

Design Catalogs: An Efficient Search Approach for Improved Flexibility in Engineering Systems Design

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Outline

- Issue:
 - Too many combinations to analyze
 - Traditional approach: very simplified
- Analytical Problem:
 - How do we take more realistic approach, within available analytical resources (time, modeling complexity)
- Proposed Solution:
 - Concept: use of “Design Catalog”
 - Implementation: depends on nature of industry
- Example application: parking garage



The Analytical Issue

- Complete analysis of an engineering system involves modeling and optimizing:
 - Basic infrastructure (oil rig, plant, network, etc.)
 - Considering possible evolutions of several factors over many periods (price and demand for products; quality and quantity of mineral in deposit)
 - Along with many modes of operations (routing of vehicles on network, allocation of production lines to products, etc)
 - Provide a range of measures of merit (NPV, Capex, Return on Investment)
- **IMPRactical TO DO EXHAUSTIVELY!**



The Full Problem

Initial Design	Uncertain Variables	Managers Adjust	Lifecycle Performance
Physical infrastructure (Many possibilities)	Price, demand for services (Many possibilities)	Best use of existing facilities; development of additional facilities (Many possibilities)	Realized net present value, rate of return, etc. (Many possibilities)



Size of Problem: Astronomical!

- Full analysis of variations is impractical
- Example 1: possible price variations over 20 periods, if the demand for capacity could be low, medium or high. The total number of combinations would be $3^{20} \sim 3 \frac{1}{2}$ billion...

And this is for only 3 demand levels!

- Example 2: possible decisions rules for expanding a facility. One could expand with 1, 2, or 3 unit capacity; at different times; under different conditions.

Over 20 periods, the possibilities are orders of magnitude greater than above!



Analytical Problem

- We know we can increase value by
 - Recognizing uncertainty
 - Dealing proactively with it, by creating flexibility
 - ... and enabling management to adjust
- How do we take this more realistic approach to deal with uncertainty in the design and management process, within available analytical resources?
- Specifically, how do we
 - Focus effort on most productive parts?
 - Expand variables considered – and stay within limits of capability (this session)

