## Lecture 21

# Flexibility in Multidisciplinary Design: Theory and Experimental Validation

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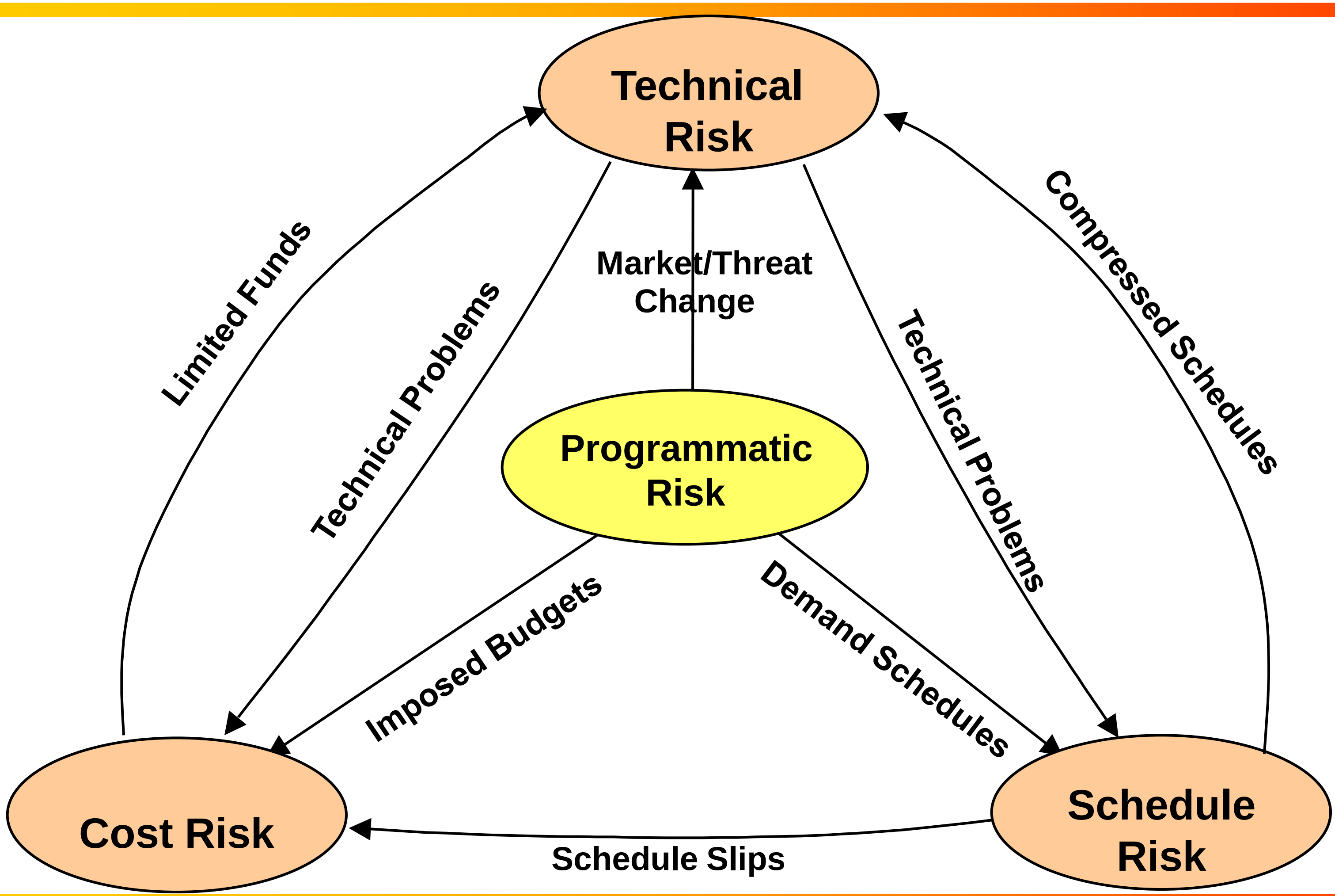
# Outline

- Introduction
  - Flexibility in Systems Design
    - Emphasis on "Infrastructures"
    - Garage Case Example
- Experimental Research
  - Design of Experiment
  - Preliminary Analysis and Results
- Discussion

# Risk Categories



# Value at Risk Concept

- Value at Risk (VAR) recognizes fundamental reality: actual value of any design or project can only be known probabilistically

- Because of inevitable uncertainty in
  - Future demands on system
  - Future performance of technology
  - Many other market, political factors

# Systems that Suffered Because of Unmitigated Risk

## B-58 Hustler (1960-70)

… Originally intended to fly at high altitudes and speeds to avoid Soviet fighters, the introduction of highly accurate Soviet surface-to-air missiles forced the B-58 into a low-level penetration role that severely limited its range and strategic value. This led to a brief operational career between 1960 and 1969.

## Iridium Constellation (1997-)

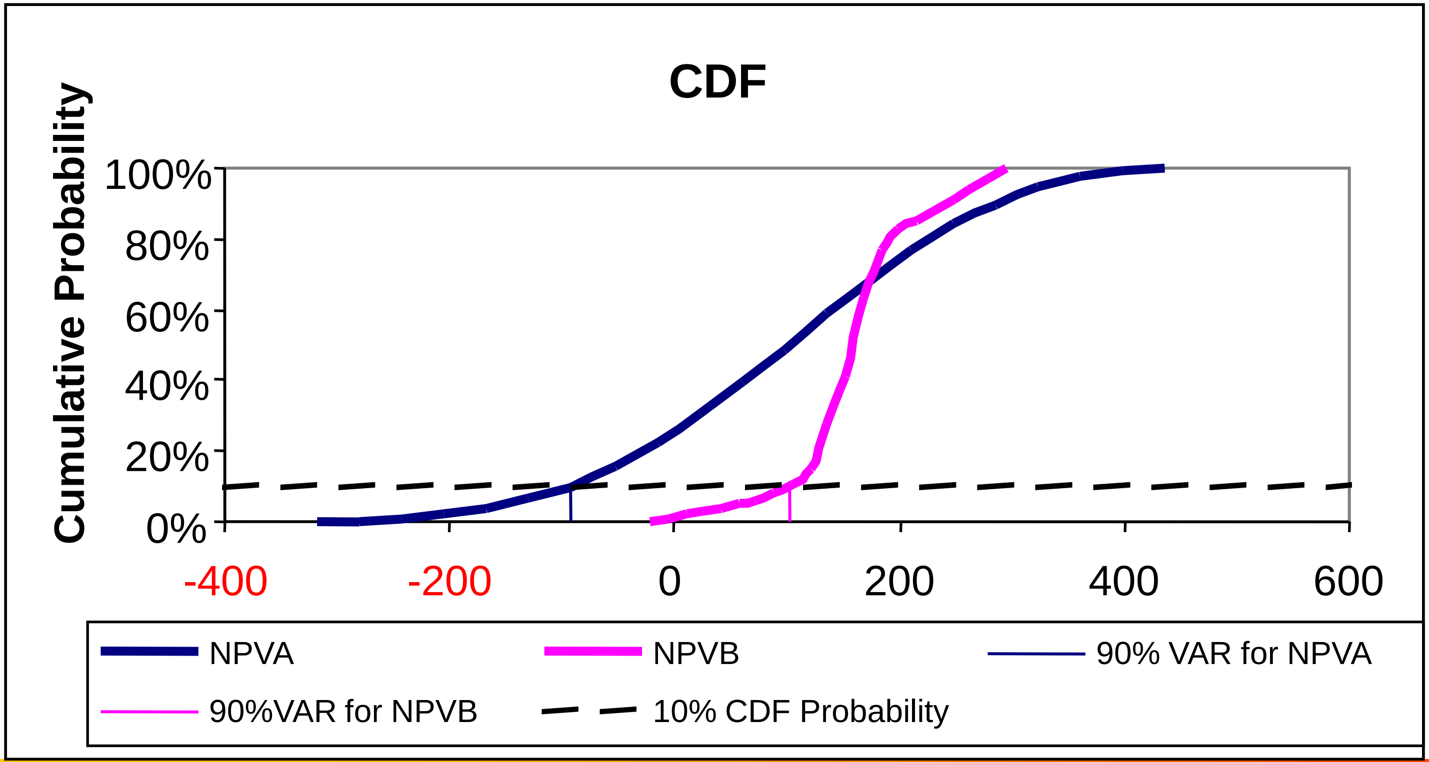
Iridium went public in 1997 with an ambitious plan to use a 66-satellite constellation of low earth orbit satellites to compete with the mobile phone companies in the market for wireless communications. But for a host of reasons … there were a host of regulatory, marketing and technical complications. By 1999, the company had filed Chapter 11.

