ESD.33 -- Systems Engineering

Operating Windows for Robust Concept Design (and other advanced topics in Robust Design)

Dan Frey

Plan for the Session

- From last time: a new research result
- Operating window methods
- Concept design strategies
  - Relax a constraint limit …
  - Use physics of incipient failure to avoid failure
  - Create two distinct operating modes …
  - Exploit interdependence …
- Adaptive OFAT for robust design
- Noise strategy

More Observations of Industry

- Time for design (concept to market) is going down
- Fewer physical experiments are being conducted
- Greater reliance on computation / CAE
- Poor answers in computer modeling are common
  - Right model → Inaccurate answer
  - Right model → No answer whatsoever
  - Not-so right model → Inaccurate answer
    - Unmodeled effects
    - Bugs in coding the model

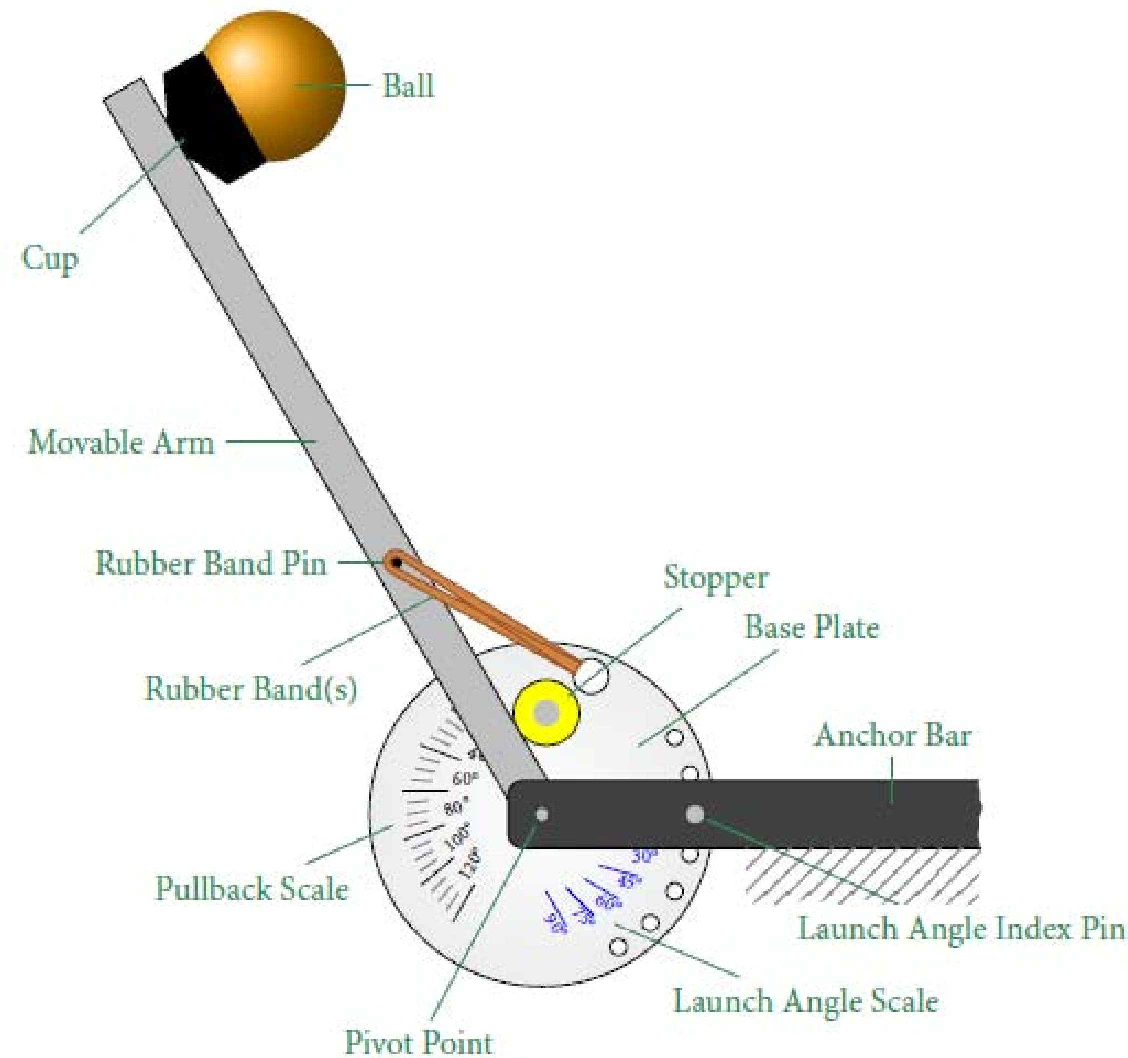
Human Subjects Experiment

- Hypothesis: Engineers using a flawed$_S$ imulation are more likely to detect the flaw while using OFAT than while using a more complex design.

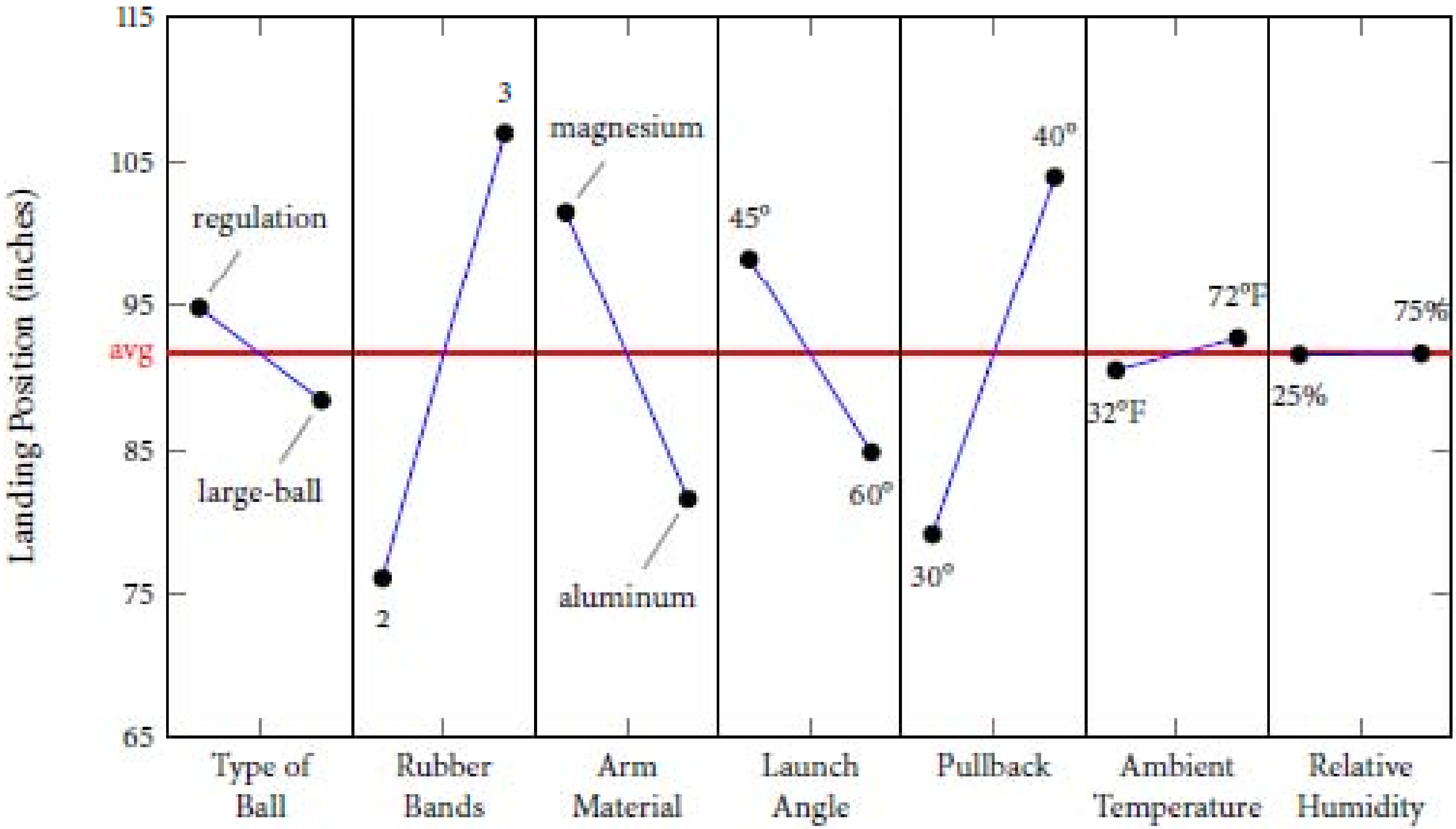
- Method: Between-subjects experiment with human subjects (engineers) performing parameter design with OFAT vs. designed experiment.

Savoie, Troy B., 2010, Human detection of computer simulation mistakes in engineering experiments," PhD thesis, Massachusetts Institute of Technology.