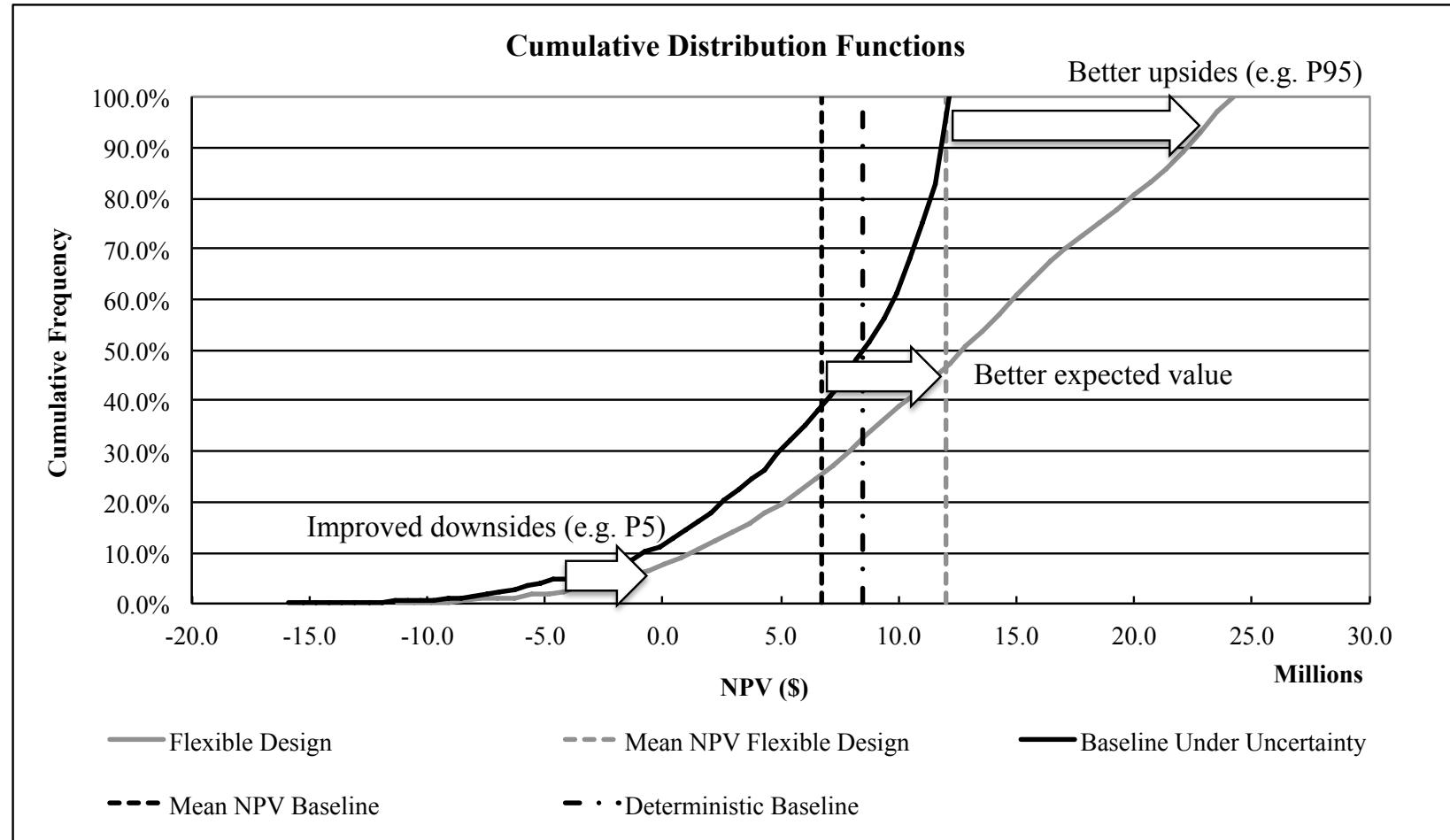


Benefits of Flexibility

- Provides the “right, but not the obligation, to change a complex system in the face of uncertainty”
- Changes expected lifecycle performance in two ways:
 - Recognizes value added by manager’s ability to adjust to changing uncertain conditions
 - Value can be large, should not be ignored
 - Adds value through explicit consideration of flexibility in design and operations
 - Several case studies support this
 - E.g. satellite systems, mining, real estate development, automotive, etc.
- Challenge: **needs to be carefully designed in system**



Benefits of Flexibility



Concept of Solution

We want:

- Middle ground between:
 - The simplest possible assumption typically used (e.g., market price is fixed over project life)
 - Complete set of possibilities
- Representative range of possibilities:
 - Small enough to be manageable analytically
 - Broad enough to cover all major situations
- Provide ability to adapt as uncertainty unfolds
 - E.g. better/worst market conditions than expected



Outline of Solution

- Use “Catalog” of possible conditions, with associated responses or “Operating Plans”
- The “Catalog” provides a limited number of scenarios and responses intended to describe relevant patterns designers might wish to anticipate
- Instead of 3^{20} combinations of 3 price levels over 20 periods, we consider a “handful” of scenarios:
 - Steady rising and falling prices
 - High prices at beginning, low at end
 - Low prices at start, surge in prices at end
- **Design flexibility to deal with uncertainty**



A “Design Catalog” Approach

Initial Design	Uncertain Variables	Managers Adjust	Lifecycle Performance
Physical infrastructure (Many possibilities)	Price, demand for services (5-10 scenarios)	Best use of existing facilities; development of additional facilities (5-10 responses)	Realized net present value, rate of return, etc. (Several)

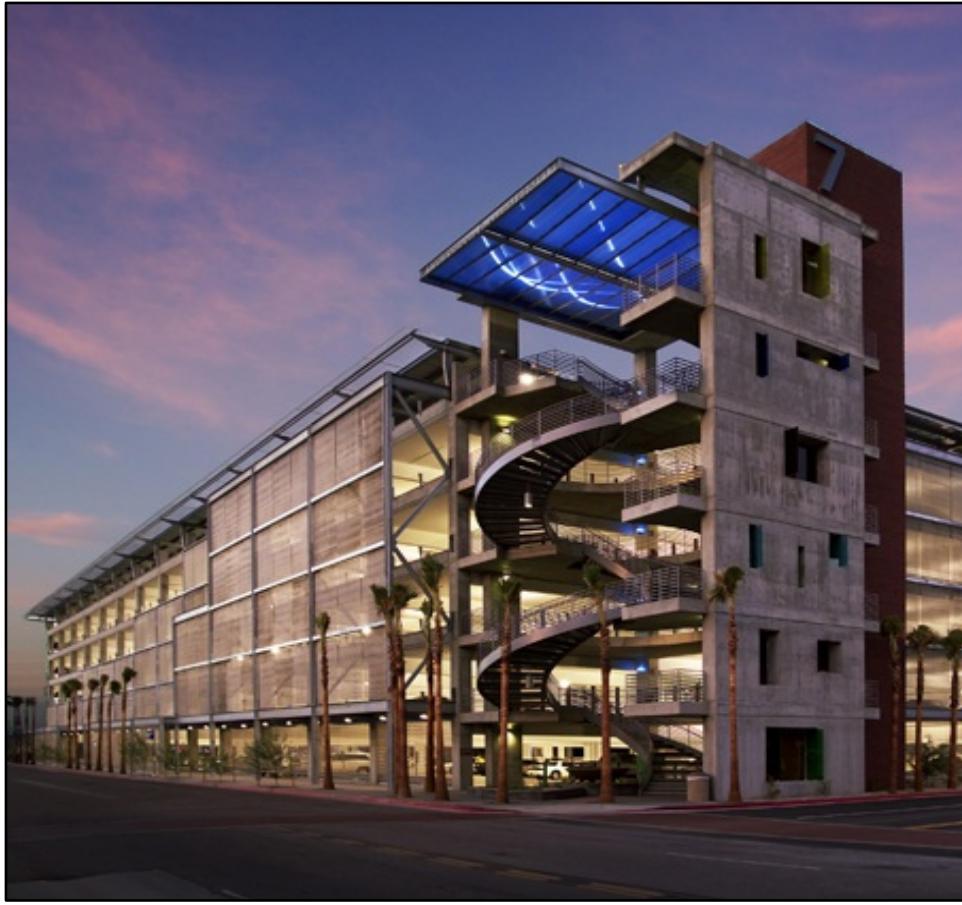


Benefits of Catalog Approach

- Enables consideration of major scenarios
- Avoids intractable exhaustive design analysis
- Encourages deeper investigation of risks and uncertainty with greatest impact on lifecycle performance
 - Additional scenarios and responses easily added
- Can be tailored to design problem
 - Catalog can be larger or smaller, focused on specific uncertainties
- Using modern computers, expanding analysis effort factor is easy



Parking Garage Example



Source: <http://www.cambridgearchitectural.com>



How to Construct Design Catalog?