# Value at Risk Definition

- Value at Risk (VAR) definition:
  - A loss that will not be exceeded at some specified confidence level
  - "We are *p* percent certain that we will not loose more than *V* dollars on this project"
- VAR easy to see on cumulative probability distribution (see next figure)

# VAR Cumulative Distribution Function

- Look at distribution of NPV of designs A, B:
  - 90% VAR for NPVA is -$91M
  - 90% VAR for NPVB is $102M

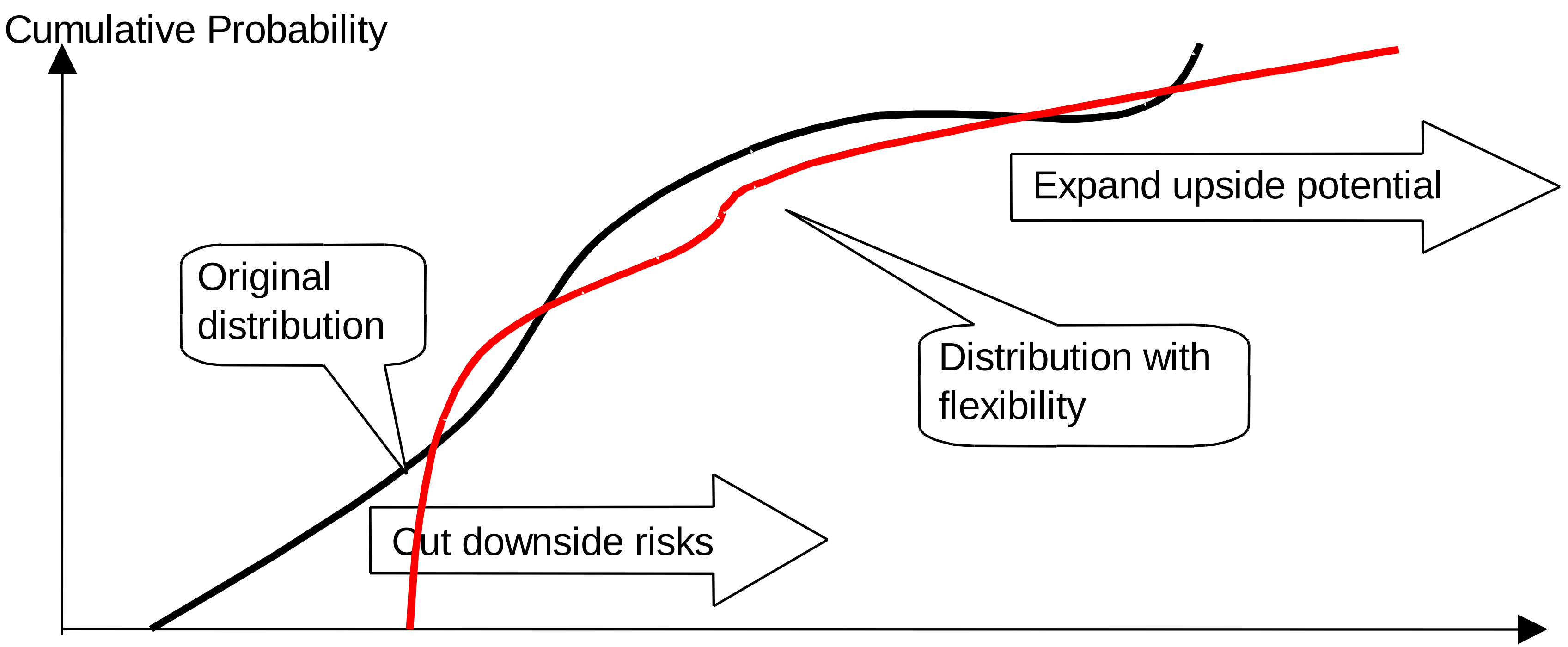


# VAR and Flexibility

- VAR is a common financial concept
- It stresses downside losses, risks
- However, designers also need to look at upside potential: "Value of Gain"
- Flexibility in design provides value by both:
  - Decreasing downside risk
  - Increasing upside potential
  - See next figure

# Sources of Value for Flexibility

## Cut downside ; Expand Upside




Value-at-Risk-and-Gain (VARG)

# Why Focus on Flexibility?

- Uncertainty affects future performance

- Wide-spread engineering practice is very "deterministic"
  - Optimize to "fixed" objectives or forecasts
  - Easy to be "sub-optimal" in the real world
  - Sensitivity analysis done *ex post*

- Flexibility shown to improve expected value and performance significantly (10% to 80% vs. initial design)
  - Example case studies in aerospace, automotive, mining, oil, real estate industries
  - See
    - http://ardent.mit.edu/real_options/Common_course_materials/papers.html
    - http://strategic.mit.edu

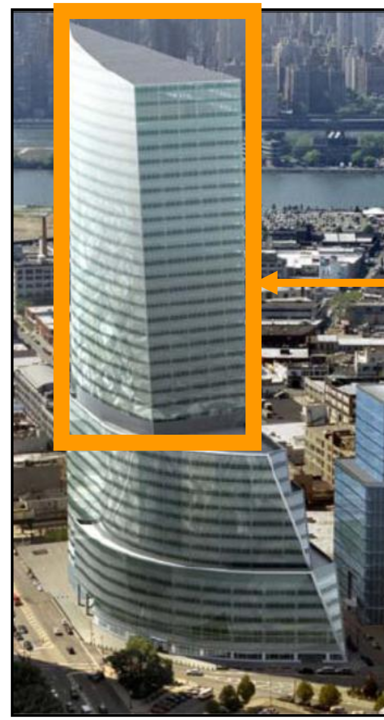
# What Do We Mean by "Flexibility"?

