Design of Experiments
The Science of Test

The Tooth Fairy in Experimental Design: Lying to Our Software

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Mr. Gregory Hutto is Wing Operations Analyst for the 96th Test Wing, responsible for embedding designed experiments as the principal test method for several hundred tests each year. He teaches an extensive series of short courses in test methods to all testers in the Wing from the Wing Commander to our 520 scientists and engineers. As a LtCol in the USAF Reserves, he served as senior military advisor to AF Operational Test & Evaluation Center Test Support Director and as special advisor for test design to the AF Flight Test Center commander at Edwards AFB, California. Mr. Hutto is a distinguished graduate of the US Naval Academy in Operations Research and holds a Master’s in the same field from Stanford University. Over the past 41 years, he has served in nearly every branch of test and evaluation from laboratory basic science to joint operational field testing. He would like to publicly repent of his 11 years of testing without the benefits of the principles of well-designed experiments.

He is proud of his two children who make their livings in the sky – one serves martinis; the other mayhem. Ariel is a Delta Flight Attendant and Daniel is a F-15E Strike Eagle WSO - bomb/nav. He is inordinately proud of his highly educated wife, Dr. Deb, with 6 degrees.
Abstract

Many of us told our children about the mythical Tooth Fairy when they were young, to add a little enchantment and mystique to childhood. Similarly, we don’t always tell our software the whole truth. This talk will feature three examples making use of Design Expert’s comprehensive design-building facilities to build the desired design while not revealing everything to DX. **Case 1 -- Aircraft Single Engine Climb** replaces numeric variables with categoric in the build to achieve an even spread of values in the design. Once built, we switch the variables back to numeric. **Case 2 -- Bomb Envelope** builds a comprehensive design piecemeal – two overlapping constrained optimal designs are built, then combined into a single candidate set from which the final design is built … with one more twist. **Case 3 explores a new design class Sensor Cross-blocks** – a replicated geometric full-factorial crossed with easy to change modal variables to achieve a split-plot-like structure with good modeling properties.
But … There Really is a Tooth Fairy!

…there is a veil covering the unseen world which not the strongest man…could tear apart. Only faith…can push aside that curtain and view … the supernal beauty and glory beyond. Is it all real? Ah, VIRGINIA, in all this world there is nothing else real and abiding.

No Santa Claus! Thank God! he lives, and he lives forever. A thousand years from now, Virginia, nay, ten times ten thousand years from now, he will continue to make glad the heart of childhood.*

- I make a tradition of reading this beautiful piece of prose every Christmas … join me?

* https://www.newseum.org/exhibits/online/yes-virginia-there-is-a-santa-claus/
Eglin AFB Florida – Weapons, Spec Ops, Fighters & Joint Ops

We’re recruiting great experimentalists … or at least enthusiastic ones!
AF Ops Research Recognized

US Air Force awarded the 2017 Institute for Operations Research and the Management Sciences (INFORMS) Prize for Operations Research

The INFORMS Prize honors effective integration of advanced analytics and operations research/management sciences (OR/MS) into organizational decision making. The award is given to organizations that have repeatedly applied the principles of OR/MS in pioneering, varied, novel, and lasting ways. Past recipients of the award include General Motors, Intel, UPS, HP, IBM, Ford, Procter & Gamble, and GE Research.
It All Started with Beer!

- Gosset – Dublin Guinness Brewery circa 1899-1908
- Brewing stouter porter, stout, or Guinness
- Guinness decided to make brewing scientific
- Formed Experimental Brewery and Gosset as Brewer-in-Charge
- Needed better hops and barley, small samples and much variation
- Gosset, a chemist -- self-taught and worked for Karl Pearson in statistics
- Paper on *Probable Error of A Mean* forms the basis for our statistical t tests
- Temperature, robust hops, and Archer breed of barley - - plus experimentation key in Guiness findings!
Case 1 Aircraft Single Engine Climb

Source: https://www.ww2online.org/image/b-25-bomber-attacking-axis-forces-italy
Description: Twin Engine Single Engine Climb