- Suggested methodology
 - Step 1: build basic economic model (typical approach)
 - Step 2: find representative uncertain scenarios
 - Step 3: identify potential sources of flexibility in design and management
 - How we “add” value to the system
 - Step 4: for each scenario, find the best operating plan
 - This creates the “flexible” catalog
 - Step 5: assess value added by the catalog approach
 - How we “recognize” the value of managerial adjustments



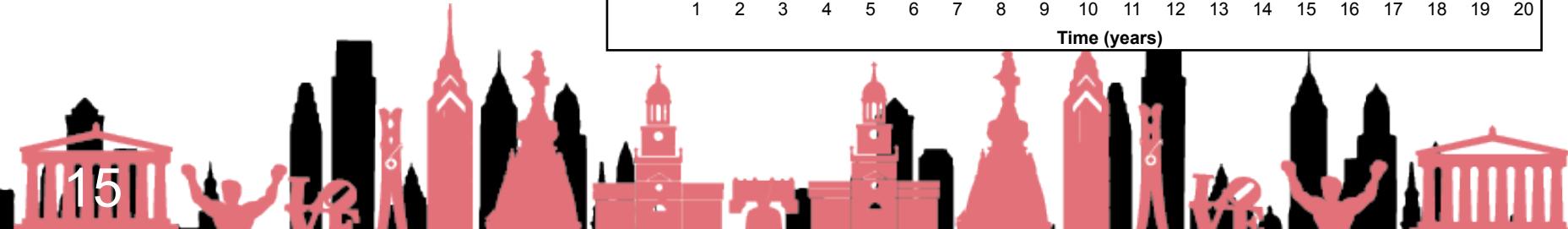
Step 1: Build Basic Model

- Take deterministic demand projection and price
- Build economic model of system, get initial performance of designs

Year	0	1	2	3	4	5
Demand		750	893	1015	1120	1210
Capacity	0	1200	1200	1200	1200	1200
Revenue	\$0	\$7,500,000	\$8,930,000	\$10,150,000	\$11,200,000	\$12,000,000
Operating costs	\$0	\$2,400,000	\$2,400,000	\$2,400,000	\$2,400,000	\$2,400,000
Land leasing and fixed costs	\$3,600,000	\$3,600,000	\$3,600,000	\$3,600,000	\$3,600,000	\$3,600,000
Cashflow	\$0	\$1,500,000	\$2,930,000	\$4,150,000	\$5,200,000	\$6,000,000
DCF		\$1,339,286	\$2,335,778	\$2,953,888	\$3,304,694	\$3,404,561
Present value of cashflow	\$36,899,412					
Capacity cost for up to two levels	\$6,400,000					
Capacity costs for levels above 2	\$16,336,320					
Net present value	\$10,563,092					
Initial CAPEX	\$22,736,320					

