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How to Minimize Configuration Switching Time and Cost for Design of Experiments

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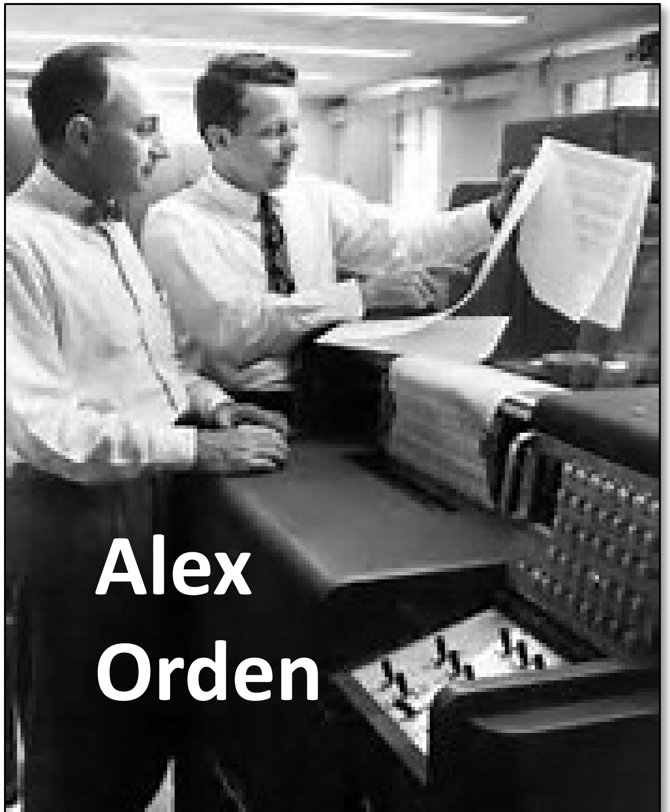
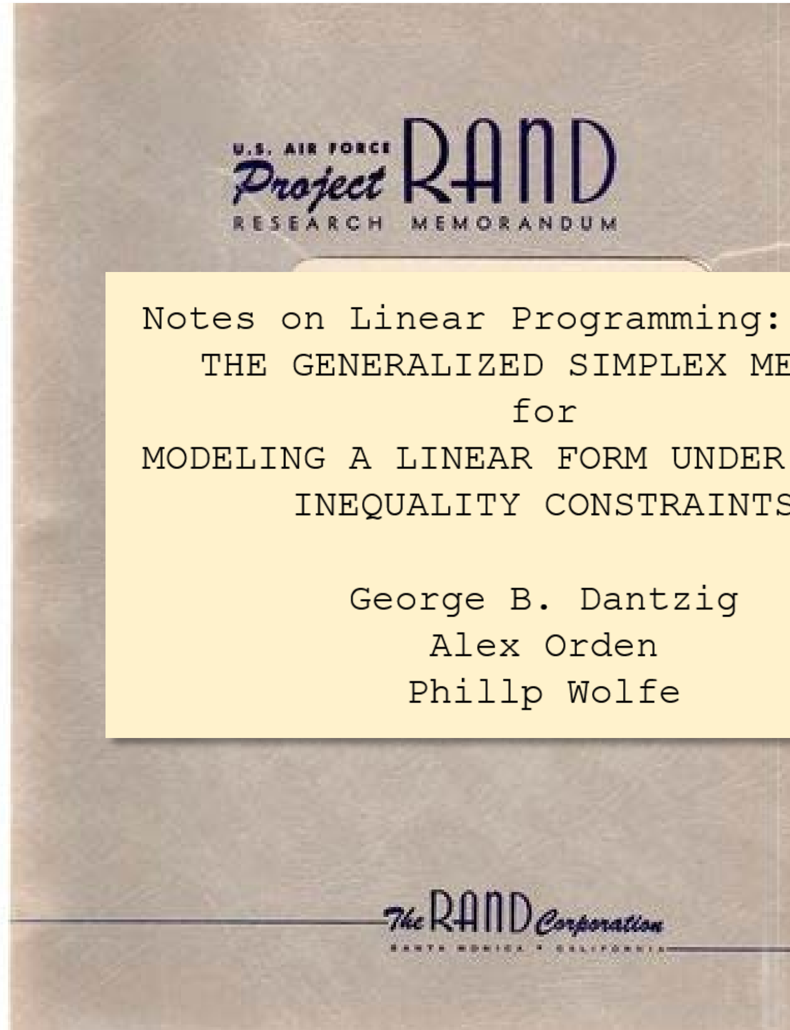
Dedication





Notes on Linear Programming: Part I
THE GENERALIZED SIMPLEX METHOD
for
MODELING A LINEAR FORM UNDER LINEAR
INEQUALITY CONSTRAINTS

George B. Dantzig
Alex Orden
Phillp Wolfe

Motivation

If we have solid reasons to conclude that we can improve the efficiency of DT&E (and we should always be looking for sources of efficiencies), then we should take those efficiencies into account in our planning, but hope is still not a method.

Frank Kendall, Under Secretary of Defense for Acquisition, Technology and Logistics

"Perspectives on Developmental Test and Evaluation," *ITEA Journal* 2013; 34: 6–10

Motivation

Design of Experiments (DOE)

- Technique to select a minimal and adequate set of test configurations
- Quantitative criteria for completeness and confidence
- DOT&E requires ("should") for
  - Developmental Testing (DT)
  - Operational Testing (OT)

- Typically dozens of test configurations
- *Many* configuration sequences possible
- If some configuration sequences are more expensive than others:

How to sequence configurations?