Device Used as the Topic of Consideration in the Experiment



Factors and their Experimentally Determined Effects

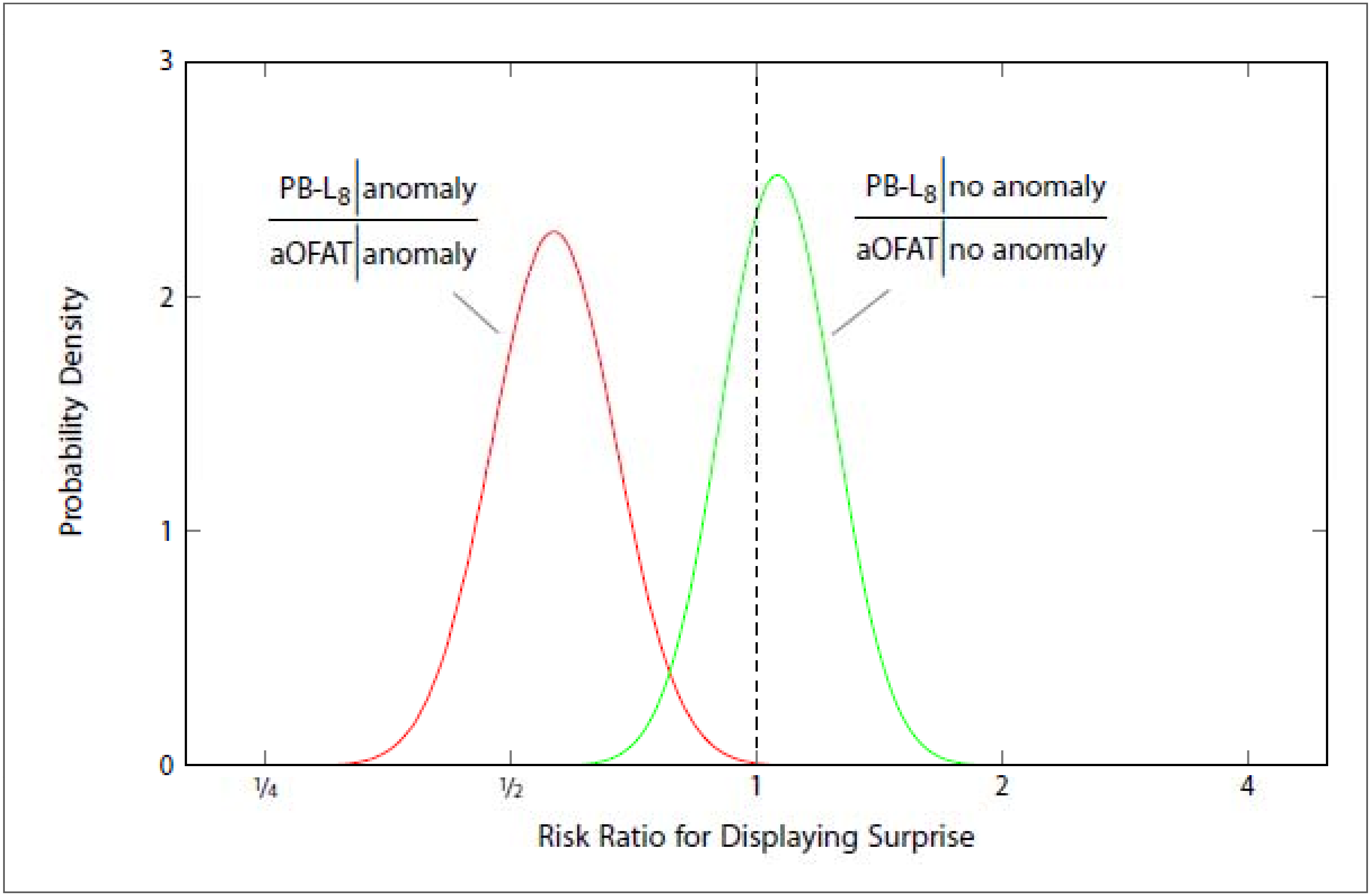


Results of Human Subjects Experiment

- Pilot with N = 8
- Study with N = 55 (1 withdrawal)
- External validity high
  - 50 full time engineers and 5 engineering students
  - experience ranged from 6 mo. to 40+ yr.
- Outcome measured by subject debriefing at end

Method	Detected	Not detected	Detection Rate (95% CI)
OFAT	14	13	(0.3195,0.7133)
PBL8	1	26	(0.0009,0.1897)

Registering Surprise



Preliminary Conclusions from this Investigation

- Computer simulations are an increasingly critical part of Systems Engineering
- As confident as you may be in your models, they probably still have mistakes in them
- Simplification of your search strategy will make you more capable of perceiving errors in computer simulations

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Reliability and Systems Engineering

- Reliability is among the most important topics in systems engineering
- Reliability is the proper functioning of the system under the full range of conditions experienced in the field
- Reliability requires robustness

Definitions of Reliability

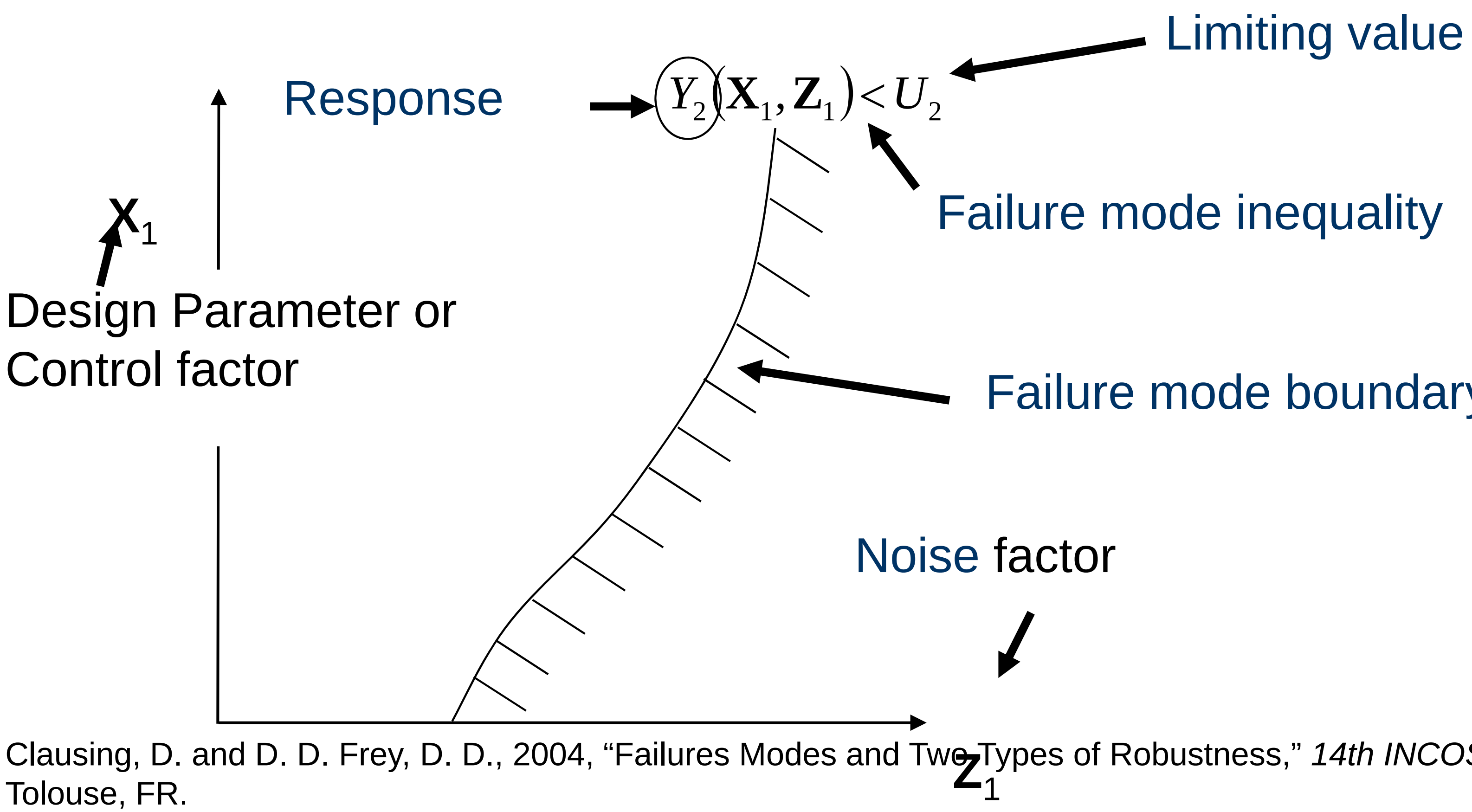
- In its traditional formulation reliability is stated as the probability of failure under specified operating conditions
- Here, we explore a conception of reliability as **failure-mode avoidance**

Advantages of this Conception

- Rooted in the physics of the failure
- More appropriate to early stages of SE
- An enhancement to creativity
- Requires less information

One-sided Failure Modes

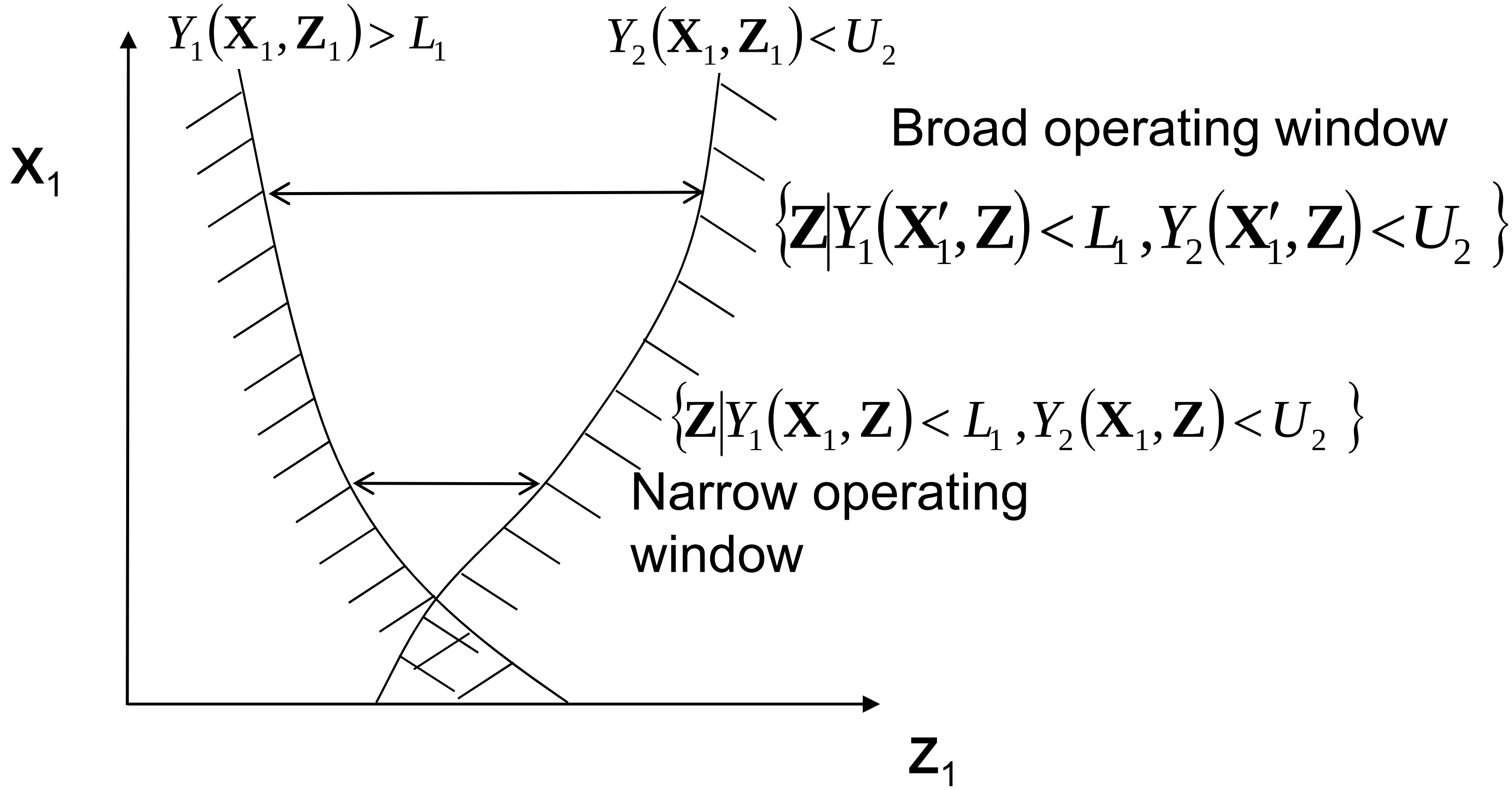
- The failure occurs at only one end of a noise factor's range