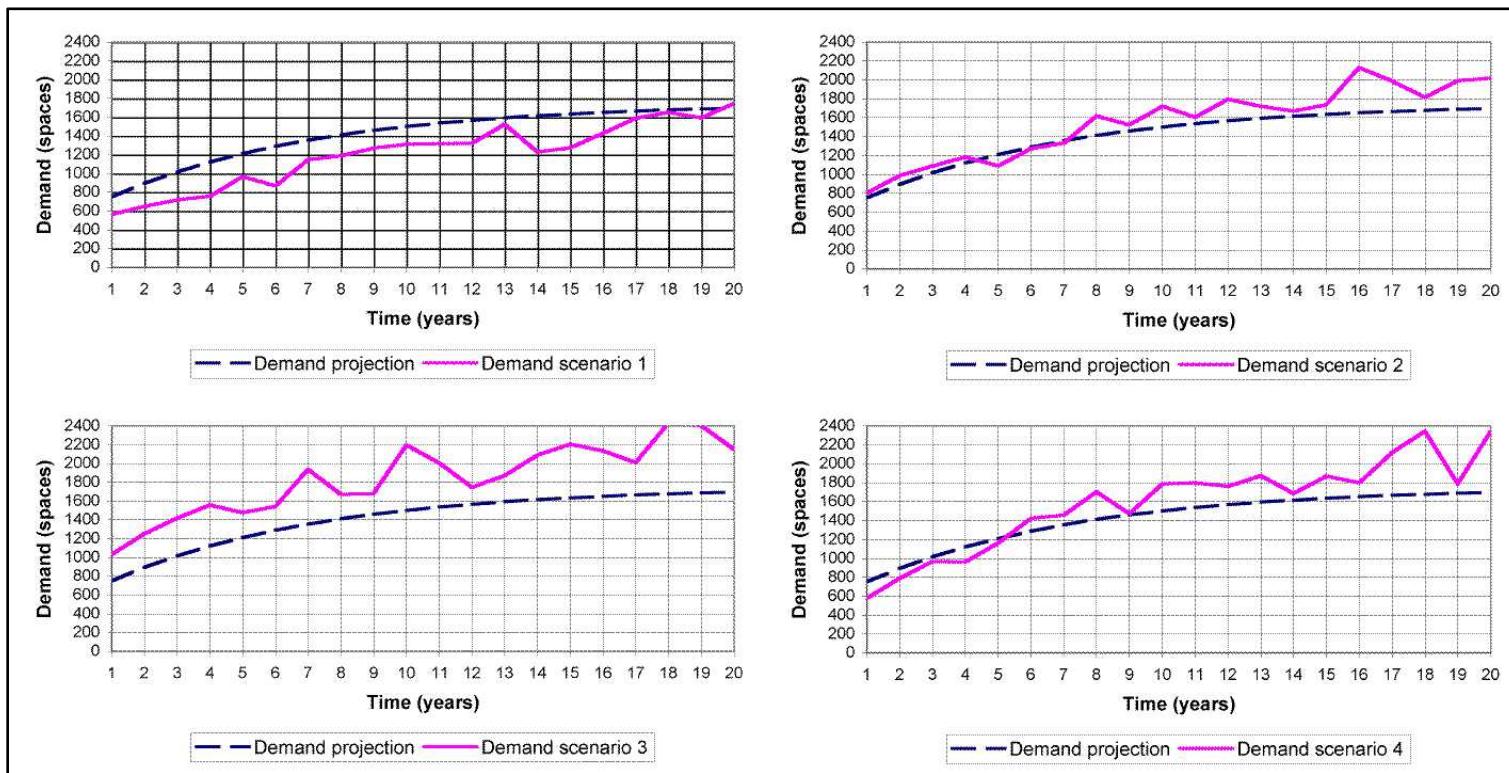


6 floor design → NPV
= \$10.6 million



Step 2: Find Representative Scenarios

- Determine sources of uncertainty (e.g. **demand**, price)
- Incorporate fluctuations around deterministic projection
- Produce a few demand scenarios (10 to 20) and look at representative properties. Any idea?



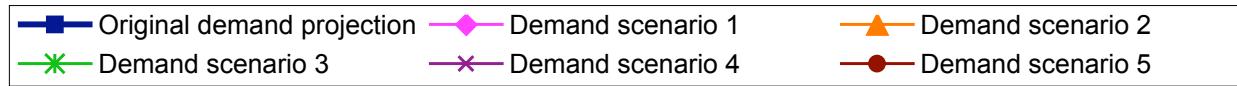
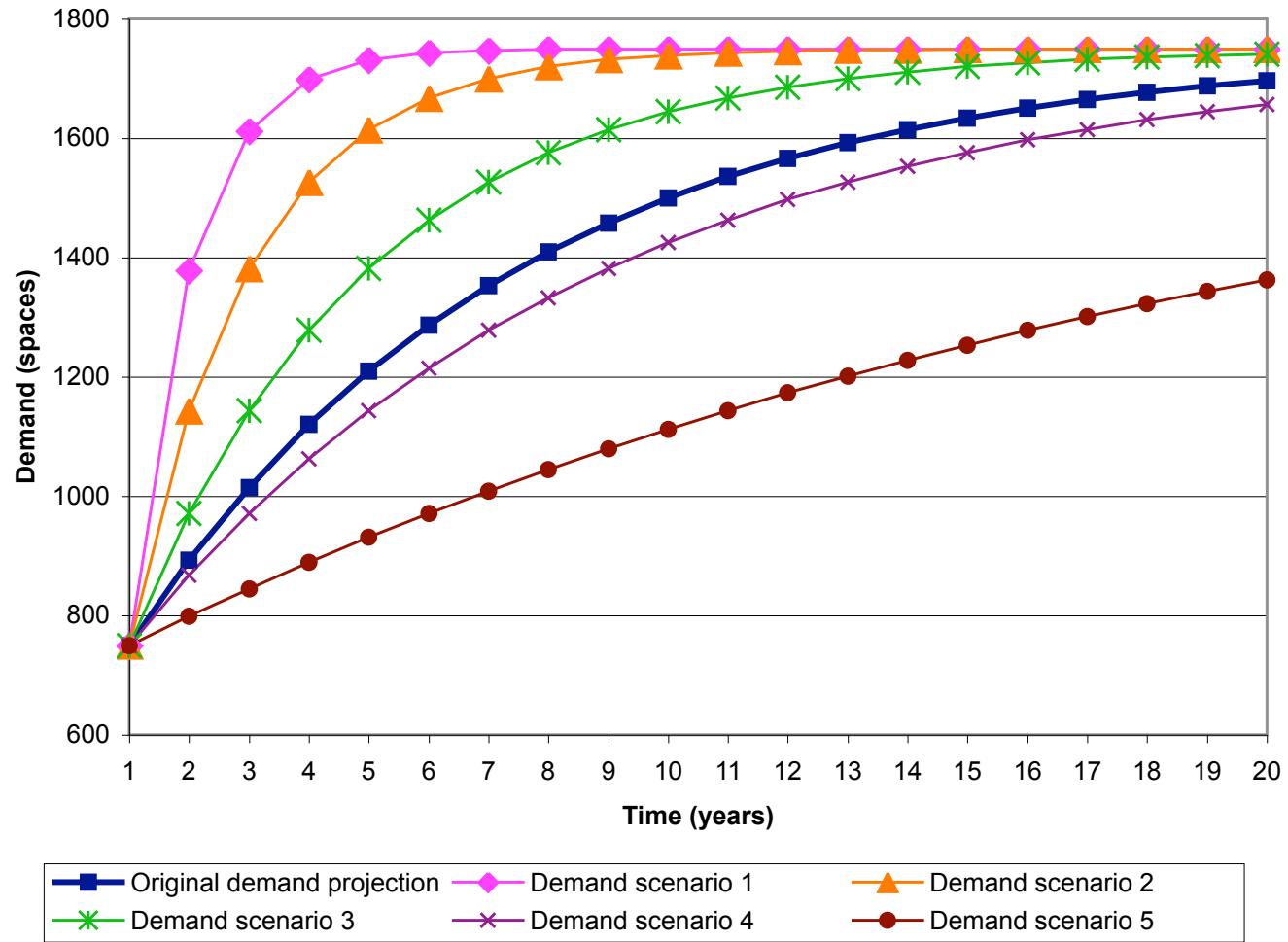
Finding Representative Scenarios