What is the least cost sequence?

What is the shortest sequence?

Test Configurations: Factors and Levels

FACTOR	LEVEL
Terrain	Desert
	Mountain
	Urban
	Littoral
Target Orientation	Horizontal Face
	Vertical Face
Contrast	High
	Low
Sun Elevation	<1/2 peak AM or PM
	>1/2 peak AM or PM

	Terrain	Target	Contrast	Sun
1	Desert	Horizontal	Low	Over Peak
2	Desert	Vertical	High	Under Peak
3	Mountain	Horizontal	High	Over Peak
4	Mountain	Vertical	Low	Under Peak
5	Urban	Horizontal	High	Under Peak
6	Urban	Vertical	Low	Over Peak
7	Littoral	Horizontal	High	Under Peak
8	Littoral	Vertical	Low	Over Peak

- 8 test configurations cover all two-way interactions
- 40,320 possible configuration sequences

Precision Guided Weapon Example. Table D-4. OT&E Factors and Levels for STW. *DOT&E TEMP Guidebook 3.0*, 2015.

Test Configurations: Factors and Levels

FACTOR	LEVEL
Mission Load	Standard
	High
Track Density	Standard
	High
Mission Duration	Short (4 hours)
	24 hour
Configuration	Small
	Medium
	Large
Environment	Desert
	Hot & Humid
	Cold

	Load	Density	Duration	Size	Envmt
1	High	High	24Hour	Small	Desert
2	Standard	Standard	Short	Small	HotHumid
3	High	Standard	24Hour	Small	Cold
4	Standard	High	Short	Medium	Desert
5	High	Standard	24Hour	Medium	HotHumid
6	Standard	High	Short	Medium	Cold
7	High	Standard	Short	Large	Desert
8	Standard	High	24Hour	Large	HotHumid
9	High	High	Short	Large	Cold

- 9 test configurations cover all two-way interactions
- 362,880 possible configuration sequences

Example for Software-Intensive System. Table 3-3. Overview of DOE Strategy to assess COI 1: System's ability to support mission of agency 1. *DOT&E TEMP Guidebook 3.0*, 2015.

Switching Costs

Typical testing activities

- Setup configuration
- Run test
- Analyze results
- Teardown configuration

Configuration switch cost

- Total of all factor/level switch costs for C_p to C_q
- Switch *pq* =

  Teardown *pq* + Setup *pq* +

  Run *pq* + Analyze *pq*
- May be same or zero

	From/To	Desert	Mountain	Urban	Littoral
Setup	Desert	100	1500	500	1000
	Mountain	3000	250	3500	4500
	Urban	500	2000	250	2500
	Littoral	1000	5000	3500	500
Run	*From/To*	Desert	Mountain	Urban	Littoral
	Desert	250	400	100	175
	Mountain	250	400	100	175
	Urban	250	400	100	175
	Littoral	250	400	100	175
Analyze	*From/To*	Desert	Mountain	Urban	Littoral
	Desert	200	200	200	200
	Mountain	200	200	200	200
	Urban	200	200	200	200
	Littoral	200	200	200	200
Teardown	*From/To*	Desert	Mountain	Urban	Littoral
	Desert	150	500	3000	1500
	Mountain	4500	300	2500	250
	Urban	2500	250	300	2000
	Littoral	500	3500	950	350
TOTAL	*From/To*	Desert	Mountain	Urban	Littoral
	Desert	700	2600	3800	2875
	Mountain	7950	1150	6300	5125
	Urban	3450	2850	850	4875
	Littoral	1950	9100	4750	1225

All values notional

Switching Costs

Change to any level can result in switching cost. In the example:

- *Setup* costs depend on travel
- *Run* costs differ, no relation to prior level
- *Analyze* costs all same
- *Teardown* costs depend on locale
- YMMV

Assumptions

- First and last unique
- Costs mostly different
- Costs significant (“material”)
- Independent of other factors

	From/To	Desert	Mountain	Urban	Littoral
Setup	Desert	100	1500	500	1000
	Mountain	3000	250	3500	4500
	Urban	500	2000	250	2500
	Littoral	1000	5000	3500	500
Run	*From/To*	Desert	Mountain	Urban	Littoral
	Desert	250	400	100	175
	Mountain	250	400	100	175
	Urban	250	400	100	175
	Littoral	250	400	100	175
Analyze	*From/To*	Desert	Mountain	Urban	Littoral
	Desert	200	200	200	200
	Mountain	200	200	200	200
	Urban	200	200	200	200
	Littoral	200	200	200	200
Teardown	*From/To*	Desert	Mountain	Urban	Littoral
	Desert	150	500	3000	1500
	Mountain	4500	300	2500	250
	Urban	2500	250	300	2000
	Littoral	500	3500	950	350
TOTAL	*From/To*	Desert	Mountain	Urban	Littoral
	Desert	700	2600	3800	2875
	Mountain	7950	1150	6300	5125
	Urban	3450	2850	850	4875
	Littoral	1950	9100	4750	1225