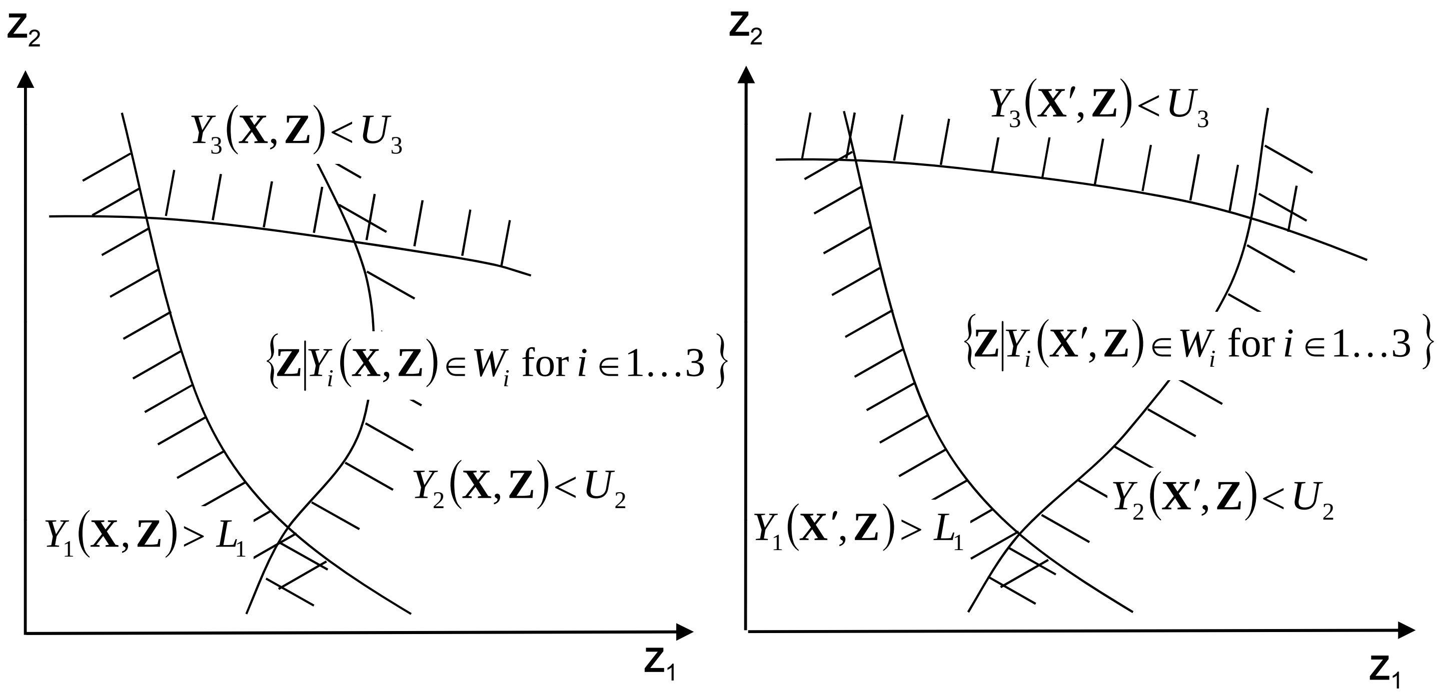
Clausing, D. and D. D. Frey, D. D., 2004, "Failures Modes and Two Types of Robustness," *14th INCOSE Symposium,* Tolouse, FR.

Operating Windows

- Operating window = the range of noise factors satisfying all failure mode criteria



Concept Design



- A conceptual design change can create a larger operating window

A Theorem

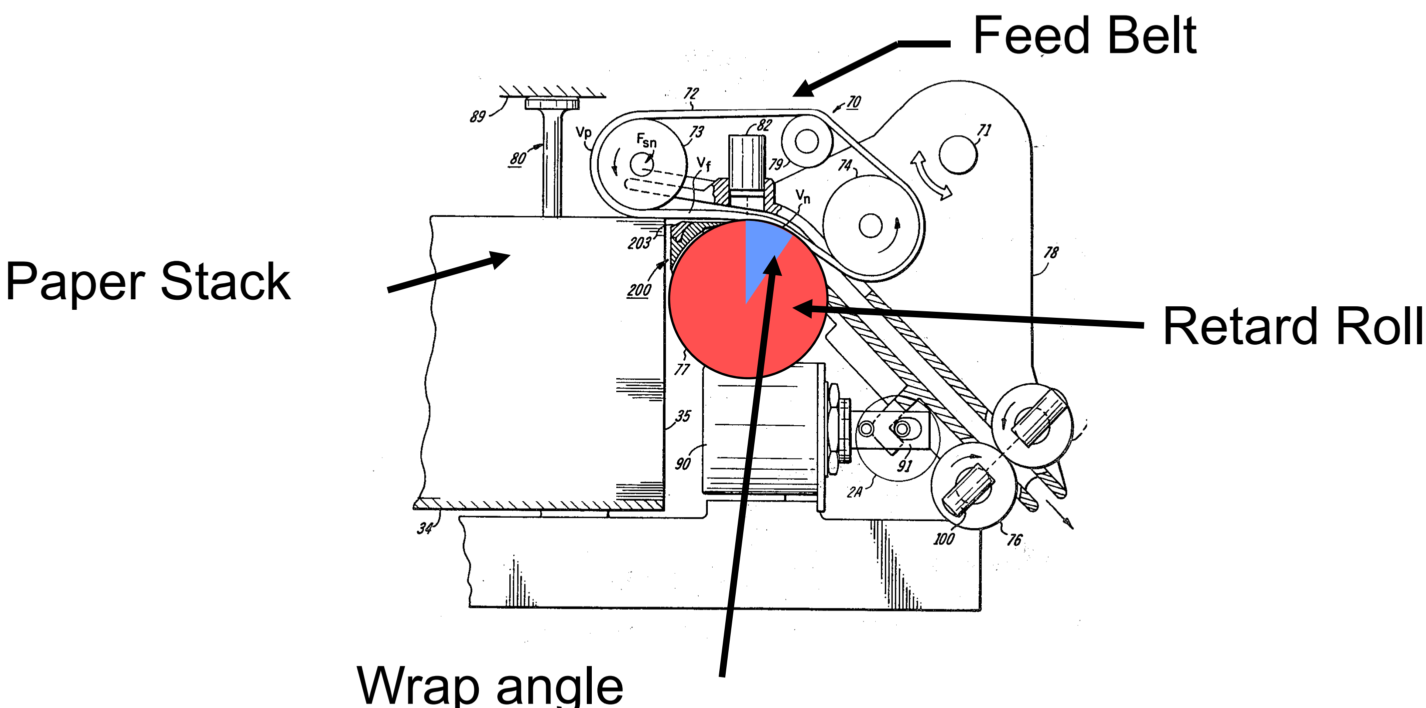
Operating Windows and Conceptual Design -- If the conceptual design of a system is changed including a change in functional responses Y_i to Y_i' and corresponding design parameter changes from $\mathbf{X}$ to $\mathbf{X}'$ and the new operating window holds the old operating window as a subset $\{\mathbf{Z} | Y_i(\mathbf{X}, \mathbf{Z}) \in W_i \text{ for all } i\} \in \{\mathbf{Z} | Y_i'(\mathbf{X}', \mathbf{Z}) \in W_i \text{ for all } i\}$, then reliability has improved.

- Reliability improved regardless of probability distribution

Relax a Constraint Limit on an Uncoupled Control Factor

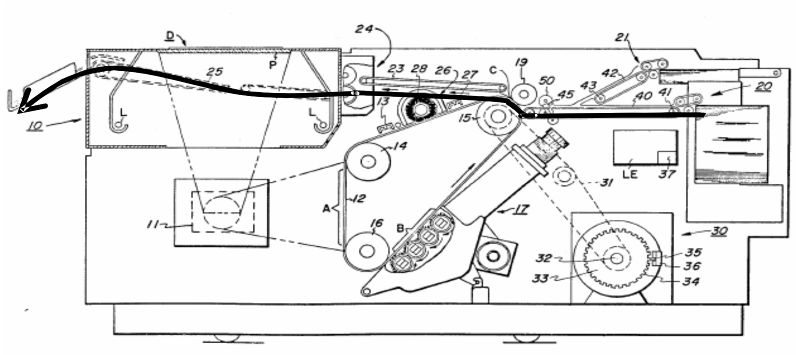
- When a system variable only affects one of the …failure modes, take its value to its constraint limit… seek new architectures or technologies that relax the constraint.

Primary Example of the Strategy

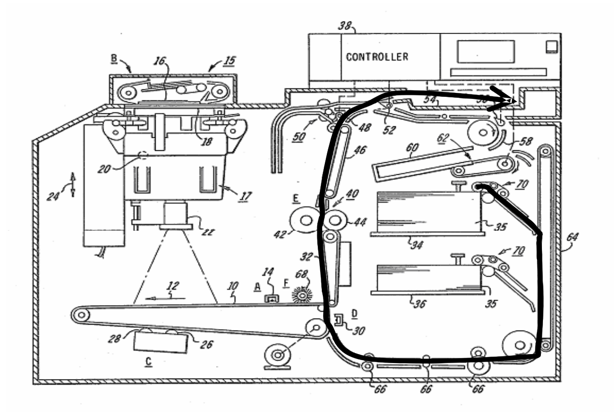


It was known that increasing wrap angle tended to improve multifeed reliability and not particularly hamper misfeed reliability. Still, most copiers only had about 13 degrees of wrap angle.

Primary Example of the Strategy



Architecture with nearly linear paper path

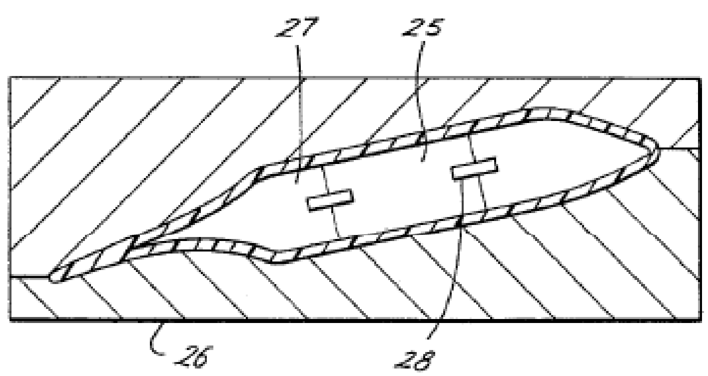


Architecture with looping paper path

A newer architecture on the right has a looping paper path, which enabled a larger wrap angle, Patent # 4,475,732 [Clausing et al, 1984].