- Citygroup Campus, Court Square One and Two, Long Island, New York

Start smaller

Reduce exposure to downside risk of overcapacity

Pearson and Wittels, 2008



Expand when needed

Extra gains on upside opportunity

# Other Real-World Examples

- Ponte 25 de Abril, Lisbon

Estudio Mario Novais, iblioteca de Arte-Fundação , Calouste, Gulbenkian (1966)

http://en.wikipedia.org/wiki/File:Ponte25Abril1.jpg

- Bluewater commercial center parking garage, U.K.

# Parking Garage Project Example

Valuing Options by Spreadsheet: Parking Garage Case Example
Richard de Neufville, Stefan Scholtes and Tao Wang -- ASCE Journal of Infrastructure Systems, Vol.12, No.2. pp. 107-111, 2006

# Intended "Take-Aways"

- Design project for fixed objective (mission or specifications) is engineering base case
  - Can use optimization as discussed in this class

- Recognizing uncertainty $\Rightarrow$ different design (because of system non-linearities)

- Harnessing flexibility $\Rightarrow$ even better design (it avoids costs, expands only as needed)

# Parking Garage Case

- Garage in area where population expands
  - New commercial/retail opportunities
- Actual demand is necessarily uncertain
  - Demand drives capacity for # of parking spots
- Design Opportunity: Strengthened structure
  - Enables future addition of floor(s) (flexibility)
  - Costs more initially (flexibility costs) for same capacity
- Design issue: is extra cost worthwhile?

# Parking Garage Case Details

- Demand
  - At start is for 750 spaces
  - Over next 10 years is expected to rise (exponentially) by another 750 spaces
  - After year 10 maybe 250 more spaces
  - could be 50% off the projections, either way;
  - Annual volatility for growth is 10%
  - Consider 20 years
- Average annual revenue/space used = $10,000
- The discount rate taken to be 12%

# Parking Garage Details (Cont)

- Costs
  - annual operating costs (staff, cleaning, etc.) = $2,000 /year/space available

    (note: spaces used is often < spaces available)
  - Annual lease of the land = $3.6 Million
  - construction cost = $16,000/space + 10% for each level above the first level
- Site can accommodate 200 cars per level

# Step 1: Set Up Base Case

## Demand growth as predicted, no variability

| Year | 0 | 1 | 2 | 3 | 19 | 20 |
|---|---|---|---|---|---|---|
| Demand | | 750 | 893 | 1,015 | 1,688 | 1,696 |
| Capacity | | 1,200 | 1,200 | 1,200 | 1,200 | 1,200 |
| Revenue | | $7,500,000 | $8,930,000 | $10,150,000 | $12,000,000 | $12,000,000 |
| Recurring Costs | | | | | | |
| Operating cost | | $2,400,000 | $2,400,000 | $2,400,000 | $2,400,000 | $2,400,000 |
| Land leasing cost | $3,600,000 | $3,600,000 | $3,600,000 | $3,600,000 | $3,600,000 | $3,600,000 |
| Cash flow | | $1,500,000 | $2,930,000 | $4,150,000 | $6,000,000 | $6,000,000 |
| Discounted Cash Flow | | $1,339,286 | $2,335,778 | $2,953,888 | $696,641 | $622,001 |

| | |
|---|---|
| Present value of cash flow | $32,574,736 |
| Capacity costs for up to two levels | $6,400,000 |
| Capacity costs for levels above 2 | $16,336,320 |
| Net present value | **$6,238,416** |