All values notional

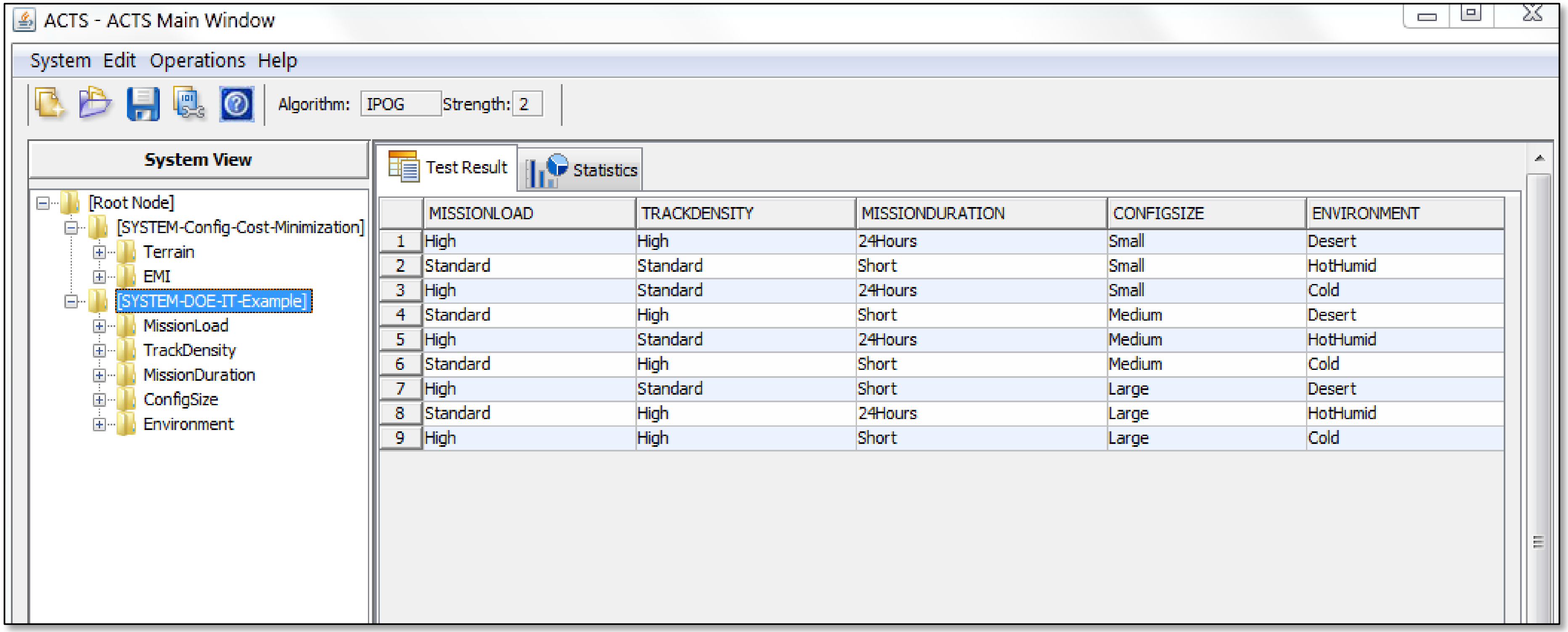
Consider a simple two-factor design

FACTOR	LEVEL
Terrain	Desert
	Urban
Electro Magnetic Interference (EMI)	Nominal
	Jamming

	Terrain	EMI
C1	Desert	Nominal
C2	Desert	Jamming
C3	Urban	Jamming
C4	Urban	Nominal