Second Example of the Strategy

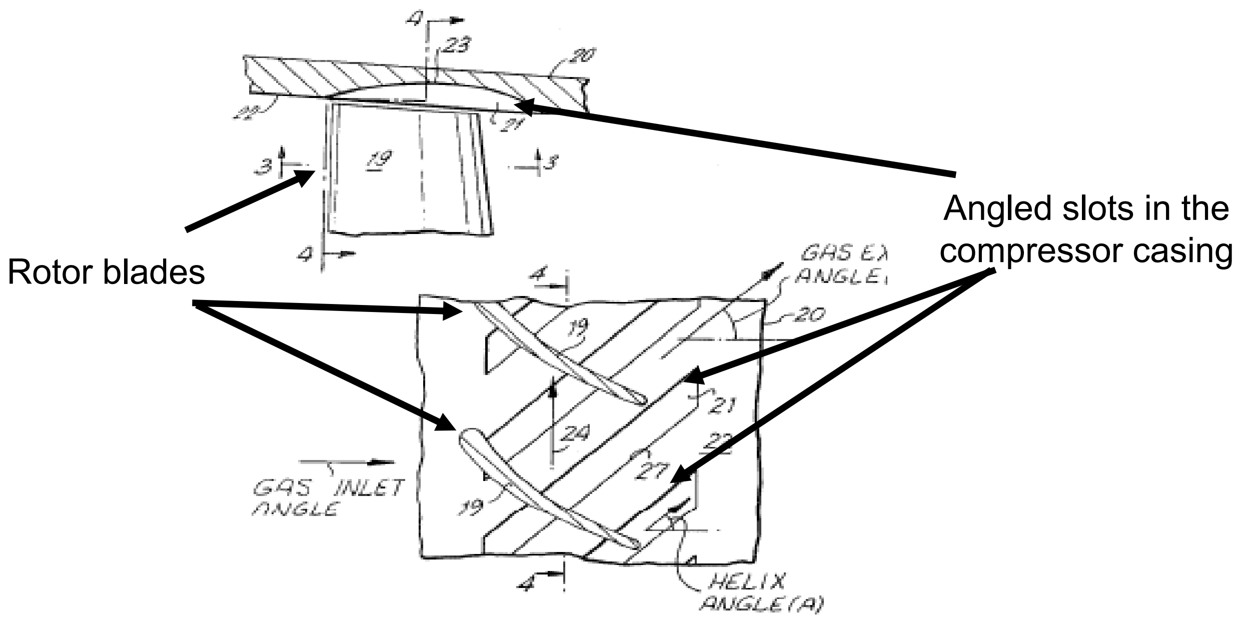
- A critical failure mode of fans is flutter
- Flutter = vibration due to the length of the blades and their exposure to inlet flow distortions.
- It had long been known that increasing the chord of a fan blade stiffened the blade and thereby reduced the incidence of the failure mode of flutter, but the chord of the blade was limited by constraints on weight [Koff, 2004].
- New technologies for manufacturing enabled wide-chord fans without added weight [Patent #4,345,877 & Patent #4,720,244]



Use Physics of Incipient Failure to Avoid Failure

- Exploit the physical mechanisms associated with an incipient failure to offset the failure mode, thereby increasing size of the operating window.

Example of the Strategy

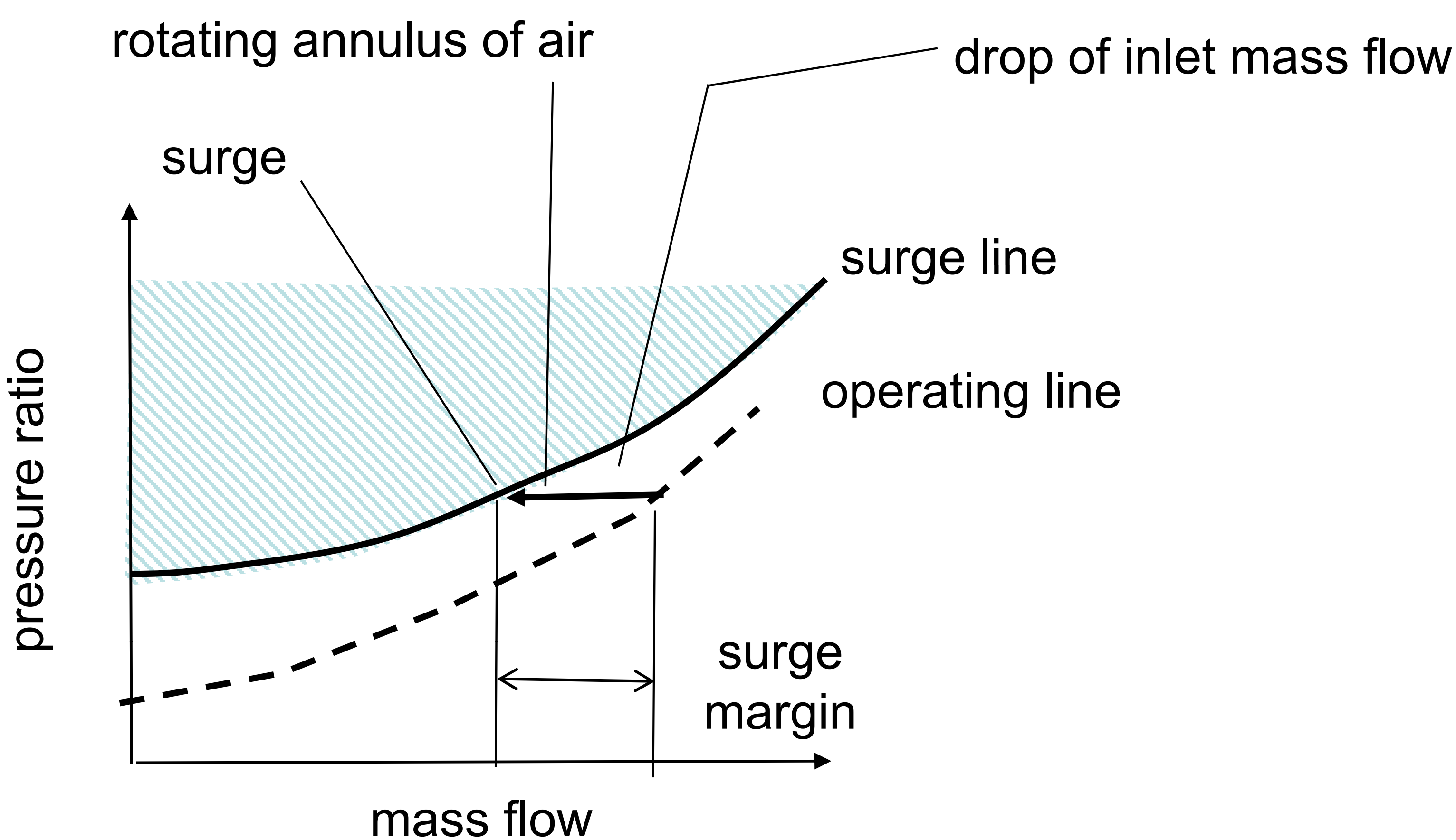


Courtesy of Wiley Periodicals. Used with permission.

"Gas turbine engine with improved compressor casing for permitting higher air flow and pressure ratios before surge"

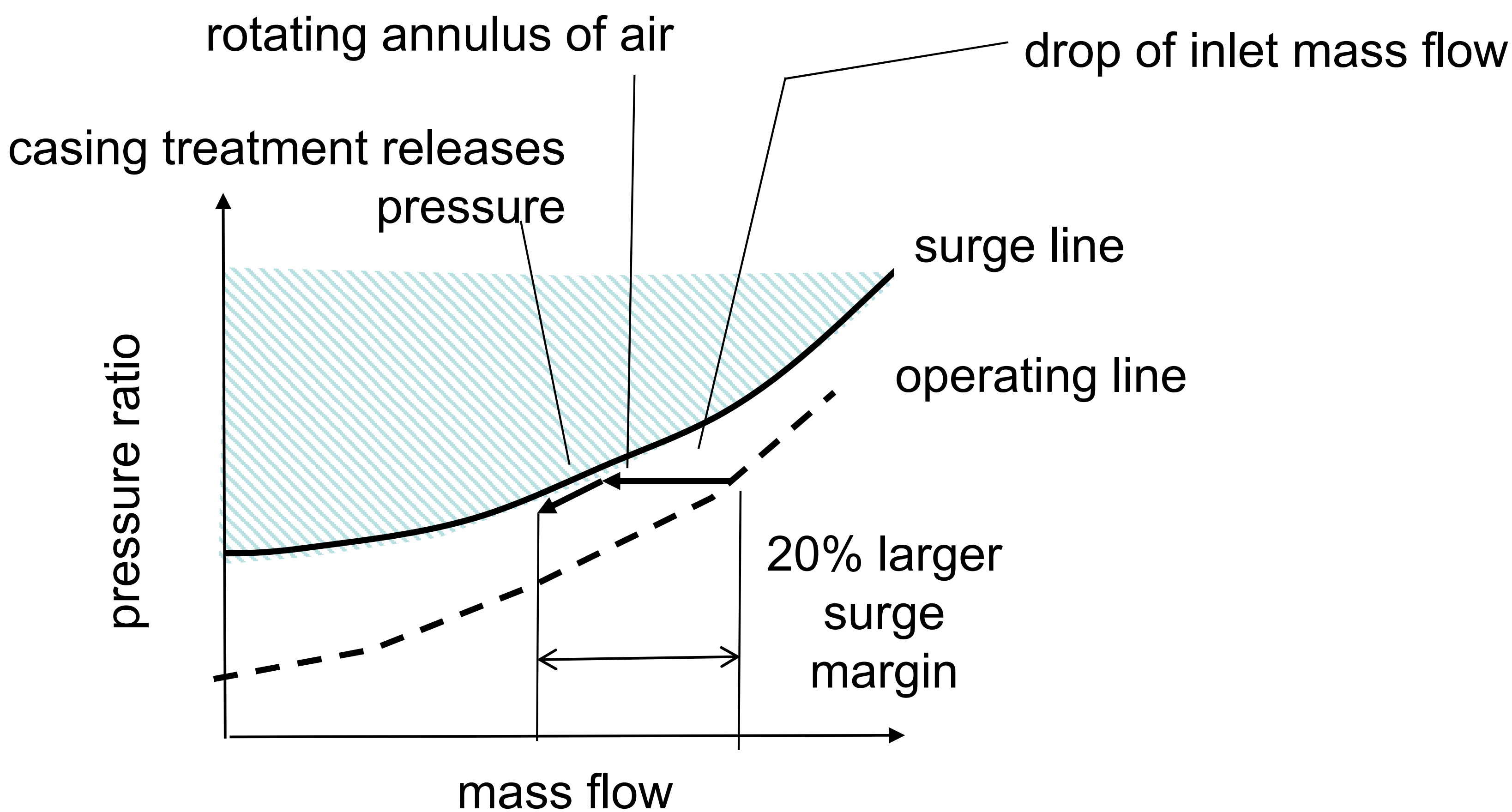
Patent #4,086,022 [Freeman and Moritz, 1978].