capex= capital expenditures=initial investment



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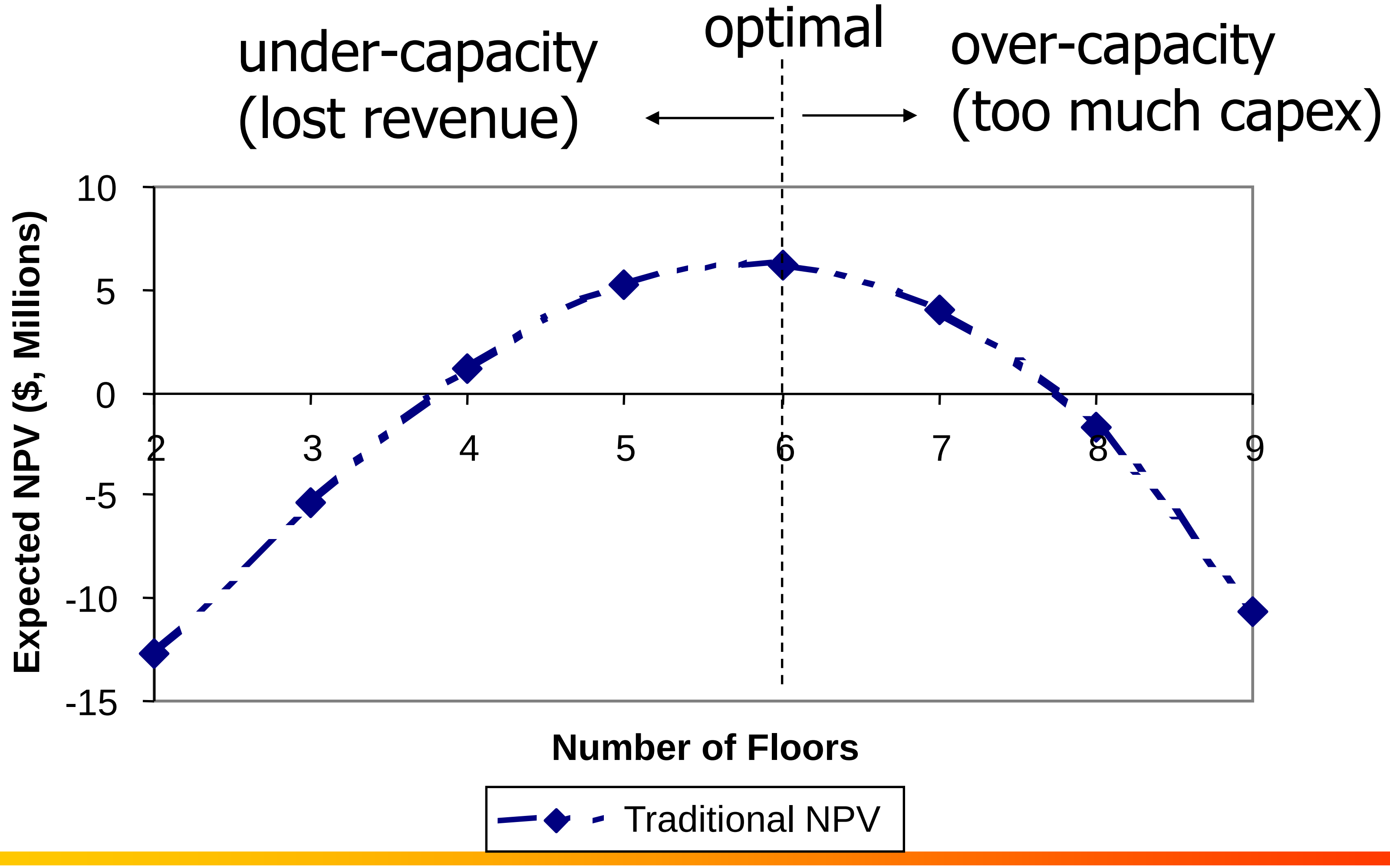
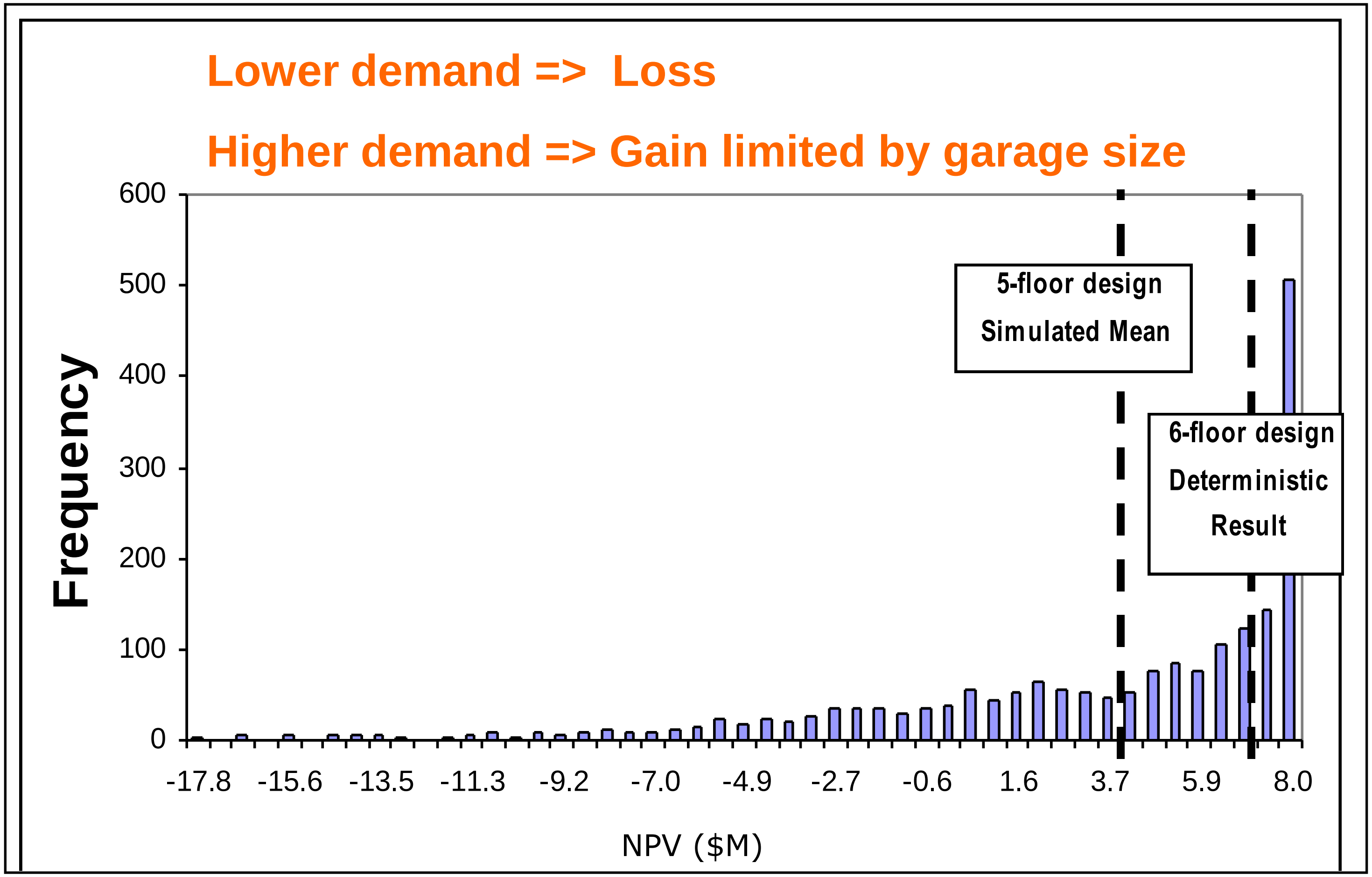
# Optimal Design for Base Case
# No Uncertainty