- 4 Configurations cover all 2-way interactions

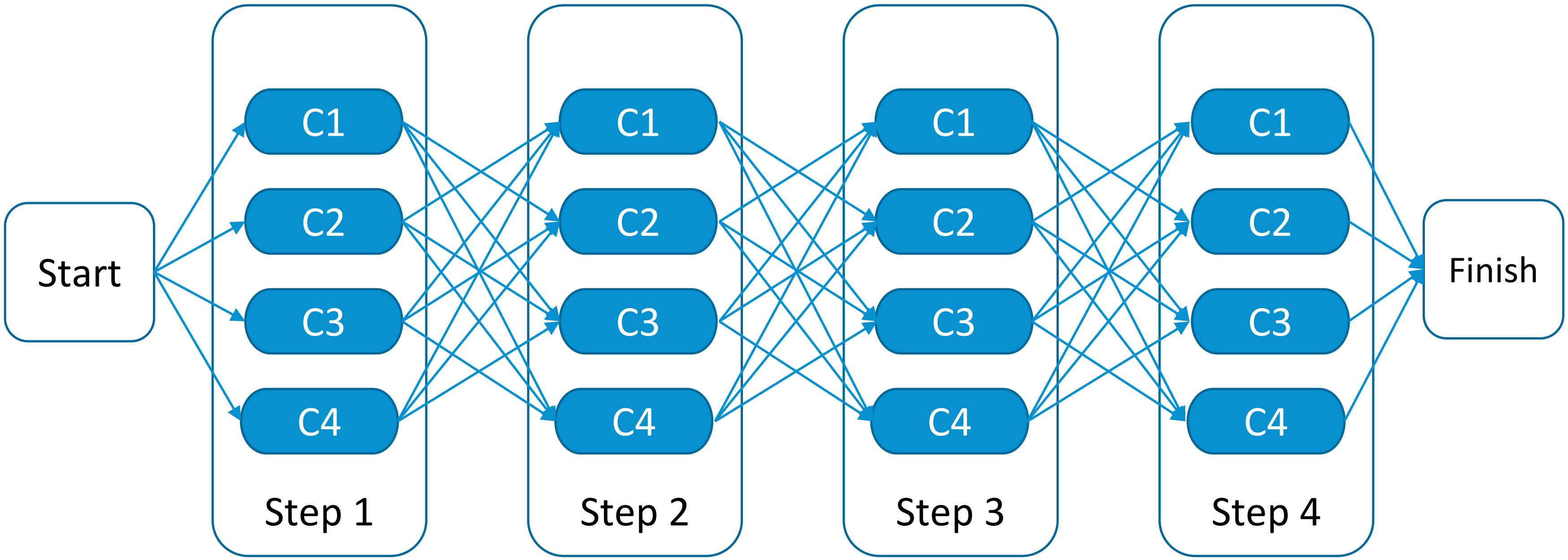
Generate n-way covering configurations



	MISSIONLOAD	TRACKDENSITY	MISSIONDURATION	CONFIGSIZE	ENVIRONMENT
1	High	High	24Hours	Small	Desert
2	Standard	Standard	Short	Small	HotHumid
3	High	Standard	24Hours	Small	Cold
4	Standard	High	Short	Medium	Desert
5	High	Standard	24Hours	Medium	HotHumid
6	Standard	High	Short	Medium	Cold
7	High	Standard	Short	Large	Desert
8	Standard	High	24Hours	Large	HotHumid
9	High	High	Short	Large	Cold

- ACTS, free Combination test design tool from NIST
- http://csrc.nist.gov/groups/SNS/acts/index.htm

Which plan has the lowest switching costs?



- 24 possible configuration sequences

Switching costs, each factor and level

	Factor 1: Terrain				Factor 2: EMI		
SETUP	*From/To*	Desert	Urban		*From/To*	Nominal	Jamming
	Desert	100	4500		Nominal	100	500
	Urban	3500	250		Jamming	500	250
RUN	*From/To*	Desert	Urban		*From/To*	Nominal	Jamming
	Desert	100	100		Nominal	100	300
	Urban	100	300		Jamming	200	100
ANALYZE	*From/To*	Desert	Urban		*From/To*	Nominal	Jamming
	Desert	200	200		Nominal	200	200
	Urban	200	200		Jamming	200	200
TEARDOWN	*From/To*	Desert	Urban		*From/To*	Nominal	Jamming
	Desert	150	3000		Nominal	100	500
	Urban	2500	300		Jamming	500	250
TOTAL	*From/To*	Desert	Urban		*From/To*	Nominal	Jamming
	Desert	550	7800		Nominal	500	1500
	Urban	6300	1050		Jamming	1400	800

All values notional

Desert:Jamming → Urban:Nominal = 7800 + 1400 = 9200

Configuration Switching Costs

From/To	Initial	C1: Desert, Nominal	C2: Desert, Jamming	C3: Urban, Nominal	C4: Urban, Jamming	Final
Initial	NA	200	350	350	500	NA
C1: Desert, Nominal	NA	1050	2050	6800	9300	250
C2: Desert, Jamming	NA	1950	1350	9200	8600	400
C3: Urban, Nominal	NA	6800	7800	1550	2550	400
C4: Urban, Jamming	NA	7700	7100	2450	1850	550
Final	NA	NA	NA	NA	NA	NA

All values notional

Which plan has the lowest switching costs?

From/To	Initial	C1: Desert, Nominal	C2: Desert, Jamming	C3: Urban, Nominal	C4: Urban, Jamming	Final
Initial	NA	1 200	350	350	500	NA
C1: Desert, Nominal	NA	1050	2 2050	6800	9300	250
C2: Desert, Jamming	NA	1950	1350	9200	3 8600	400
C3: Urban, Nominal	NA	6800	7800	1550	2550	5 400
C4: Urban, Jamming	NA	7700	7100	4 2450	1850	550
Final	NA	NA	NA	NA	NA	NA

All values notional

Heuristic A:
Always choose lowest **13,700**

Which plan has the lowest switching costs?

From/To	Initial	C1: Desert, Nominal	C2: Desert, Jamming	C3: Urban, Nominal	C4: Urban, Jamming	Final
Initial	NA	*1* 200	350	350	*1* 500	NA
C1: Desert, Nominal	NA	1050	*2* 2050	*3* 6800	9300	250
C2: Desert, Jamming	NA	1950	1350	9200	*3* 8600	*5* 400
C3: Urban, Nominal	NA	6800	*4* 7800	1550	2550	*5* 400
C4: Urban, Jamming	NA	*2* 7700	7100	*4* 2450	1850	550
Final	NA	NA	NA	NA	NA	NA

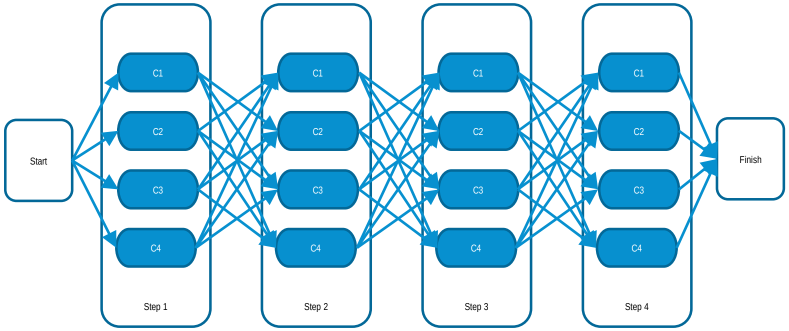
All values notional

Heuristic A - Always choose lowest **13,700**

Heuristic B - Always choose highest **23,200**

Optimal: *Stay tuned*

Which plan has the lowest switching costs?