- Take demand growth projection between years 1-5 as criterion
 - Create five representative scenarios differentiated by early growth level
- How to differentiate categories?
 - Use mid-value between two categories
 - E.g. simulated scenario with growth above 123% similar to scenario 1, between 100%-123% scenario 2, etc.

Demand scenario category	Percentage increase from first to fifth year	Mid-value
1	131%	123%
2	115%	100%
3	84%	68%
4	52%	38%
5	24%	



Representative Scenarios



Step 3: Identify Flexibility

- Demand is uncertain, how to adapt?
 - Reduce losses: build fewer floors initially, reduce initial CAPX
 - Increase profits: expand as demand increases
 - Other sources of flexibility?
- Every system is different. Not obvious where to find flexibility!
 - Brainstorm, experts' opinions, etc.
 - Topic of active research



Step 3: Identify Flexibility

- Many ways to exploit flexibility to expand, in system design and management

DVs and DRs	Factor Description	Levels		
		-	0	+
a_{1-4}	Expansion allowed in years 1-4	No		Yes
a_{9-12}	Expansion allowed in years 9-12	No		Yes
a_{17-20}	Expansion allowed in years 17-20	No		Yes
dr	Expansion decision rule (years)	2	3	4
f_t	Number of floors expanded by	1	2	3
f_0	Number of initial floors	4	5	6

- “Levels” correspond to specific choice of design variable (DV) of management decision rule (DR)
- Note: $3^3 \times 2^3$ possibilities: 216 combinations!