- When taking off - safety calls for ability to minimally climb with single engine ~150 feet per minute (fpm)
- Return to land from pattern altitude
- A number of factors – gross weight and air density -- impact this mission planning check

*B-25 was not our test aircraft but it is twin engine...*
Input Process Output
Single Engine Climb

INPUTS
(Factors)
 Pressure Altitude
 Aircraft Weight
 Gear Setting
 Flaps
 Temperature

OUTPUTS
(Responses)
 Process:

weather, training, pilot

Noise

Climb versus Chart

B-25 – an Eglin favorite – the steed Doolittle’s Raiders rode to bomb Tokyo 14 Apr ’42. Col Dick Cole died 9 Apr 21 @ 103 – Last Raider
The White Lie I

- Gross weight is primarily \( f(\text{fuel}) \)
  - Cannot ever be 0 or 100%
  - Mostly in *between* extremes
  - Factorials *love* edges and corners
- Options – optimal polynomial, discrete
- Hit on building numeric gross weight as categoric for balanced number of interior levels
The White Lie II

- Inconvenient physics – temperature lapse rate 3 deg / 1000 feet
- Correlates density altitude
- Multiple (10+) attempts to generate balanced, constrained optimal design
- Pay attention to VIF for Temp X Altitude interaction
- Augment 4-8 points **Design Tools>Augment>Optimal** with Temp, Alt, TxA interaction
White Lie III

- Flaps can be at any degrees from 0 to 30; practically – only one or the other
- Gear is either up or down
- Treated as numeric, discrete, categoric
Final Design – Rube Goldberg

- Must have built 20 optimal designs
- Built & defaced Face Centered CCD
  1. Manually adjusted temperature & altitude
  2. Manually moved center point values of gear & flaps to edges
  3. Accept multiple gross weight & temperature settings as set point errors
  4. Adjust unsafe combos
- Comparison not bad – knew AB was a problem
As executed – God has a sense of humor – all afternoons CNX
Final Design As Executed

Unsafe test points

- Gross weight
- Flaps
- Down
- GearDown
- Up
- Delta Fg
- Temp C
- Pr Alt
- Gross weight
- Flaps
- GearDown

Less
Safe
Safe

0 difference
Case 2: Building an uber-design from constrained sub-designs – A Franken-design!

Team: Mike Huffman, Greg Hutto, Teresa Dailey, Blake Zessin, Francisco Ortiz, Dave Harmon, Nathan Selling
Case 2: Bomb Flight Test Matrix

Test Objective:
- Four groups designing bomb drops
- Contractor has 6-7 shots; Agency 9-11, Air Force has approx 19 shots
- Task 1 – convince partners to conduct Integrated Test
- Task 2 – how to plan a robust program in face of likely budget cuts

DOE Approach:
- Partner with Designers to select conditions
- Exploit likely behavior based on similar technologies
- Create menu of 8 different designs, each with pros and cons
- Objectively grade each; present Program Office with recommendations

Result:
- Initial Design: N=19; 27% Mgt Reserve
## Basic Report Card - Designed Experiments

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Design Approach for fast-running Physics model

• Used simulation to evaluate 58 system variables
• Spanned spec range for “noise variables” (cannot control in flight)
• Designed 6-8 run sets over ranges of control/noise variables
Input Process Output Bomb Drop

**INPUTS (Factors)**
- Pressure Altitude
- Velocity
- Climb-Dive Angle
- Range
- XYZ+V Errors from Aircraft
- Aircraft Type
- Cross-Range
- Down-Range

**OUTPUTS (Responses)**
- Miss distance - aimpoint
- Noise

**PROCESS:**
- wind, aircraft, pilot

NOT the actual bomb under test here…
Traditional Designs Don’t Fit Our Constrained Envelopes

We need a level (outer) and loft (inner) magenta LAR design … and OBTW – don’t really want many lofts in 26 point design
White Lie I – Just build this one set