- Number of possible configuration sequences is *n!*
- Expert or randomized plan very likely non-optimal

N configurations	Possible Sequences
1	1
2	2
3	6
4	24
5	120
6	720
7	5,040
8	40,320
9	362,880
10	3,628,800
11	39,916,800
12	479,001,600
13	6,227,020,800
14	87,178,291,200
15	1,307,674,368,000
16	20,922,789,888,000

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Quantitative Optimization

What is quantitative optimization?

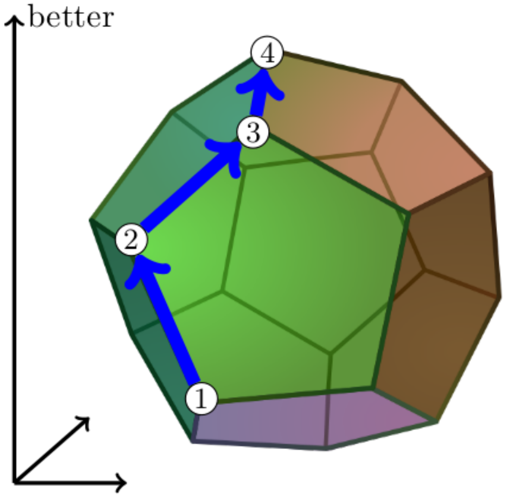
Aka *Operations Research*

- First used during WW II for logistics planning
- Successful and routine application in many domains

Linear Programming is a foundational technique

- Model with system of linear equations
  - Constraints and costs
  - Decision variables
  - Objective function

Many low cost, high-power, user-friendly software solvers available



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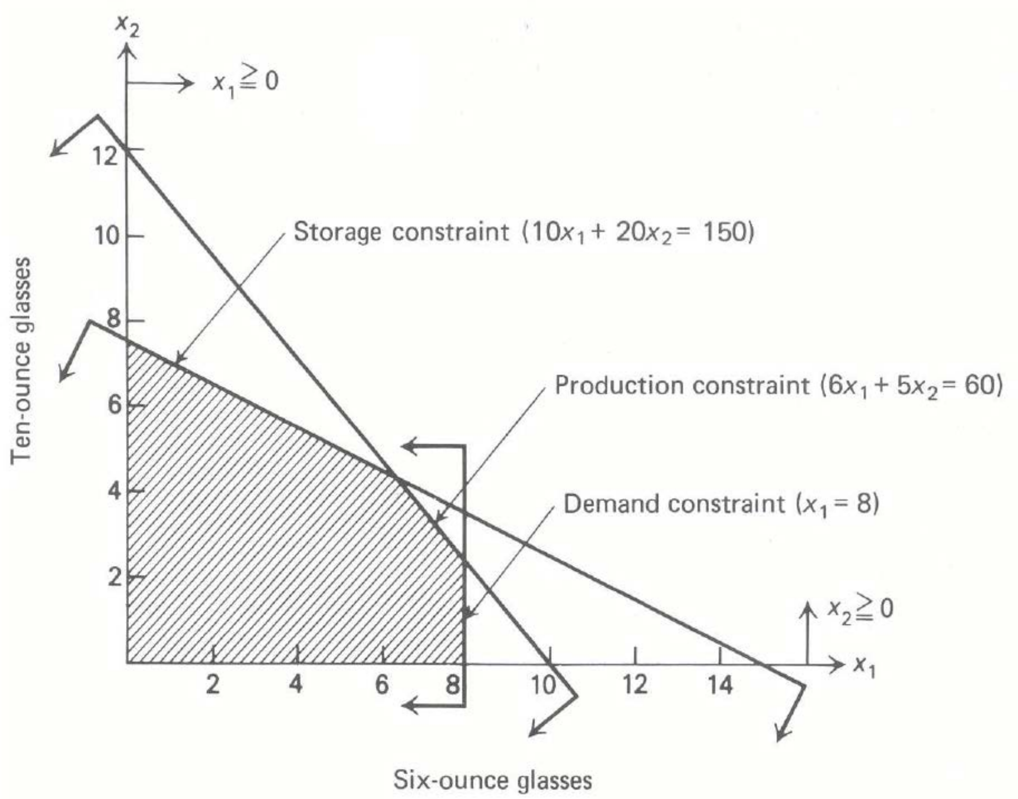
What is Linear Programming?



x1: number of 6 oz. to make, each yields 500 units of profit
x2: number of 10 oz. to make, each yields 450 units of profit
Z: total profit for a given quantity of x1 and x2