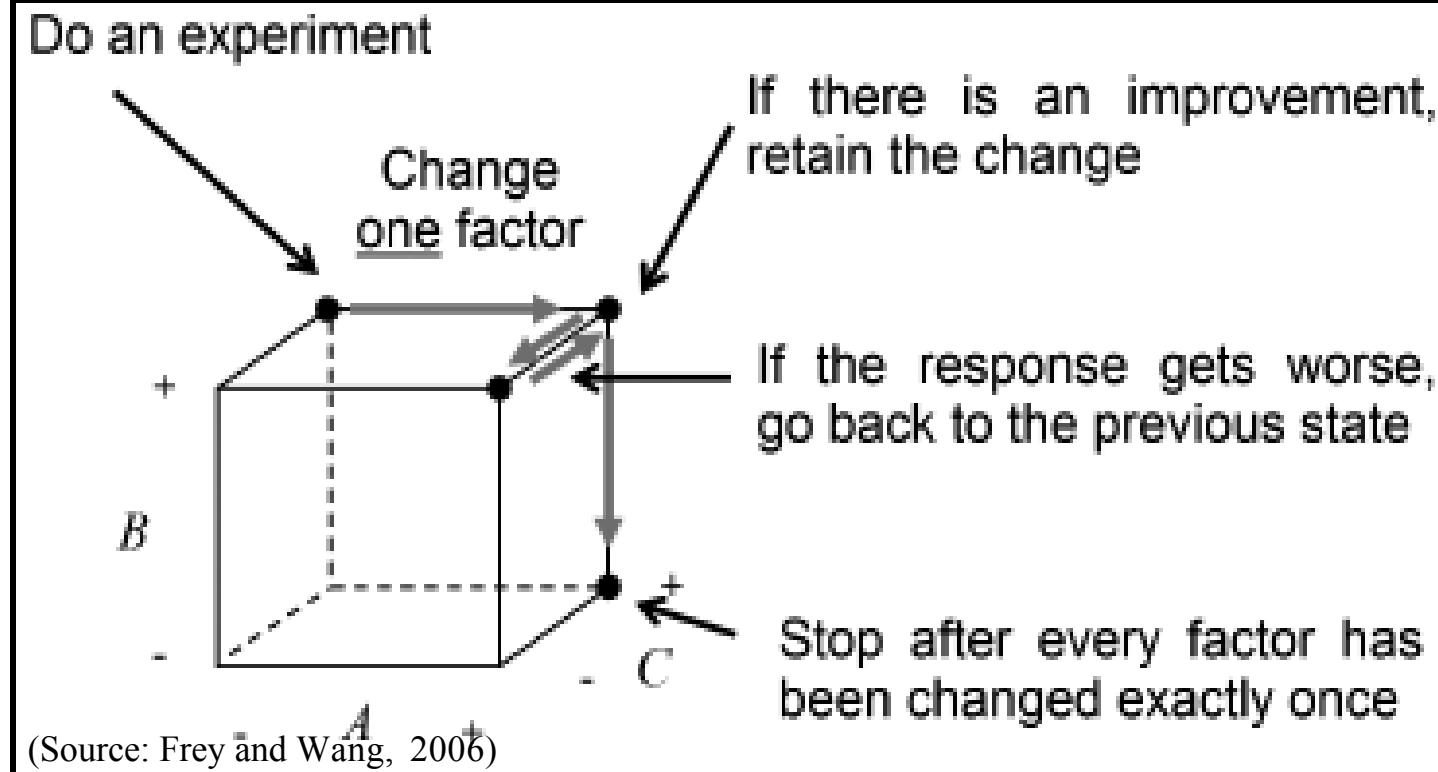


Step 4: Design Catalog

- Introducing adaptive One Factor At a Time (aOFAT) algorithm (Frey and Wang, 2006)
 - Used in design of experiments (DOE)
 - Applied to design of engineering systems to effectively search best design combinations
 - Provides shortcut to full factorial analysis
 - Cost-effective way to explore the space of possibilities
- Method inspired from adaptive aOFAT...
 - We do not perform statistical experiments while exploring the space of possible combinations
 - Consider one scenario at a time