Example of the Strategy



BEFORE casing treatment

Example of the Strategy

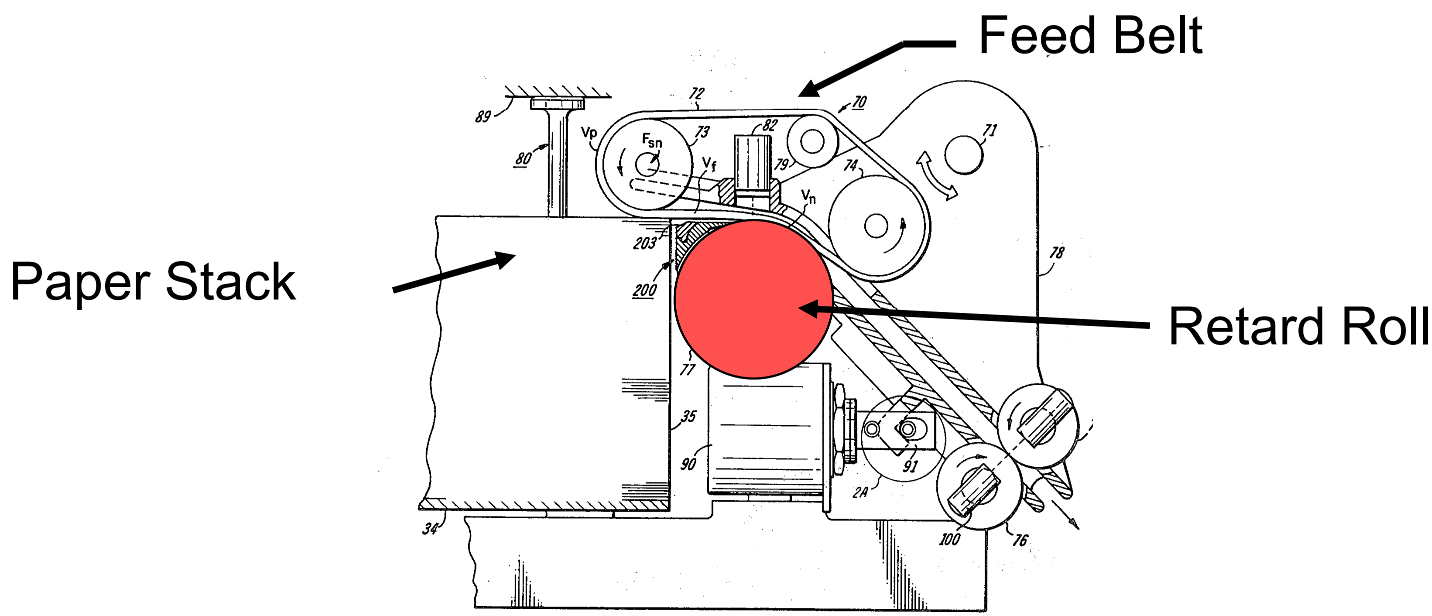


AFTER casing treatment

Employ Two Different Operating Modes

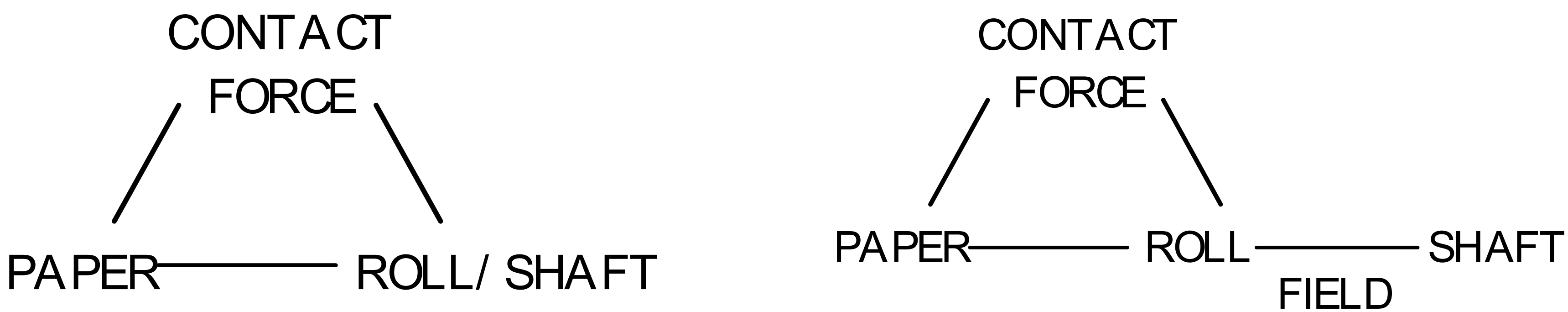
- When it is not possible to simultaneously avoid two one-sided failure modes due to a wide range of noise values, consider defining two distinct operating modes so that at least one of the failure modes will be moved away from the operating range

Example of the Strategy



During normal operation, the sheet rubs over the retard roll. Eventually, wear leads to failure. The early solution was to distribute wear across the circumference, but this was still unsatisfactory.

Example of the Strategy

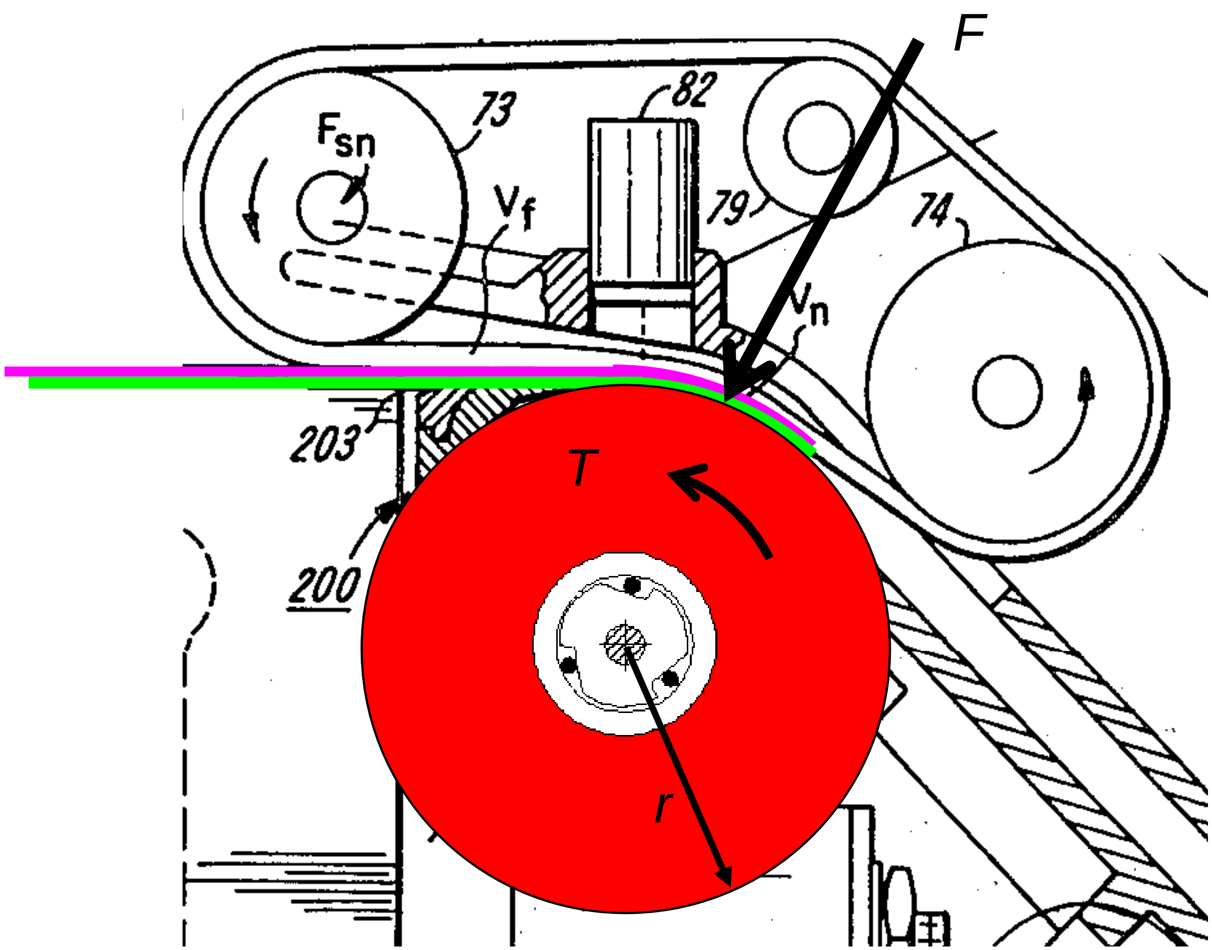


"What is claimed is: a forward rotatable roll retard member … including a *drag brake* located interiorly thereof, said drag brake being adapted such that single sheets passing through said retard nip will rotate and retard roll and multifeeds through said retard nip will cause said drag brake to inhibit rotation of said retard roll.

Patent # 4,475,732 [Clausing et. al., 1984]

Implemented in Xerox 1075 copier

Example of the Strategy



$T < rF\mu_{fp}$

Feedbelt on paper

$T > rF\mu_{pp}$

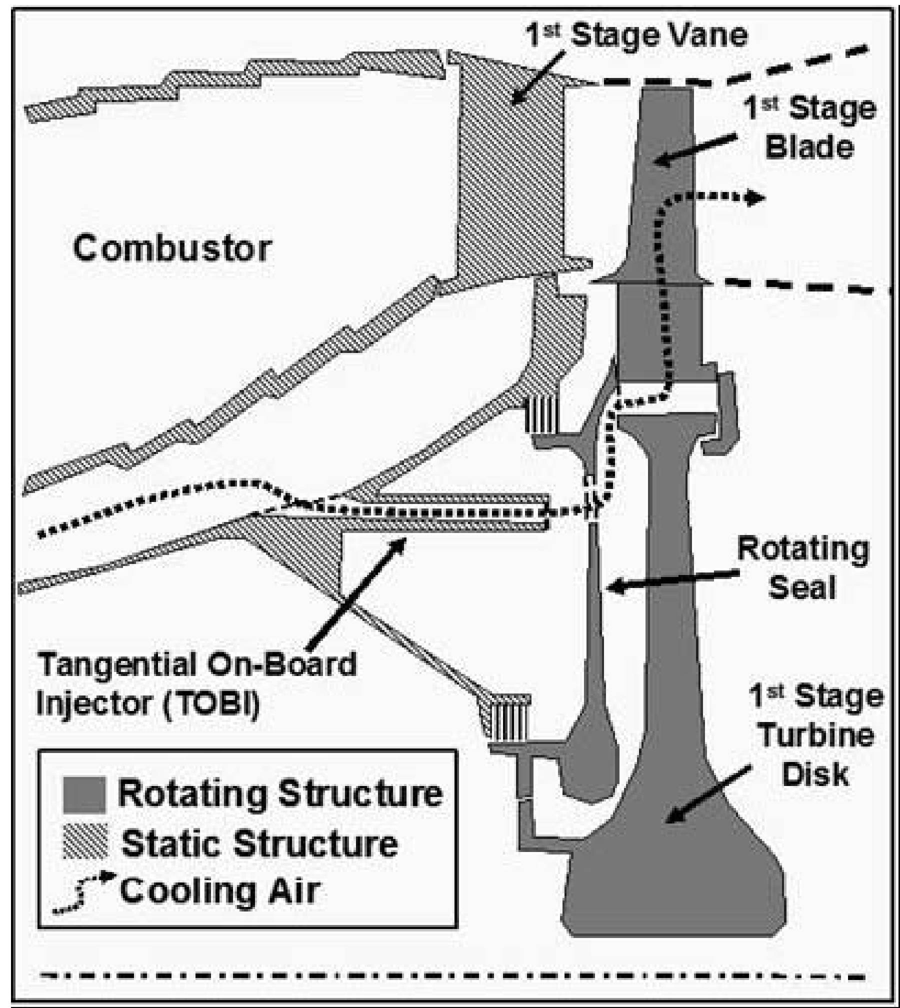
Paper on paper

Identify and Exploit Dependencies Among Failure Modes

- When there are dependencies among failure modes, look for ways to use those dependencies to counteract the effects of noise factors