Maximize

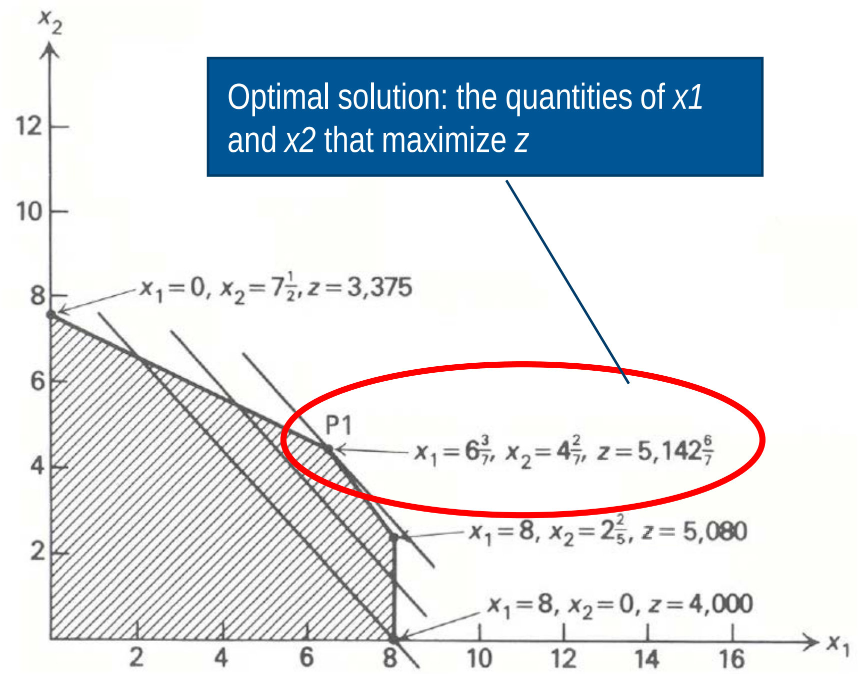
$z = 500x1 + 450x2$

Subject to

$6x1 + 5x2 \leq 60$	production hours
$10x1 + 20x2 \leq 150$	sq. ft. storage
$x1 \leq 8$	sales limit, 6 oz. unit
$x1 \geq 0, x2 \geq 0$	

Bradley, *Applied Mathematical Programming*, MIT Press, 1997.

What is Linear Programming?



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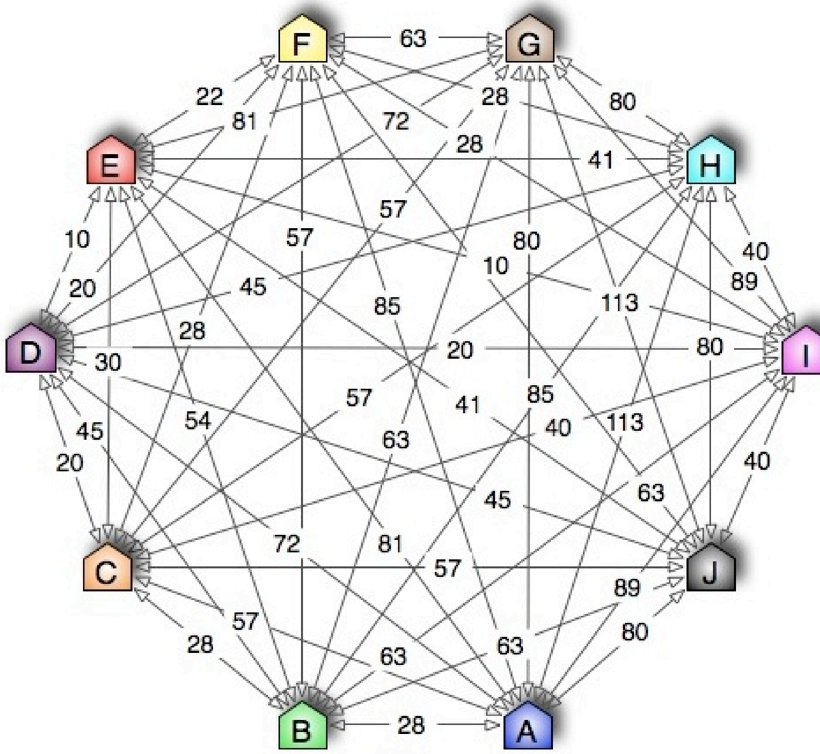
$x1 \geq 0,\ x2 \geq 0$	

Bradley, *Applied Mathematical Programming*, MIT Press, 1997.

The Traveling Salesman Problem

What is the least cost route to visit each city once, starting and stopping at the same city?

- In theory, NP-complete
- In practice, many feasible strategies for exact optimization
- Solved with *Integer Programming*
  - Just like Linear Programming, but variables may be limited to whole numbers



http://www.codeproject.com/Articles/259926/Introduction-to-Genetic-Algorithm-Encoding-Camel

Which plan has the lowest switching costs?

From/To	Initial	C1: Desert, Nominal	C2: Desert, Jamming	C3: Urban, Nominal	C4: Urban, Jamming	Final
Initial	NA	1 200	1 350	350	1 500	NA
C1: Desert, Nominal	NA	1050	2 2050	3 6800 2	9300	250
C2: Desert, Jamming	NA	3 1950	1350	9200	3 8600	5 400
C3: Urban, Nominal	NA	6800	4 7800	1550	4 2550	5 400
C4: Urban, Jamming	NA	2 7700	7100	4 2450	1850	5 550
Final	NA	NA	NA	NA	NA	NA

All values notional

Heuristic A - Always choose lowest **13,700**

Heuristic B - Always choose highest **23,200**

Optimal: **12,200**

Test Configuration Sequence Optimization Model

- Many FOSS and COTS solvers

https://en.wikipedia.org/wiki/List_of_optimization_software

- Demo uses “What’s Best”
- Excel front-end for the Lindo Systems optimization suite

http://www.lindo.com/

Test Configuration Optimization

Objective

Find a sequence of test configurations that minimizes switching cost of test configurations.