Adaptive OFAT Algorithm

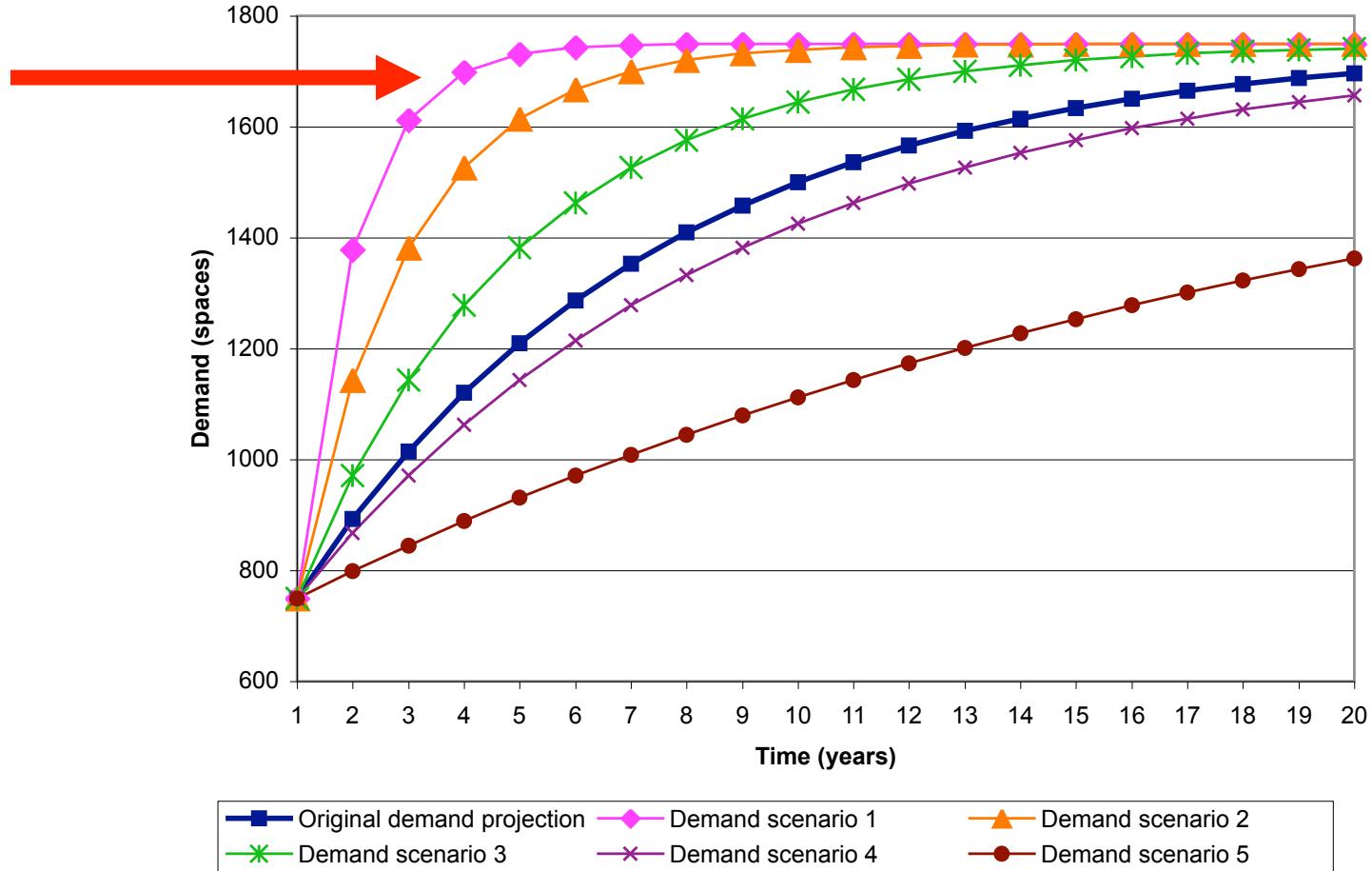


Step 4: Setup Search

- Pick one representative scenario (e.g. scenario 1)
- Choose one combination of design variables and management decision rules ⇒ Baseline condition
- Choose aOFAT sequence arbitrarily
 - Determines sequence in which combinations of design elements and decision rules are explored
 - No need to be arbitrary
- Measure NPV for each combination, following aOFAT sequence



Representative Scenarios



Step 4: Setup Search

- Example:

DEs and Management DRs	Description	Baseline Experiment	OFAT Sequence
A	Expansion allowed in years 1-4	No	f_t
B	Expansion allowed in years 9-12	No	f_0
C	Expansion allowed in years 17-20	No	a_{9-12}
D	Expansion decision rule (years)	3	dr
E	Number of floors expanded by	3	a_{17-20}
F	Number of initial floors	6	a_{1-4}

- Management DR: management decision rules (represented here by letters A to E in OFAT sequence)
- DE: design elements (also referred as design variable DV)
- Baseline experiment: set of design elements and management decision rules chosen for 1st experiment



Step 4: Explore Possibilities

- Measure NPV \Rightarrow Baseline value
- Change one “level” in the combination:
 - If NPV is higher, keep change; if lower, go back to previous state
- Explore all levels at least once, keep best combination
- Notice: only 10 combinations explored instead of 216!

Iteration	DV/DR changed:	DV/DR Level changed to:	NPV Output (million)	Best NPV output so far? (million)	Keep change?
1			\$13.4		
2	f_t	1	\$12.7	\$13.4	No
3	f_t	2	\$13.5	\$13.4	Yes
4	f_0	4	\$8.9	\$13.5	No
5	f_0	5	\$11.1	\$13.5	No
6	a_{9-12}	Yes	\$13.5	\$13.5	No
7	dr	2	\$13.5	\$13.5	No
8	dr	4	\$13.5	\$13.5	No
9	a_{17-20}	Yes	\$13.5	\$13.5	No
10	a_{1-4}	Yes	\$14.6	\$13.5	Yes

Step 4: Get the Catalog

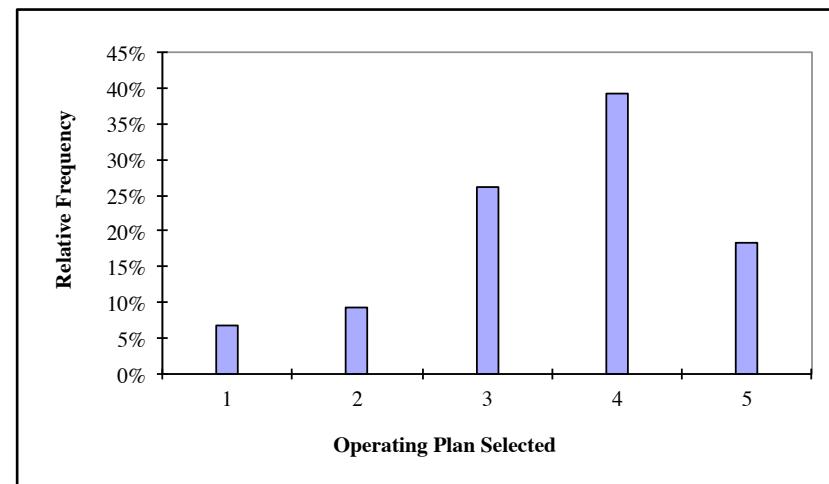
- Repeat same procedure for remaining 4 representative demand scenarios
- Get one operating plan best suited for each representative scenario
 - Now have a Catalog of Operating Plans!

DVs and DRs	Op. Plan 1	Op. Plan 2	Op. Plan 3	Op. Plan 4	Op. Plan 5
a_{1-4}	Yes	Yes	Yes	Yes	No
a_{9-12}	No	Yes	Yes	Yes	Yes
a_{17-20}	No	No	No	No	Yes
dr	3	2	2	2	4
f_t	2	2	2	1	1
f_0	6	6	4	4	4