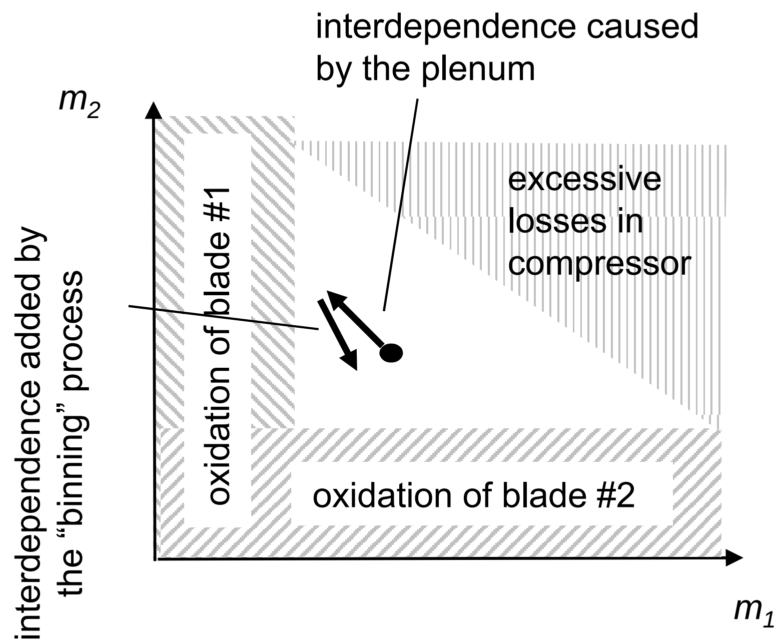
Example of the Strategy

- First stage turbine blades are limited in life by oxidation
- Cooling flow is provided from the compressor
- But the flow is different from blade to blade due to manufacturing variability (cooling passages)



Example of the Strategy

- There exists an interdependence of flow between adjacent blades
- Low flowing blades contribute to high pressure in upstream plenum
- “Binning” of blades – ensuring low flowing blades are adjacent to other low flowing blades
- >50% increase in life



C. V. Sidwell, On the impact of variability and assembly on turbine cooling flow and oxidation life, Ph.D. Thesis, MIT, 2004.

Summary of Operating Windows

- Reliability can be viewed as failure mode avoidance
- This conception can facilitate innovations that increase the operating window between failure modes
- Many of these innovations improve reliability regardless of probability distribution
- The four strategies
  - Relax a constraint limit …
  - Use physics of incipient failure to avoid failure
  - Create two distinct operating modes …
  - Exploit interdependence …
- Each strategy has provided large improvements in both jet engines and paper feeding for copiers

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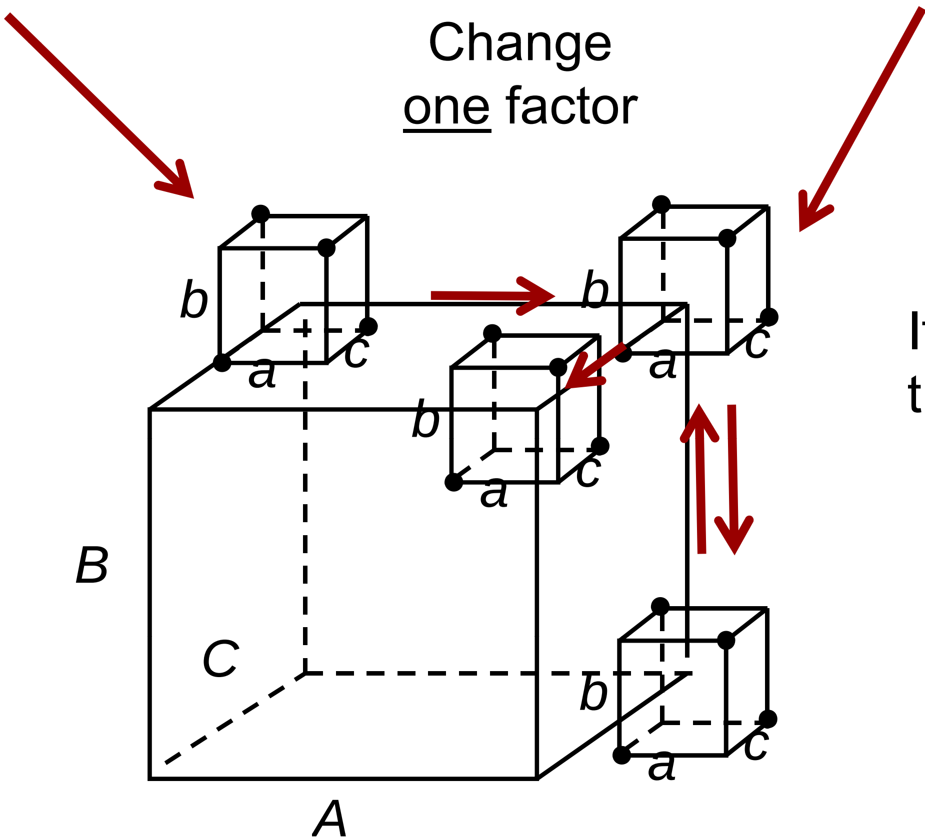
Adaptive "One Factor at a Time" for Robust Design

Run a resolution III on noise factors

Again, run a resolution III on noise factors. If there is an improvement, in transmitted variance, retain the change

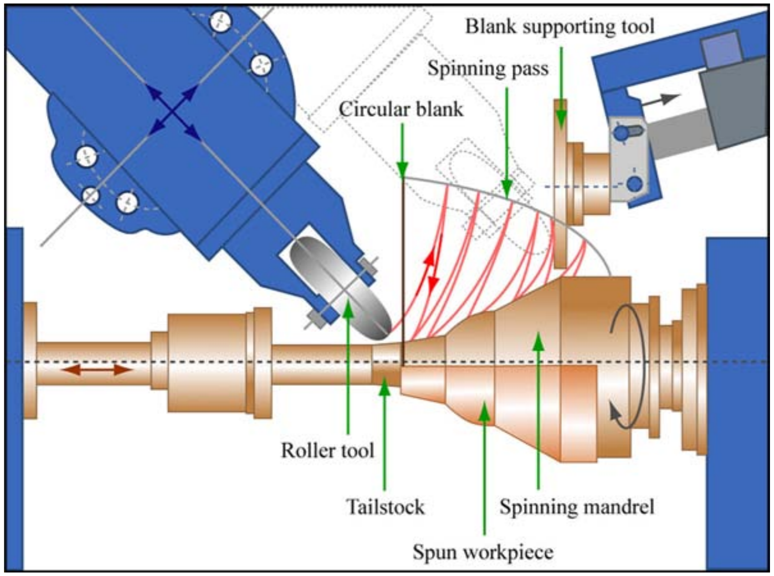


If the response gets worse, go back to the previous state

Stop after you've changed every factor once

Frey, D. D., and N. Sudarsanam, 2007, "An Adaptive One-factor-at-a-time Method for Robust Parameter Design: Comparison with Crossed Arrays via Case Studies," accepted to *ASME Journal of Mechanical Design*.

Sheet Metal Spinning



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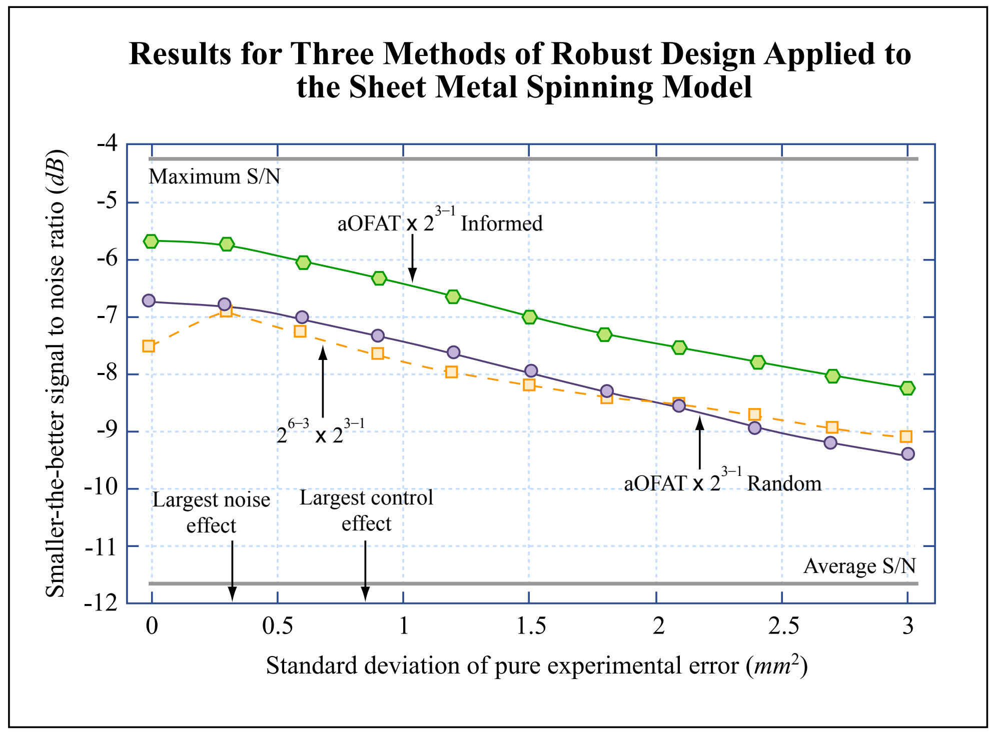