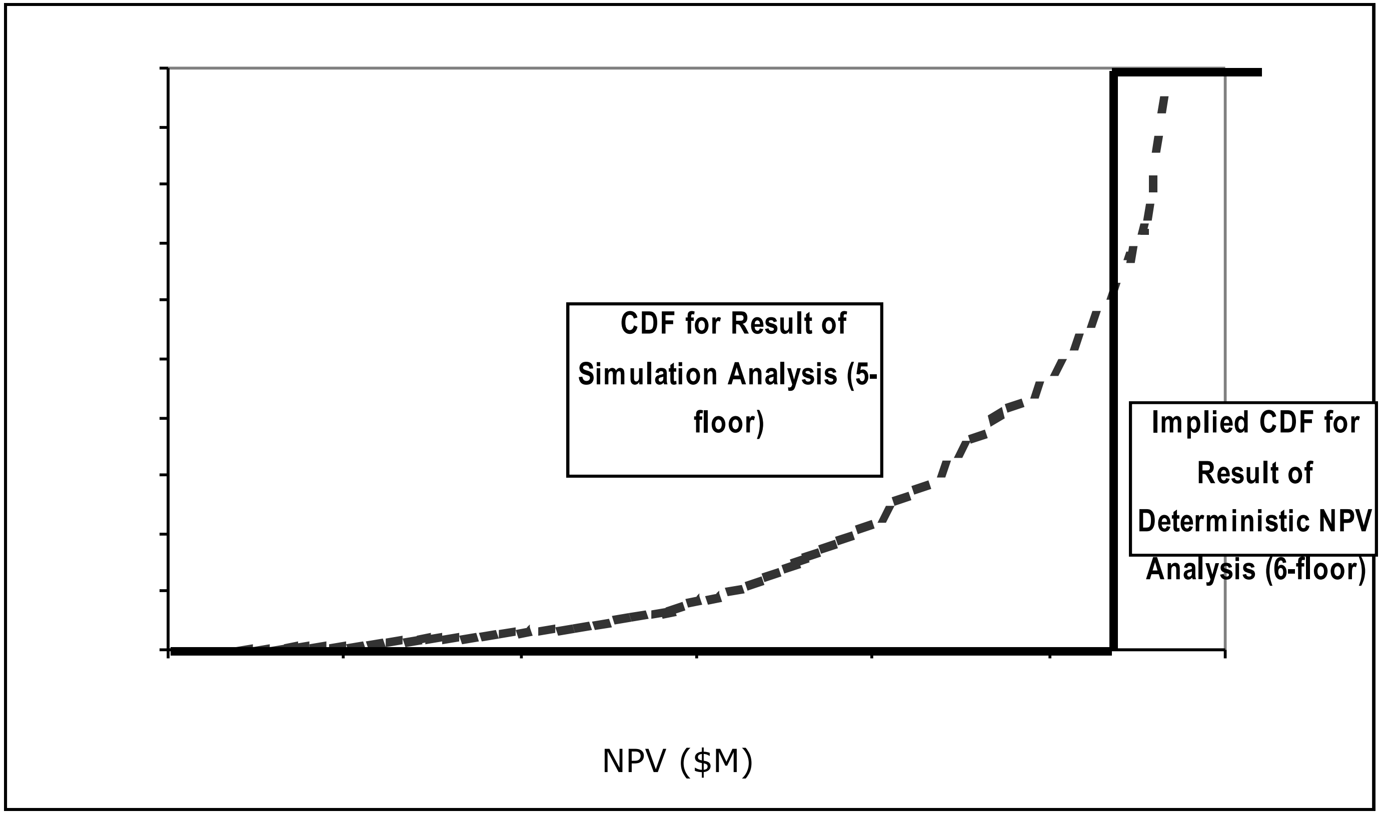


# Step 2: Simulate Uncertainty



# NPV Cumulative Distributions

## Compare CDF of (5 Fl) with (unrealistic) fixed 6 Fl design



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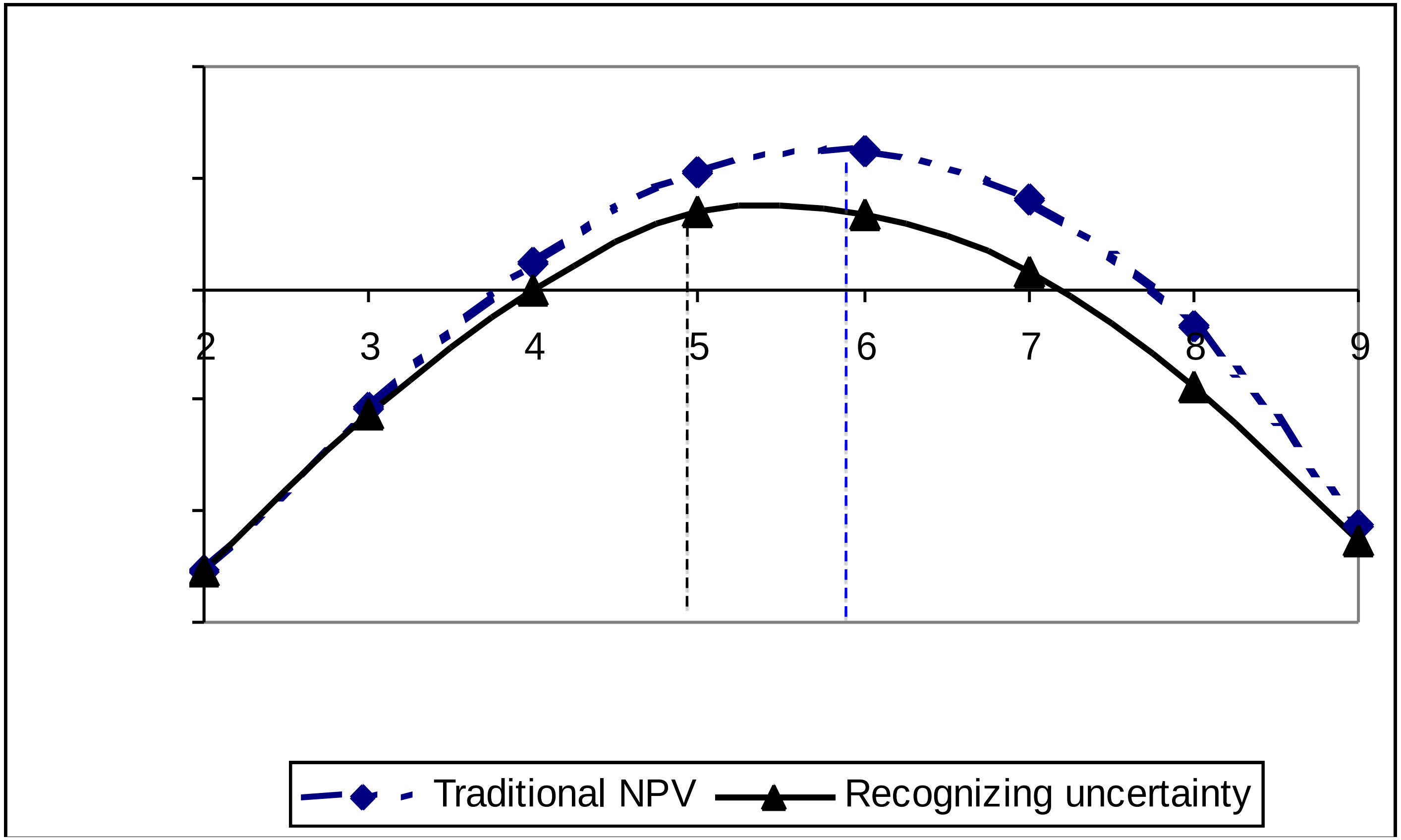
# Recognizing Uncertainty ⇒ Different Design (5 floors)