Minimize Total Cost $12,200 dollars

Configuration Switching Cost Matrix

Each cell in the transition cost matrix is the estimated total cost of switching from one configuration t

This is the total of teardown, setup, run, and analyze cost for each factor in the configuration.

For any pair of configurations x and y, the switching cost x->y is not necessarily the same as that of

	From\To	α-ω	Des-Nom	Des-Jam	Urb-Nom	Urb-Jam
1	α-ω	0	200	350	350	500
2	1 Des-Nom	250	1050	2050	6800	9300
3	2 Des-Jam	400	1950	1350	9200	8600
4	3 Urb-Nom	400	6800	7800	1550	2550
5	4 Urb-Jam	550	7700	7100	2450	1850
		1	2	3	4	5

Configuration Sequence Selections

A selected transition is indicated with a "1" and indicates that the TC of that row
is followed by the TC of that column. This is the output of the optimization model.

From\To	α-ω	Des-Nom	Des-Jam	Urb-Nom	Urb-Jam	Require row sur	
						Each configurat	
α-ω	0	0	1	0	0	1	#####
1 Des-Nom	0	0	0	1	0	1	#####
2 Des-Jam	0	1	0	0	0	1	#####
3 Urb-Nom	0	0	0	0	1	1	#####
4 Urb-Jam	1	0	0	0	0	1	#####
Sum:	1	1	1	1	1		
Must enter:	#NAME?	#NAME?	#NAME?	#NAME?	#NAME?		
	1	1	1	1	1		

Require column sum == 1: each configuration must be used exactly once

Tour Constraints

Do not allow partial or unconnected sequences. Aka Miller/Tucker/Zemlin subtour constraints.

Number of configurations 5

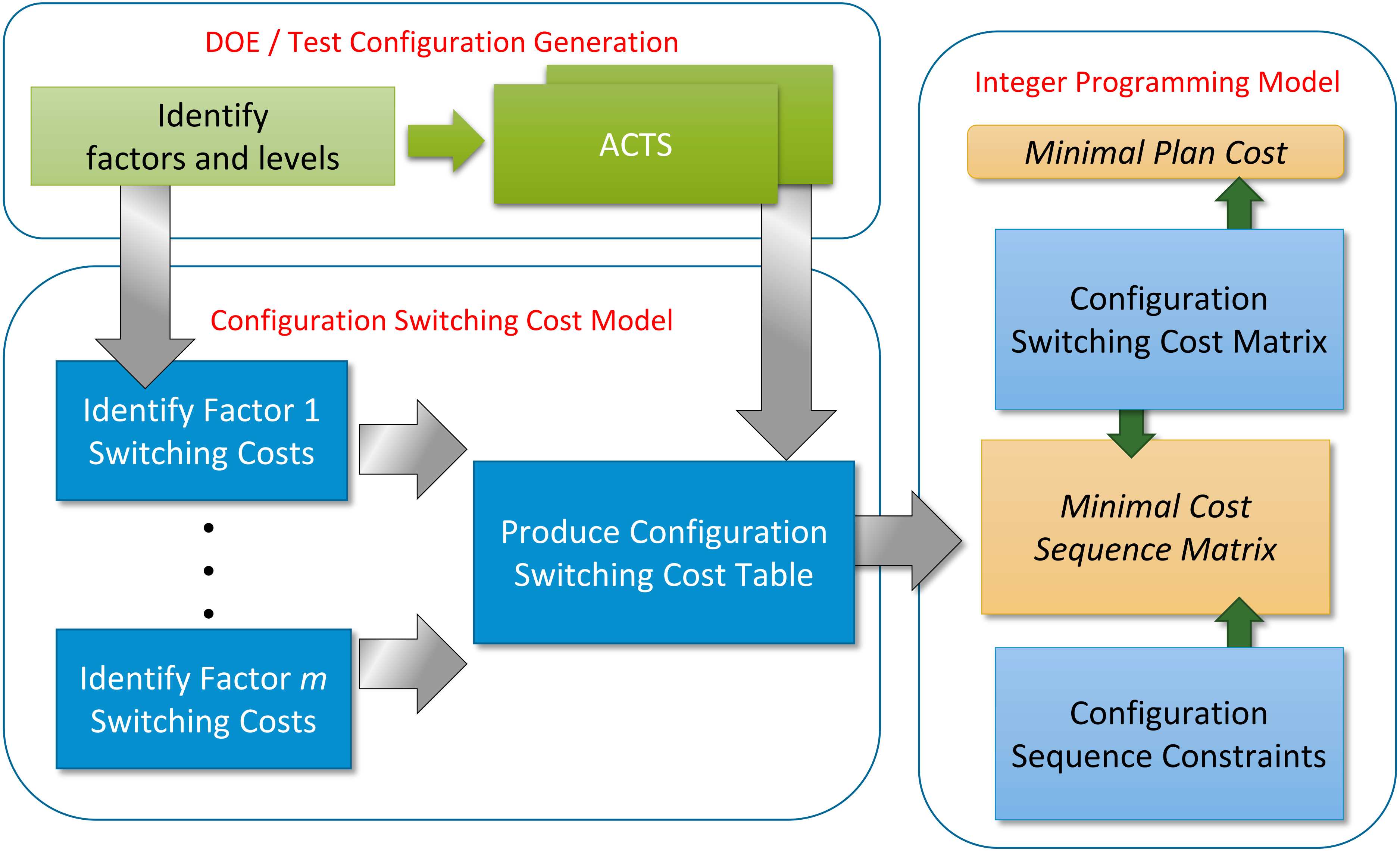
Assigned

Step		α-ω	Des-Nom	Des-Jam	Urb-Nom	Urb-Jam
0	α-ω		#NAME?	#NAME?	#NAME?	#NAME?
2	1 Des-Nom			#NAME?	#NAME?	#NAME?
1	2 Des-Jam		#NAME?		#NAME?	#NAME?
3	3 Urb-Nom		#NAME?	#NAME?		#NAME?
4	4 Urb-Jam		#NAME?	#NAME?	#NAME?	