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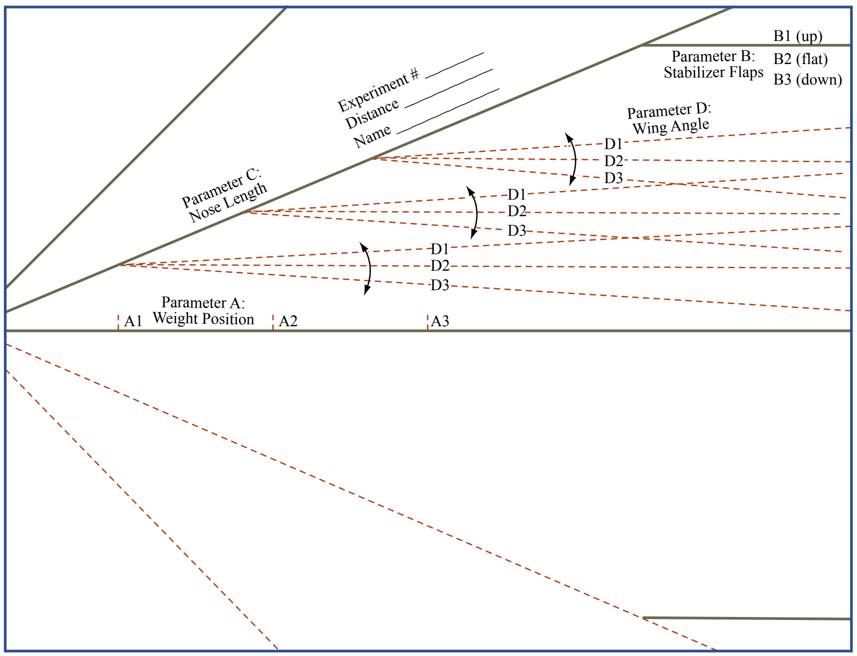
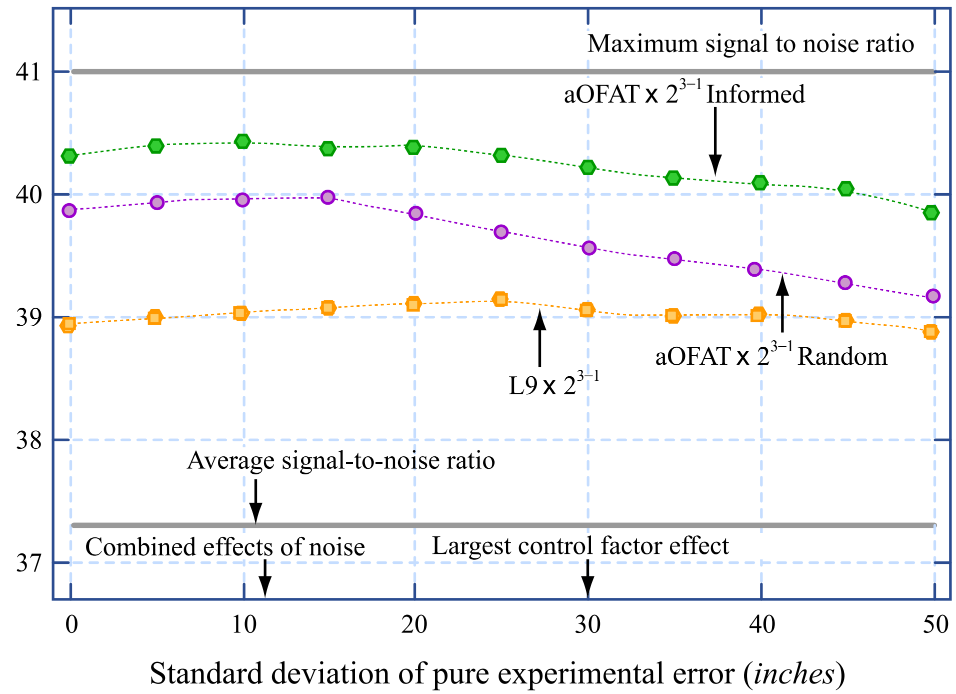
Paper Airplane

MIT Design of Experiments Exercise v2.0



Expt. #	Weight. A	Stabiliz. B	Nose C	Wing D
1	A1	B1	C1	D1
2	A1	B2	C2	D2
3	A1	B3	C3	D3
4	A2	B1	C2	D3
5	A2	B2	C3	D1
6	A2	B3	C1	D2
7	A3	B1	C3	D2
8	A3	B2	C1	D3
9	A3	B3	C2	D1

Results for Three Methods of Robust Design Applied to the Paper Airplane Physical Experiment



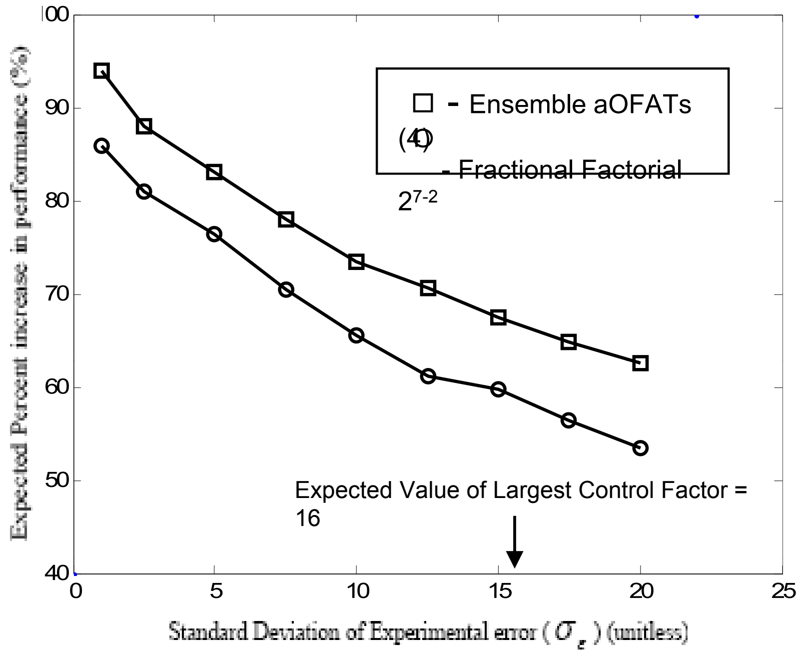
Results Across Four Case studies

		Method used		
		Fractional array x 2_{III}^{k-p}	aOFAT x 2_{III}^{k-p}	
			Informed	*Random*
Sheet metal Spinning	Low ε	51%	75%	56%
	High ε	36%	57%	52%
Op amp	Low ε	99%	99%	98%
	High ε	98%	88%	87%
Paper airplane	Low ε	43%	81%	68%
	High ε	41%	68%	51%
Freight transport	Low ε	94%	100%	100%
	High ε	88%	85%	85%
Mean of four cases	Low ε	74%	91%	84%
	High ε	66%	70%	64%
Range of four cases	Low ε	43% to 99%	75% to 100%	56% to 100%
	High ε	36% to 88%	57% to 88%	51% to 87%

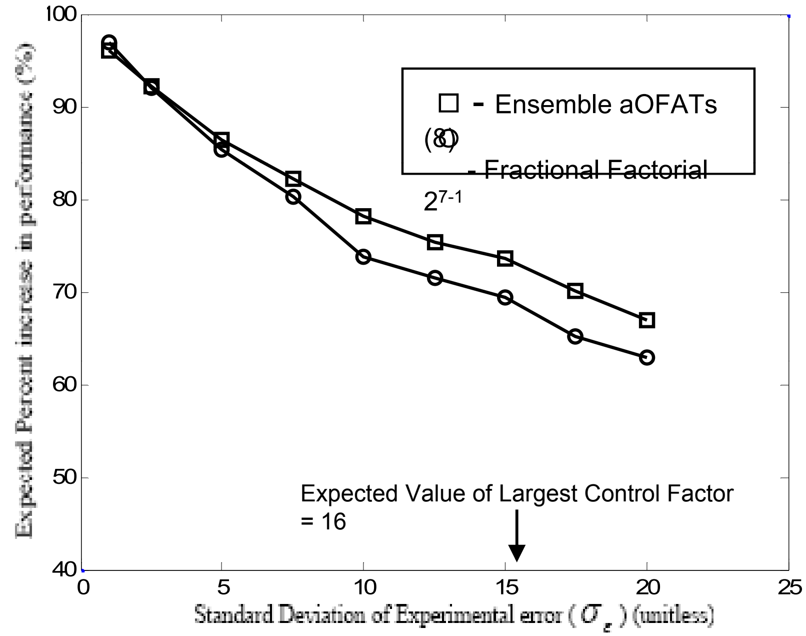
Image by MIT OpenCourseWare.

Frey, D. D., N. and Sudarsanam, 2006, “An Adaptive One-factor-at-a-time Method for Robust Parameter Design: Comparison with Crossed Arrays via Case Studies,” accepted to *ASME Journal of Mechanical Design*.

Ensembles of *a*OFATs



Comparing an Ensemble of 4 *a*OFATs with a 2^{7-2} Fractional Factorial array using the HPM



Comparing an Ensemble of 8 *a*OFATs with a 2^{7-1} Fractional Factorial array using the HPM

Conclusions on aOFAT for Robust Design

- A new model and theorems show that
  - Adaptive OFAT plans exploit two-factor interactions especially when they are large
  - Adaptive OFAT plans provide around 80% of the benefits achievable via parameter design
- Adaptive OFAT can be “crossed” with factorial designs which proves to be highly effective

Frey, D. D., and N. Sudarsanam, 2007, “An Adaptive One-factor-at-a-time Method for Robust Parameter Design: Comparison with Crossed Arrays via Case Studies,” accepted to *ASME Journal of Mechanical Design*.

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Crossed Arrays

Noise Factors 2_{III}^{3-1}

a	-1	-1	+1	+1
b	-1	+1	-1	+1
c	-1	+1	+1	-1

Control Factors

2_{III}^{7-4}

	A	**B**	**C**	**D**	**E**	**F**	**G**				
1	-1	-1	-1	-1	-1	-1	-1				
2	-1	-1	-1	+1	+1	+1	+1				
3	-1	+1	+1	-1	-1	+1	+1				
4	-1	+1	+1	+1	+1	-1	-1				
5	+1	-1	+1	-1	+1	-1	+1				
6	+1	-1	+1	+1	-1	+1	-1				
7	+1	+1	-1	-1	+1	+1	-1				
8	+1	+1	-1	+1	-1	-1	+1				

$$2_{III}^{7-4} \times 2_{III}^{3-1}$$

Single Arrays

- Single arrays achieve improved run size economy or resolution
- Focus on control by noise interactions which are essential for robust design
- “Some of the single arrays … are uniformly better than corresponding cross arrays in terms of the number of clear main effects and two factor interactions”
- Example of a suggested design (Wu & Hamada)

2^{10-5}

A=1, B=2, C=3, D=4, E=234, F=134, G=123,
a=5, b=124, c=1245

Comparing Crossed & Single Arrays

$$2_{III}^{7-4} \times 2_{III}^{3-1}$$

- 32 runs
- All control factors aliased with CXC
- All noise factors estimable
- 21 CxN interactions
  clear of 2fi
  clear of CxCxC
  clear of NxNxN

$$2^{10-5}$$

- 32 runs
- All control factors clear of 2fi
- All noise factors estimable
- 14 CxN interactions clear of 2fi