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# Step 3: Introduce Flexibility into Design (Expand only When Needed)

| Year | 0 | 1 | 2 | 3 | 19 | 20 |
|---|---|---|---|---|---|---|
| Demand | | 820 | 924 | 1,044 | 1,519 | 1,647 |
| Capacity | | 800 | 800 | 1,200 | 1,600 | 1,600 |
| Decision on expansion | | | expand | | | |
| Extra capacity | | | 400 | | | |
| Revenue | | $8,000,000 | $8,000,000 | $10,440,000 | $15,190,000 | $16,000,000 |
| Recurring Costs | | | | | | |
| Operating cost | | $1,600,000 | $1,600,000 | $2,400,000 | $3,200,000 | $3,200,000 |
| Land leasing cost | $3,600,000 | $3,600,000 | $3,600,000 | $3,600,000 | $3,600,000 | $3,600,000 |
| Expansion cost | | | $8,944,320 | | | |
| Cash flow | | $2,800,000 | -$6,144,320 | $4,440,000 | $8,390,000 | $9,200,000 |
| Discounted Cash Flow | | $2,500,000 | -$4,898,214 | $3,160,304 | $974,136 | $953,734 |
| Present value of cash flow | $30,270,287 | | | | | |
| Capacity cost for up to two levels | $6,400,000 | | | | | |
| Capacity costs for levels above 2 | $7,392,000 | | | | | |
| Price for the option | $689,600 | | | | | |
| Net present value | **$12,878,287** | | | | | |

**Including Flexibility ⇒ Another, better design:**

**4 Floors with strengthened structure enabling expansion**

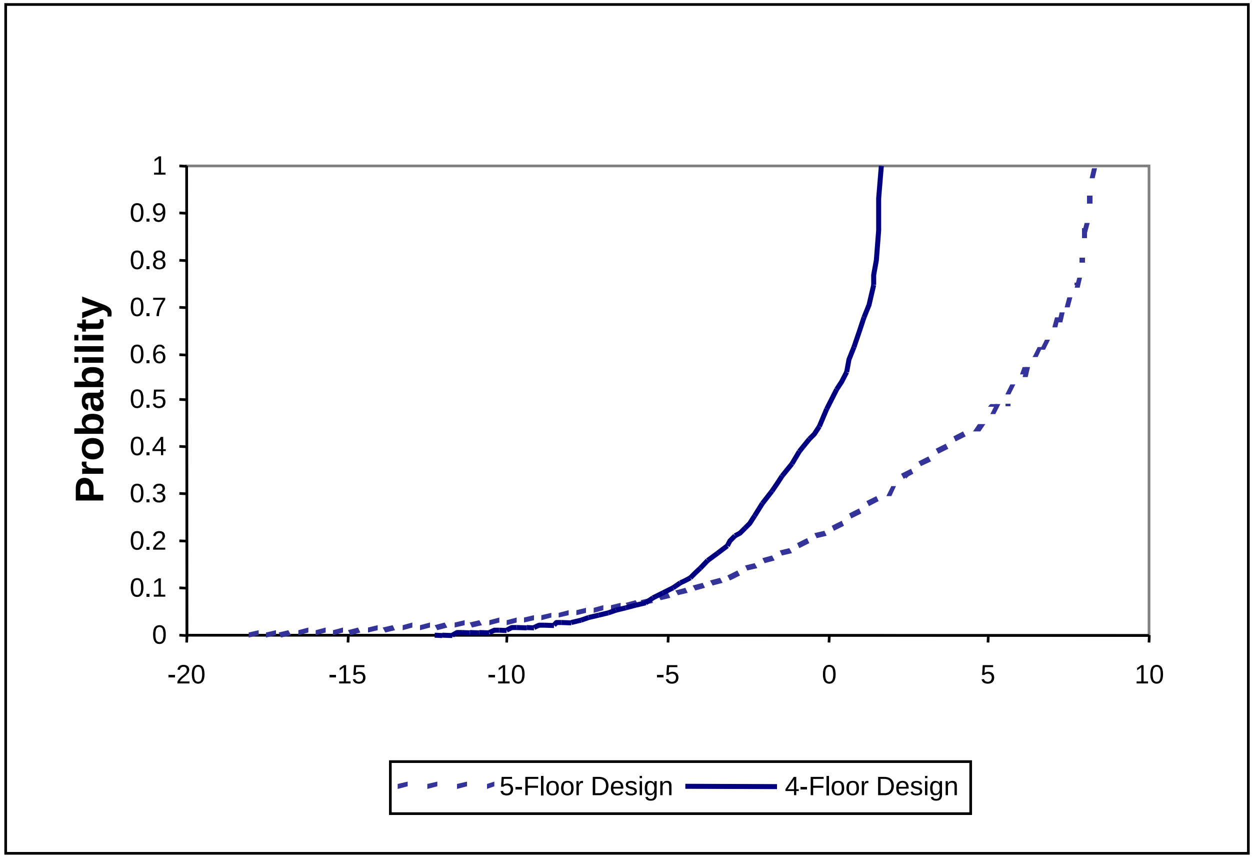
# Summary of Design Results from Different Perspectives

| Perspective | Simulation | Option Embedded | Design | Estimated Expected NPV |
|---|---|---|---|---|
| Deterministic | No | No | 6 levels | $6,238,416 |
| Recognizing Uncertainty | Yes | No | 5 levels | $3,536,474 |
| Incorporating Flexibilty | Yes | Yes | 4 levels with strengthened structure | $10,517,140 |