Step 5: Assess Catalog Value

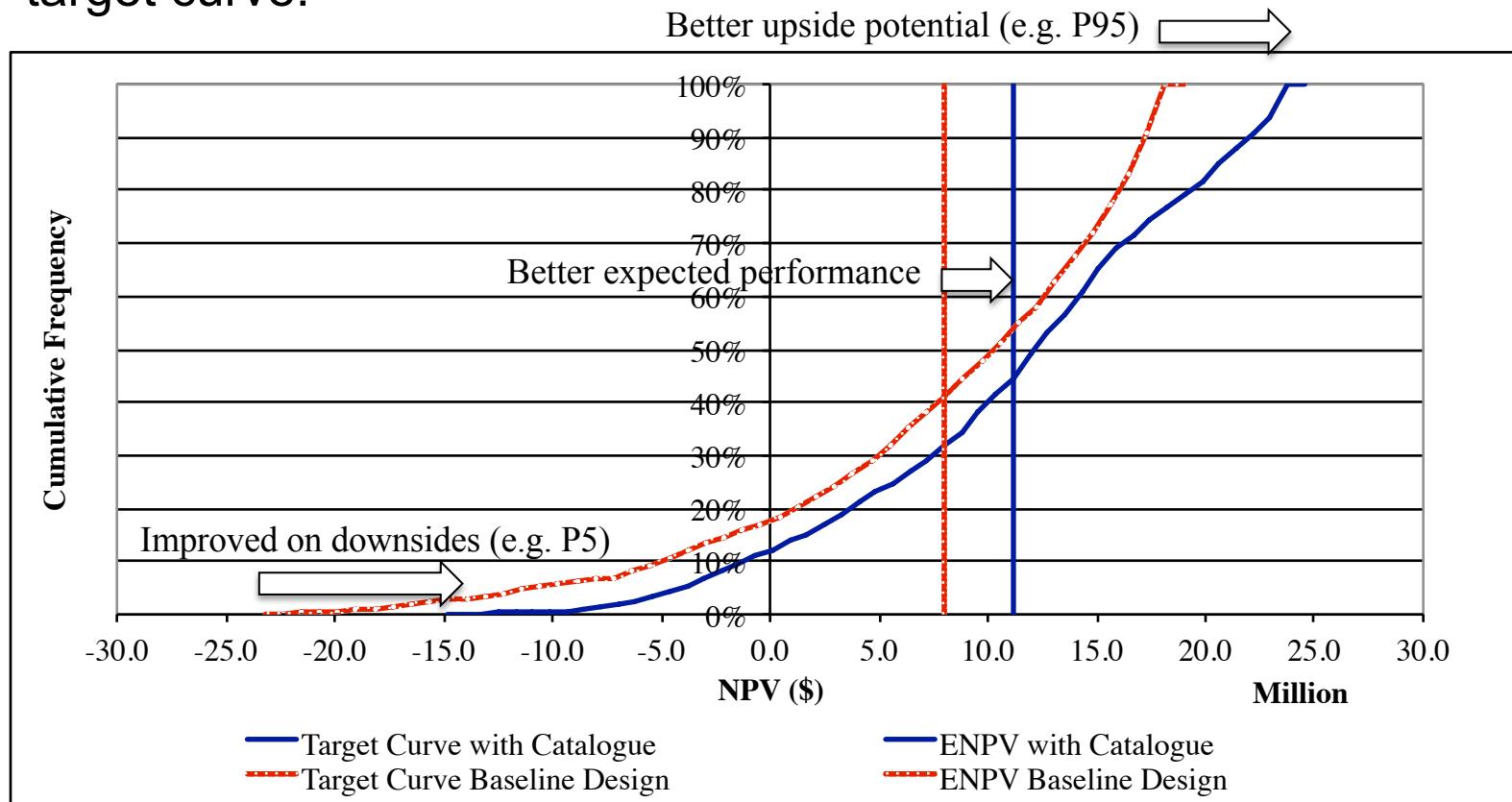
- Simulate operator's ability to choose operating plan depending on demand projection, and expand capacity along the way (2,000 demand scenarios)
- Recall, simulated scenario categorized using mid-value between categories; then assign associated operating plan
 - E.g. scenario with growth between years 1-5 above 123% is given operating plan 1, between 100%-123% operating plan 2, etc.

Demand scenario category	Percentage increase from first to fifth year	Mid-value
1	131%	123%
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Step 5: Assess Catalog Value

- Each assignment produces one NPV \Rightarrow represent distribution with target curve!



Step 5: Assess Catalog Value

- Multi-criteria table

	Deterministic	Inflexible	Catalogue	Best?
ENPV	10.6	8.0	11.2	Catalogue
P5 (Value At Risk)	N/A	-10.8	-4.2	Catalogue
P95 (Value At Gain)	N/A	17.7	23.3	Catalogue
Standard Deviation	N/A	8.9	8.3	Catalogue
E[Initial Investment]	22.7	22.7	15.2	Catalogue
E[Value of flexibility]	-	-	3.2	

- Design catalog recognizes value inherent in project by recognizing uncertainty and exploiting ideas of flexibility



Summary

- Methodology improves current practice significantly, which is simplistic regarding exogenous factors affecting value
- Not exhaustive! It does not use an “optimal” plan for each simulated scenario. This would:
 - Take far too long
 - Be very expensive
- Method uses a “Design Catalog” prepared ahead of analysis, designed to be “representative”
- Recognizes value from operational adjustments, and adds value through use of flexibility in design and operations



Suggested References

- Cardin, M.-A., R. de Neufville, D. M. Geltner, and Y. Deng. 2013. Design Catalogs: A Computationally Efficient Search Approach for Improved Flexibility in Engineering Systems. *Research in Engineering Design - Submitted 3 June 2013*.
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- Frey, D. D., and H. Wang. 2006. Adaptive One-Factor-at-a-Time Experimentation and Expected Value of Improvement. *Technometrics* 48 (3):418-431.