- Clever Trick 1: use a well-schooled candidate set
- Design Expert supports linear constraints & disallowed combos via “Candidate Sets”
  - Ensure variables are common (different ranges)
  - Build *large Level* design (optimal quartic) in DX ~250
  - Build *large Loft* design (optimal quartic) in DX ~250
- Combine two design sets - points obey *all* constraints
  - Construct I-optimal designs from this merged candidate set
White Lie II – I’ll want 4 blocks, please

- Clever Trick 2 – only get 26ish shots
  - Want only a “few” lofts but more than a 1 or 2 demo
  - => solution “block” design in 4 blocks for N=36
  - => Block is _ design -> discard loft runs in blocks 3 & 4
- Loft model mostly orthogonal to blocks so metrics don’t suffer much
White Lie III – I’ll want all 26 points, please

- Clever Trick 3 -- Want mulligans (do-overs) at end
- Sort by leverage - last runs 22+? can be mulligans
- Construct full set by augmentation
  - Build runs 1-8 for Main Effects model
  - Augment runs 9-19 for likely 2FI (we peeked) + quads
- So - by run 21, likely model is well-supported
  - Therefore 22, 23, 24, 25, 26 can either support model or replace earlier failures
Displaying only 3 of 7 dimensions – our build in blues
Case 3 Sensor Cross-Blocks Design
1. Estimating target lat/long error is a frequent, DOD-wide problem
2. The target battlespace is large, with many variables
3. The response variable is skew with increasing variance
4. We have restrictions on randomizing execution order (no transporter) ...
Complications – response distribution changes with geometry

- Coordinate error increases as slant range (radius) squared
- At low graze angle long slant range errors more skew
There are at least $3^4 * 2^3 = 648$ unique points … so a fractional design is essential
Which Coordinate System Shall We Use?

- Cartesian or Polar?
- In any case we must traverse space (alt+range)
Which Coordinate System Shall We Use?

- Cartesian or Polar?
- Collinearity in polar coordinates argues no...
Any issues? Fractional “holes” make us look dumb...

“Ummmm ... pilot take next two then skip 1 then skip 3 then...”
White Lies I & II - replicated geo factorial & the blocked modal factorial are separate.

- Build sequential geometric design & replicates (96)
- Build convenient block size of modal variables
- Rotate or cross the blocks across the geo design
Cross-Block Design

- Left side 3 replicates of a full geometric design (N=32 each)
- Right columns are $2^4$ modal variables in four convenient blocks
- Use Latin Square pattern to cross blocks with geometric replicates
- 1234 2341 3412 4123...
- Change block generators for next replicate

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<th>A-Depression</th>
<th>B-Slant Range</th>
<th>C-Direction</th>
<th>Direction</th>
<th>D-Side</th>
<th>E-Angle</th>
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Diagram of Cross-Block Design:

- Left side 3 replicates of a full geometric design (N=32 each)
- Right columns are $2^4$ modal variables in four convenient blocks
- Use Latin Square pattern to cross blocks with geometric replicates
- 1234 2341 3412 4123...
- Change block generators for next replicate
Cross-Block Design Typical Evaluation

- Mild VIF inflation
- Mild 2FI and RSM covariances
- Flown these since circa 2018 – a dozen times
- Models confirm and cross validate nicely
Tooth Fairies – Not All Bad

The physical world of flight test offers endless challenges to our creativity… DX a great partner tool

Source: https://www.washingtonian.com/2013/04/05/first-person-dont-take-my-tooth/
The White Lie(s) We Tell Our Software

Experiment with your experiment!

- Classical designs already variance optimal ... check one first before going optimal. And they can take a beating...
- Candidate sets can hold several constraints at once – great lumber!
- Don’t forget ... a design block is a nearly-orthogonal fraction
- If physical circumstances force a design order remember split plot rules*
- Take the design God gives you and roll blocks across it

* Replicate whole plots as much as you can stand and a little more!

“To call in the statistician after the experiment is . . . asking him to perform a postmortem examination: he may be able to say what the experiment died of.”

Address to Indian Statistical Congress, 1938.

DOE Founder Sir Ronald A. Fisher
White Lies We Tell Our Software

Questions?

Source: https://www.christianfaithatwork.com/ashamed-jesus/