**Why is the optimal design much better when we design with flexibility?**

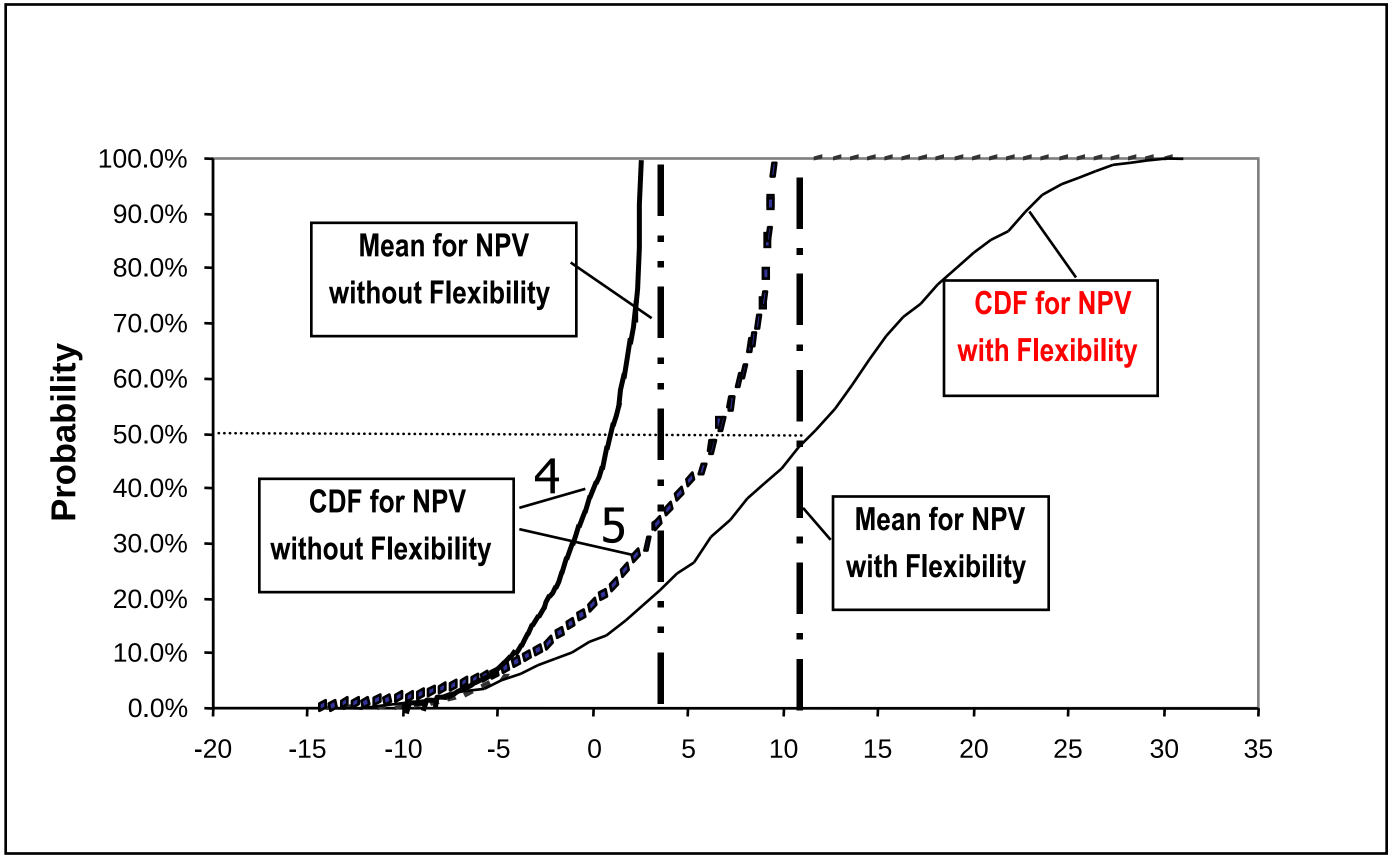
# Sources of Value for Flexibility

## 1) Minimize exposure to downside risk



# Sources of Value for Flexibility

## 2) Maximize potential for upside gain



# Comparison of Designs With and Without Flexibility

| Design | Design with Flexibility Thinking (4 levels, strengthened structure) | Design without Flexibility thinking (5 levels) | Comparison |
|---|---|---|---|
| Initial Investment | $18,081,600 | $21,651,200 | Better with options |
| Expected NPV | $10,517,140 | $3,536,474 | Better with options |
| Minimum Value | -$13,138,168 | -$18,024,062 | Better with options |
| Maximum Value | $29,790,838 | $8,316,602 | Better with options |

**Wow! Everything is better! How did it happen?**

**Root cause: change the framing of the problem**

- **recognize uncertainty**
- **add in flexibility thinking**

**However, this does not come naturally to most engineers and managers. It often seems "safer" to retreat to the simplicity of the base case.**

# A "Complete" Flexible Design Approach Contains the Following…

- Four elements are necessary
  1. A base case without flexibility
     - Need to measure value of flexibility relative to a base case. Flexibility generates value relative to base case
  2. Uncertainty that is being addressed
     - What causes the volatility in outcome?
  3. How flexibility is embedded in the design
     - What "real options" are embedded and how, where?
  4. When flexibility will be exercised
     - Conditions, incl. timing under which flexible options should be exercised (triggered)

# Experimental Design Validation Research

# Research Topic

- Develop new design procedure to guide creative thought process for flexibility
  - Access valuable "low-hanging" opportunities in early design phase

- Test in "controlled" experimental setting
  - Easily repeated for statistical analysis
  - Different from typical case study approach

- Develop new methodology to evaluate design process improvement **quantitatively**

# Motivation

- Designing flexible infrastructures is not easy
  - Communication/information issues
  - Many uncertainties, where to focus?
  - How to enable and manage in complex systems?

- Current design procedures non-systematic and/or overly complex
  - "Direct interactions" (e.g. Lin, 2009)
  - Based on Design Structure Matrix (sDSM, CPA, C-DSM)
  - Screening models

- Current design procedure validation methodologies focus on **qualitative** assessment of process and outcome

# Research Questions

- Methodological
  - "Is it possible to develop a performance-based validation methodology for a proposed design procedure different from the ones available today, which focus on impressions of quality of the process and outcome?"

- Substantive
  - "Does the proposed design procedure lead to demonstrable, quantitative performance improvements compared to a initial benchmark?"

# Proposed Design Procedure

- Two factors
  - Education mechanism about flexibility in infrastructure design and management
  - Idea creation ("ideation") mechanism

- Education mechanism (E)
  - Only prior training in engineering and applied sciences (-)
  - Short lecture on flexibility (+)

- Ideation mechanism (I)
  - Free undirected (-)
  - Collaborative, directed based on "prompting" (+)

# Design Ideation Sessions

- Collaborative sessions
  - Simplified real estate infrastructure design problem
  - Teams of 3 designers: ESD.344, 15.428, ESD.77 grad students
  - Controlled "lab" environment: do the same for ALL teams

- Each team does **two** 25 minutes sessions
  - Session 1: within-group "control" procedure (exp't 1)
  - Session 2: 1 of 4 possible exp'ts in 2 x 2 DOE setup

| **Ideation Mechanism (I)** | **Education Mechanism (E)** | |
|---|---|---|
| | Prior Training Only (-) | Lecture on Flexibility (+) |
| Free-undirected (-) | Exp't 1 | Exp't 3 |
| Prompting (+) | Exp't 2 | Exp't 4 |

# Session Description - Intro

- Design problem presentation
  - Real estate multi-family residential development project: condo and/or apartment building
  - Market description
  - Design performance $\propto$ NPV
  - Suggested benchmark design

- Task assignment
  - Recommend alternative designs with goal of improving expected performance (i.e. ENPV)

# Session Description - Ideation

- Using online Group Support System (GSS) software ThinkTank®

# Analysis

- Extract design recommendations using coding procedure on ideation reports
- Flexible design alternative(s) implemented using Excel Monte Carlo simulation model
- Assess ideation quality: "Δ" between S1 and S2
  - Number of "complete" flexibility ideas
  - Number of "good" flexibility ideas
  - "Absolute" ENPV improvement vs. benchmark design
- Statistical analysis: permutation/randomization