Optional Tightening constraints:

10	#NAME?			Step assignments must exactly correspond to numbe
3	#NAME?	4		Kill symmetry if distance matrix symmetric

Test Configuration Sequence Optimization



Usage considerations

Use cases

- Planning at any stage
- Evaluate expert plan
- Evaluate randomized plan
- Identify alternatives
- Re-plan after changes
- Retrospective analysis

Open questions

- Are switching cost assumptions valid?
- Does an optimal schedule confound statistical assumptions?
- How much better is an optimized schedule than expert or random plan?
- Is the real world too constrained or uncontrollable for optimization?

So What?

Decision support for key test management questions

- Which is the least cost sequence?
- Which is the shortest duration sequence?
- What is the time/cost effect of adding, dropping, or reducing levels or factors?
- What will an alternate plan cost?

Compelling ROI opportunity

- Program analysis and modeling cost << one person year
- Suppose TCSO reduces MDAP DT/OT cost by 1%
  - *Field critical systems sooner*
  - *Same or better DOE coverage*
  - *Avoid ~$45M of testing cost, annually*

Implementation

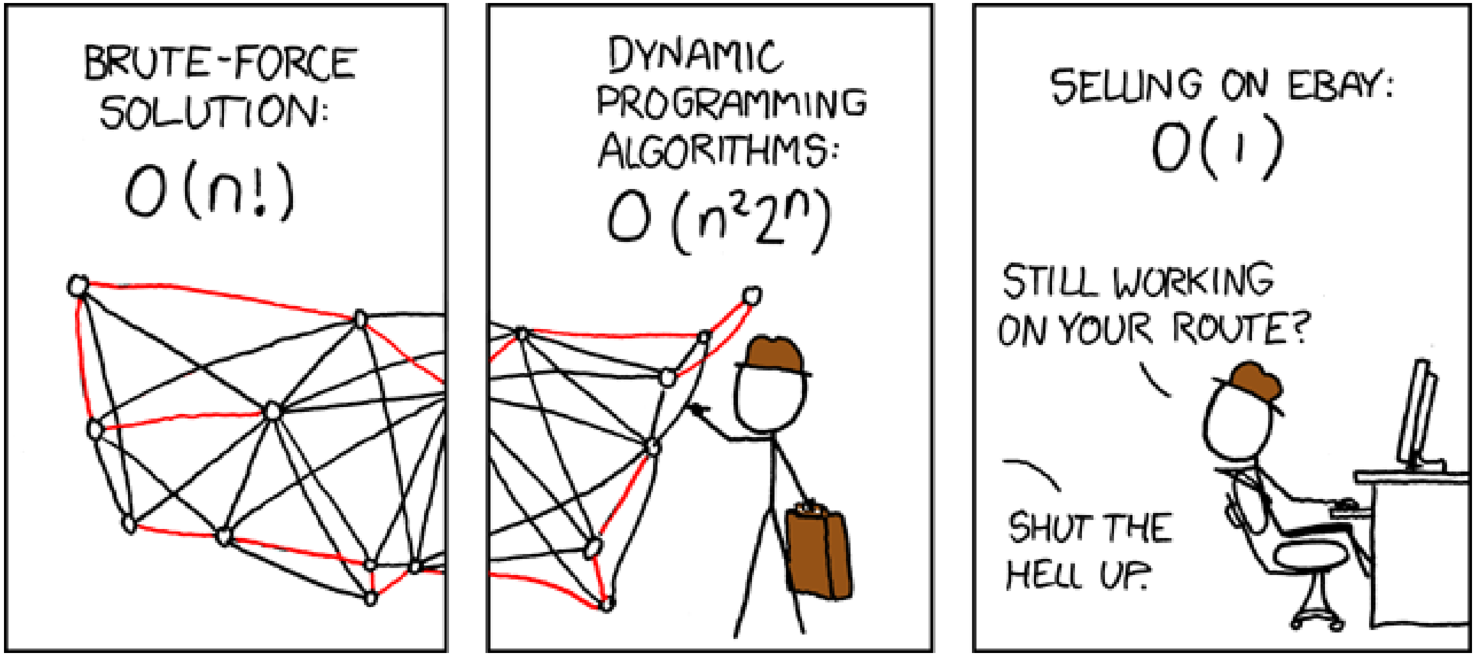
Program Applicability

- Using DOE
- Enough DT/OT lead time
- Non-trivial switching costs
- Configuration sequence is flexible

Next Steps

- Pilot program
- Refine
- Develop Dot Net UI
- Rollout, training, support

Sensitivity Analysis ;-)



http://xkcd.com/399/