Results

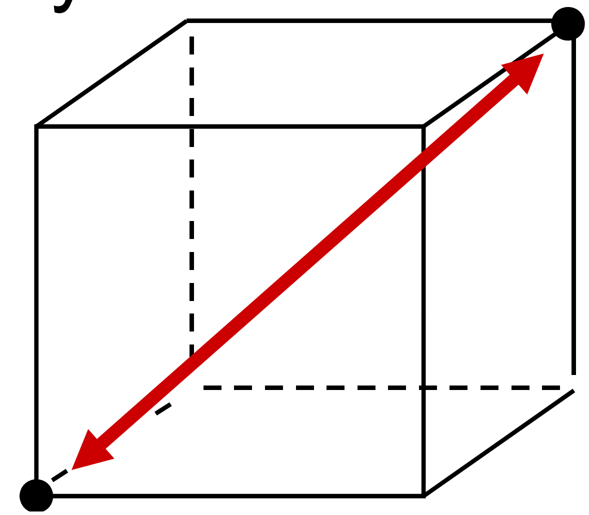
		Basic			Fitted		
Method	Experiments	WH	low w	2^{nd} order	WH	low w	2^{nd} order
$2^7 \times 2^3$	1,024	60%	81%	58%	50%	58%	40%
$2^7 \times 2_{III}^{3-1}$	512	44%	80%	52%	45%	58%	40%
2^{10-4}	64	8%	8%	56%	18%	9%	38%
2^{10-5}	32	9%	3%	33%	16%	9%	17%
$2_{III}^{7-4} \times 2_{III}^{3-1}$	32	12%	8%	51%	16%	25%	38%
$OFAT \times 2_{III}^{3-1}$	32	39%	56%	43%	36%	42%	35%
$OFAT \times OFAT$	32	31%	37%	41%	33%	31%	27%
2^{10-6}	16	4%	4%	8%	4%	2%	0%

the world assumed in classical DOE

our data

What is Compound Noise?

- Aggregate several noise factors into a single noise factor
- Example
  - Temperature, humidity, salinity
  - Compress 3D space into a single axis
- Resolution II outer array
- Extreme conditions?



An Academic Perspective on Compound Noise

Extreme settings exist iff

$$\left|\beta_j\right| \geq \sum_{i=1}^{n} \left|\gamma_{ij}\right|$$

The compound noise technique identifies the robust setting (that which minimizes variance) iff

$$\left(\sum_{j=1}^{m} \beta_j \gamma_{ij}\right)\left(\sum_{j=1}^{m} \operatorname{sgn}(\beta_j)\gamma_{ij}\right) > 0, \quad i = 1 \ldots l$$

Hou, X. Shirley, 2002, “On the use of compound noise factor in parameter design experiments”, *Applied Stochastic Models in Business and Industry* 18:225-243.

An Academic Perspective on Compound Noise

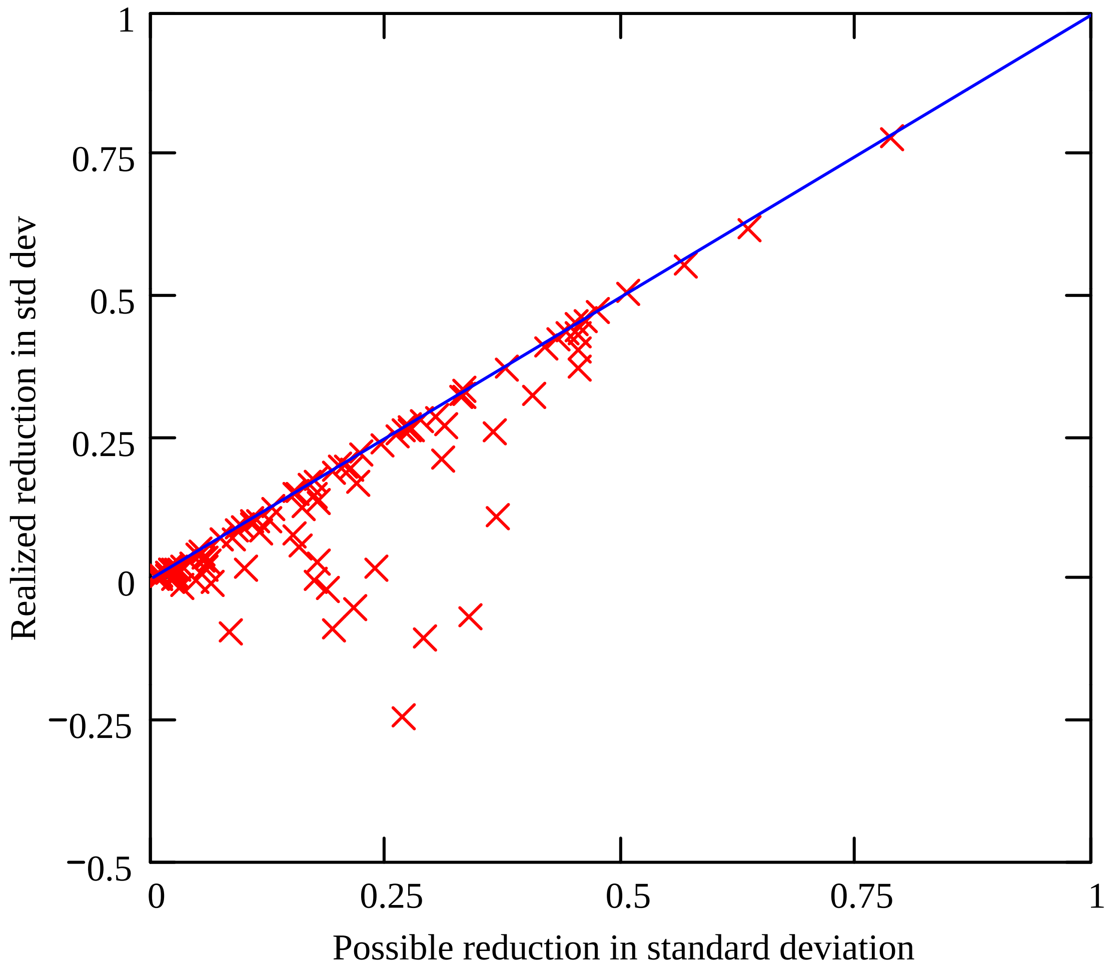
- Use of compound noise has been widespread
- Compound noise technique can identify robust settings only in limited situations
- Their limited nature suggests they are not often satisfied in practical experiments
- The message from this study is that is that compound noise technique does not perform very well in general situations

Hou, X. Shirley, 2002, "On the use of compound noise factor in parameter design experiments", *Applied Stochastic Models in Business and Industry* 18:225-243.

Method

- Select a model of engineering systems
- Create 100 instances
  - 7 control factors
  - 7 noise factors
- Run a full factorial inner array with
  - Full factorial outer array
  - Compound noise outer array
- Plot and analyze results

Results with Locally Extreme CN



c − 100
s = 3

Average strength of interactions ~0.25

Percent of possible reduction achieved ~80%

~7% “success”

None had extreme settings

Streamlining Robust Design

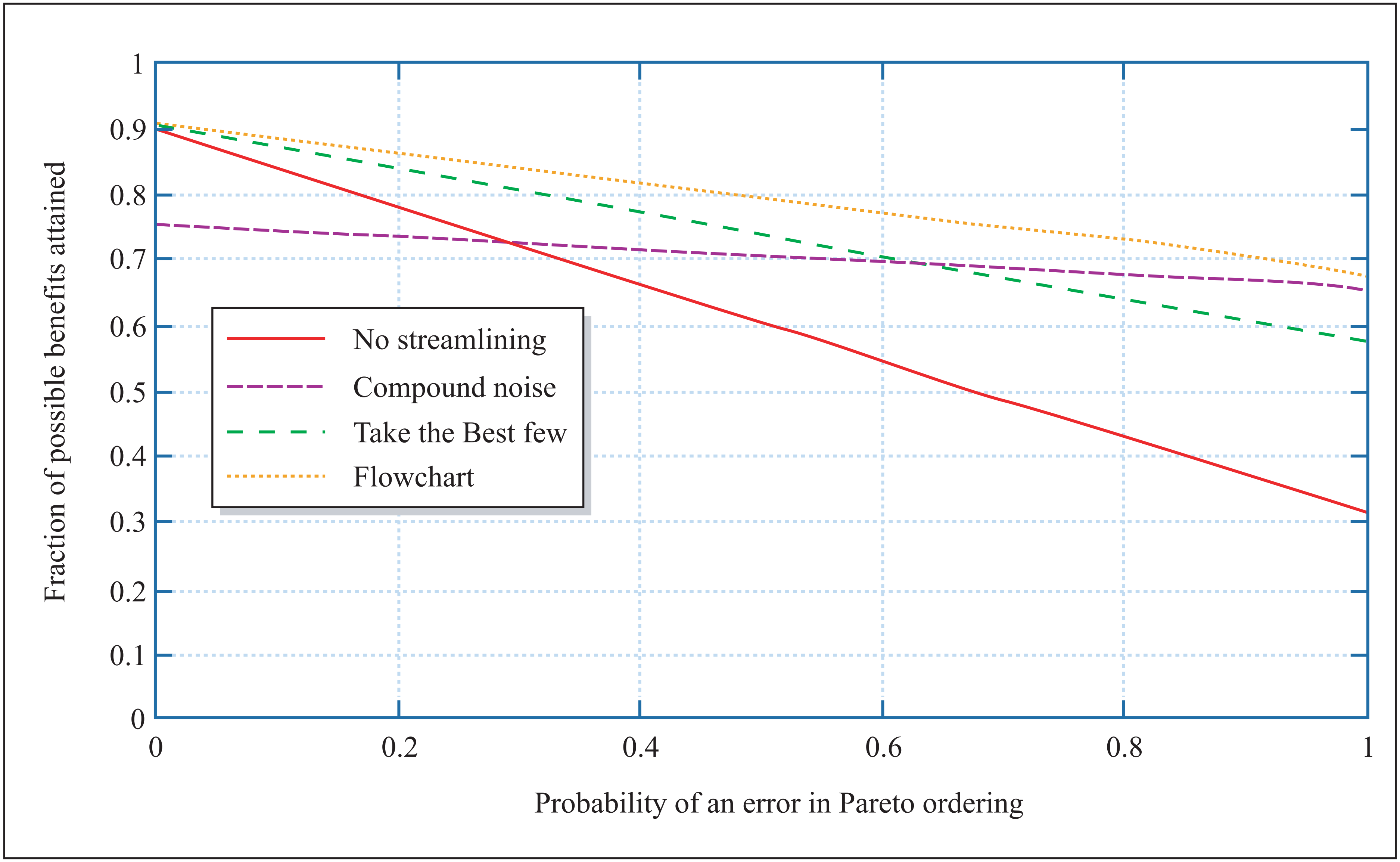


Image by MIT OpenCourseWare.

Singh, J., R. Jugulum, N. Soderborg, D. E. Whitney, and D. D. Frey, 2007, "Streamlining Robust Parameter Design Efforts," *Journal of Design Research* **5**(4):435-448.