# Design Alternatives Implementation

- Excel Monte Carlo simulation model

**NPV w Flexible Choice Each Phase:**

| | | Phase 1 | Phase 2 | Phase 3 |
|---|---|---|---|---|
| **Year** | **0** | **1** | **2** | **3** |
| *Next Phase Developed As:* | CONDO | CONDO | APT | |
| *Sales Price/Unit* | | 174,122 | 179,346 | 229,308 |
| *Units Demand* | | 117 | 103 | 117 |
| *Constr & Sales/Unit* | | 137,927 | 133,099 | 236,009 |
| *Develop Current Phase?* | | YES | YES | NO |
| *Planned Capacity Deployment* | | 309 | 0 | 0 |
| *Expand Capacity this Phase?* | | NO | NO | NO |
| *Additional Capacity* | | 0 | 0 | 0 |
| *Total Capacity Added* | | 309 | 0 | 0 |
| *Units Sold* | | 117 | 103 | 89 |
| *Sales Revenue* | | 20,375,572 | 18,512,808 | 20,352,771 |
| *Total Constr & Sales Costs* | | 42,619,551 | 0 | 0 |
| *Net Cash Flow* | | -22,243,979 | 18,512,808 | 20,352,771 |
| *PV of Cash Flow* | | -20,596,277 | 15,871,749 | 16,156,686 |
| *NPV (exclu land)* | **11,432,158** | | | |



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# Summary Preliminary Results

| Question | Prelim. answer | Remarks |
| --- | --- | --- |
| Is it possible to develop and test a quantitative performance-based validation method? | Yes | - Done 26 groups, 71 participants<br>- Extracted successfully flexible design recommendations from ideation reports<br>- Evaluated using quantitative model |
| Does design procedure improve performance vs. benchmark? | Yes | - Statistically significant mean difference between treatments, observed for all 3 criteria ($\Delta$complete ideas, $\Delta$good ideas, $\Delta$absolute ENPV)<br>- Prompting mechanism seems more effective than lecturing |

# Mean Differences: ΔComplete Ideas

| | Expt 1 (E-I-) | Expt 2 (E-I+) | Expt 3 (E+I-) | Expt 4 (E+I+) |
|---|---|---|---|---|
| Expt 1 (E-I-) | 0 | 1.75** (0.64) | 0.75* (0.30) | 2.25** (0.76) |
| Expt 2 (E-I+) | | 0 | -1.00* (0.55) | 0.50 (0.68) |
| Expt 3 (E+I-) | | | 0 | 1.50* (0.72) |
| Expt 4 (E+I+) | | | | 0 |

* $p < 0.05$; ** $p < 0.01$

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# Mean Differences: $\Delta$Good Ideas

| | Expt 1 (E-I-) | Expt 2 (E-I+) | Expt 3 (E+I-) | Expt 4 (E+I+) |
|---|---|---|---|---|
| Expt 1 (E-I-) | 0 | 1.35** (0.48) | 0.75** (0.30) | 1.88** (0.63) |
| Expt 2 (E-I+) | | 0 | -0.60* (0.30) | 0.53 (0.55) |
| Expt 3 (E+I-) | | | 0 | 1.13* (0.60) |
| Expt 4 (E+I+) | | | | 0 |

* $p < 0.05$; ** $p < 0.01$

# Mean Differences: ΔAbsolute ENPV

| (millions) | Expt 1 (E-I-) | Expt 2 (E-I+) | Expt 3 (E+I-) | Expt 4 (E+I+) |
|---|---|---|---|---|
| Expt 1 (E-I-) | 0 | 2.33** (0.90) | 2.47** (0.95) | 2.86** (1.07) |
| Expt 2 (E-I+) | | 0 | 0.14 (0.99) | 0.54 (1.08) |
| Expt 3 (E+I-) | | | 0 | 0.40 (1.09) |
| Expt 4 (E+I+) | | | | 0 |

* $p < 0.05$; ** $p < 0.01$

# How Did ESD.77/16.888 Do?

- 6 teams participated in exp'ts 1 and 4
  - Experiment 1: 3 control groups (E-I-)
  - Experiment 4: 3 treatment groups (E+I+)
- Average scores compared to SDM/CRE students?
  - Compare ΔComplete ideas, ΔGood ideas, ΔAbsolute ENPV for:
    - Experiment 1 (5 SDM/CRE control teams, 8 total)
    - Experiment 4 (5 SDM/CRE treatment teams, 8 total)
- Best team overall?

# Mean Differences: ΔComplete Ideas

- No significant difference for both control and treatment groups

| | Control SDM (E-I-) | Treatment SDM (E+I+) |
|---|---|---|
| Control ESD.77 (E-I-) | 0.40 (0.34) | 2.20* (1.17) |
| Treatment ESD.77 (E+I+) | -2.60** (1.09) | -0.80 (0.94) |

* $p < 0.05$; ** $p < 0.01$

# Mean Differences: ΔGood Ideas

- No significant difference for both control and treatment groups

| | Control SDM (E-I-) | Treatment SDM (E+I+) |
|---|---|---|
| Control ESD.77 (E-I-) | 0.40 (0.34) | 1.80* (0.90) |
| Treatment ESD.77 (E+I+) | -2.27** (1.02) | -0.86 (0.82) |

$*\ p < 0.05$; $**\ p < 0.01$

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# Mean Differences: ΔAbsolute ENPV

- No significant difference for both control and treatment groups

| (millions) | Control SDM (E-I-) | Treatment SDM (E+I+) |
|---|---|---|
| Control ESD.77 (E-I-) | 0.66 (0.45) | 2.52* (1.38) |
| Treatment ESD.77 (E+I+) | -3.87** (1.75) | -2.01 (1.56) |

* $p < 0.05$; ** $p < 0.01$

# Best Team?

- Benchmark design: ENPV = $9.3M

- Team 4-7 identified 4 good and complete flexibility ideas
  - Abandon phase temporarily if cost goes up dramatically: ENPV = $11.0M
  - Expand capacity next phase if demand > planned capacity: ENPV = $11.3M
  - Reduce capacity next phase if demand < planned capacity: ENPV = $12.0M
  - Switch next phase if profit condos > profit apts (and vice-versa): ENPV = $15.4M

- Absolute ENPV attained: $15.7M (congratulations!)

# Some Observations

- Design for uncertainty and flexibility is not an immediate "reflex"
  - Lots of value may be left on table
- Once guided, people can successfully think about flexibility; nothing magical
- Lecturing may not be sufficient to generate good complete flexibility ideas; may need a more "Socratic" ideation mechanism like prompting
- Lecturing seems to provide fewer, but as valuable ideas as with prompting mechanism; counter to typical brainstorming thinking "the more ideas the better"

# Discussion

- Surprised by results?
- Implications for engineering education?
  - "Deterministic" vs. "probabilistic" approaches to design?
  - "Socratic" prompting vs. lecture-based teaching?
  - What does "optimal design" really mean?
- Thoughts about testing design procedures in "experimental" setting?
- How does flexibility apply to your term project?