    • Allowed the team to correct for time effects
    • Allowed the team to mitigate problems, especially early
  • Study assumed the “classic” Weibull model
  • Size of the experiment assured ability to assess model
COPVs

• Total Size of the Database: Huge
  • Kept data from start of specific strand test to failure on the second
  • Kept the last 2 minutes at the .01 second from buffer
  • Buffer allowed team to investigate unusual phenomena at failure
  • Essential for proper data cleansing
COPVs

- Parallel Vessel Study
  - Reasonably large ISS study targeted to end early (< 10 yrs)
  - Opportunity to step up loads to mimic strands
  - Censored but longer censor time than strands
COPVs

• Results to Date:
  • Phase A: Surprisingly similar to national lab study
  • Phase B:
    • Serious problem occurred with the gripping in the first block
    • Serious conversations with possibility of replacing!
    • Other three blocks well behaved and by themselves produced better than the planned precision for the estimates
    • Residual analysis confirmed the Weibull model
Why is COPVs Statistical Engineering?

- Application of Scientific Method to a Complex Problem
- Sequential Data Collection/Experimentation
- Each Phase Targeted Different Questions
- Clearly Documented Assumptions, Assessed via Data
- Took Proper Steps to Cleanse Data
- Real Research Question Involves System of Systems
SE Impact for DoD, NASA, Labs

• Large, Unstructured, Complex Problems Everywhere!
• Can No Longer Afford “One-Off” Solutions
• Time/Resource Restraints Demand Effective Tactical Approaches for Problem Solutions
  • Issue has not been a lack of tools
  • Issue has been how to deploy these tools!
  • Major overlap with standards of practice for data analysis
SE Impact for DoD, NASA, Labs

HELLO STATISTICAL ENGINEERING!