Flexibility In Infrastructure Design and Management

Spring 2011

Definitions of Uncertainty

“Anything that can impact promises or business objectives in the future” (Verbraeck, 2010)

Uncertainty types (McManus and Hasting, 2005)

- Exogenous: out of managerial control
- Endogenous: managers/designers can control
- Statistically characterized: price or demand
- Known unknowns: future budget, system performance
- Unknown unknowns: hard to quantify, not considered in design

Human (In-)ability to Forecast

Heatier-than-air flying machine are impossible.
Lord Kelvin – British Mathematician, Physicist, and President of the British Royal Society, c. 1895

Everything that can be invented has been invented.
Charles H. Duell – Commissioner of the U.S. Patent Office, 1899

Reagan doesn’t have the presidential look.
United Artists Executive – dismissing Ronald Reagan for the starring role in the movie of THE BEST MAN, 1964

Environmental Uncertainty

http://www.jordoncooper.com
http://www.hurricanekatrinanews.org
http://www.washingtonpost.com

Market, Technology, and Others...

http://www.growthstock.com
http://images.angelpub.com
http://img.gsmarena.com

Uncertainty and Design

Forecast can be (severely) wrong
- No escape from line
- Infrastructure are long-lived, undergo much variations
- Analysis based on too many assumptions
- Unforeseeable surprises
- Typically over-optimistic about outcomes
- Over-confidence about prediction errors

There are many design choices beyond obvious ones
- Typically, combining different characteristics
- Enabling different future designs
- And are thus more flexible

modified from de Neufville, 2008

Fig. 1 Explicit training on flexibility slides 1-6
Current Design Process

- Very successful, BUT...
- Based on deterministic forecasts, heuristics, point value estimates (e.g. $60/oil barrel, $1/pound of copper)
- Optimized for limited set of conditions
- Uncertainty considered via post-facto sensitivity analysis
- "Compartmentalized" design, and thinking
- Often focused on risk minimization
- OPPORTUNITY TO DO BETTER!

Issues with Current Process

- Uncertainty affects performance
- Exposures remain = risk of losses, lower performance
- Update scenarios = opportunities for additional gains

"Flexible" design and management miss opportunities to recognize additional value!
- Can be sub-optimal... when reality departs from forecast!
- Cannot "reduce" exposure to risk easily
- Cannot "seize" good opportunities easily
- Adjusting project can be more costly
- Typical project valuation does not account for flexibility

Better Approach

- Recognize uncertainty a priori
- Range, distribution of possible outcomes
- Plan for flexibility in design and management
- E.g. vertical building expansion in Chicago

Better Approach (cont.)

- Find designs acting on outcome distribution, rather than optimizing point forecast

- Why Better with Flexibility?

- Forces considering downside explicitly
  - And propose for it
- Prevents over-optimism
- Forces considering upside as well
- Position to capture upside opportunities
- Both improve expected (or "average") performance compared to fixed design
  - No absolute best guaranteed, but can do BETTER THAN FIXED (INFLUENCES) DESIGN!

Example Flexible Strategies

- Flexibility "on" system: managerial
  - Delay investment until favorable conditions
  - Growth through R&D investment
  - Abandon temporarily or permanently

- Flexibility "in" system: technical
  - Phase asset deployment over time
  - Alter operating scale (expand or reduce capacity)

Fig. 2 Explicit training on flexibility slides 7-12
Criteria for “Good” Flexibility

1. Identify major uncertainty source(s) affecting anticipated performance
2. Suggest relevant flexible strategies to deal with uncertainties
3. Identify early on appropriate design variables and parameters enabling flexibility
   - E.g. stronger structure to support expansion, additional area of land, legal/financial/contractual arrangements if necessary
4. Identify relevant management decision rules to exercise flexibility
   - E.g. if demand > capacity for 2 years, expand
   - E.g. if demand < capacity for 2 years, expand

Examples from Industry

Satellite communication network (de Weck et al., 2004)
- $4BN award-winning system, $4BN development cost
- Wrong market forecasts: did not plan for land cell phones, led to over-capacity design
- Sold for $25M in bankruptcy

Expected cost saved if used flexible phased deployment strategy: ~$0.8BN (~20%)

Examples from Industry (cont.)

Offshore oil platform (Lin, 2009)
- Multi-billion project off coast of Angola
- Typical design to “most likely” oil reserves estimate
- Production capacity expansion flex.: connect more sub sea tiebacks as more oil discovered
- Study shows 80% expected NPV improvement

Take Aways

Uncertainty has downsides... BUT ALSO PROVIDES UPSIDE OPPORTUNITIES!
- Flexibility in design and management = best approach to deal with uncertainty
- Flexibility helps harvest EXTRA value from uncertainty
- Not easy however to identify and value it…

Fig. 3 Explicit training on flexibility slides 13-16
Prompting Procedure

Uncertainty
What are the major sources of uncertainty affecting the future performance of this system? Examples:

- Exogenous uncertainties (e.g. demand markets, natural catastrophes, etc.)
- Endogenous uncertainties (e.g. technology failure rates, etc.)
- Scenarios where things go really bad (e.g. prices drop, economic crisis, etc.)
- Scenarios where things go really well (e.g. demand rises suddenly, etc.)

Flexibility
What flexible strategies would enable the system to change and adapt if the uncertainty scenarios you just discussed occur during operations? Examples:

- Defer the initial capital investment until favorable market conditions
- Abandon the project to get out of bad, negative market situations
- Invest in R&D to support growth and future opportunities
- Phase capacity deployment over time instead of deploying initially all capacity at once
- Alter operating scale by expanding or reducing production capacity depending on market conditions
- Switch production output and/or input depending on observed demand

Design
How should you prepare, engineer, and design this particular system to enable the flexibilities you just discussed? Think about how to best engineer the system so it can react to:

- Negative or bad scenarios (e.g. start with a smaller initial design, and reduce risk of over-capacity and losses)
- Positive or good scenarios (e.g. engineer ability to switch product output easily, write legal contract to enable physical expansion later on if needed)
- Completely unexpected scenario (e.g. plan ahead for emergency procedure in case of hurricane)

Management
How should you manage and decide when it is appropriate to use, or exercise, the flexibilities in this system? Examples:

- If demand is lower than capacity for two years, I will shutdown operations for 6 months
- If market price gets above a certain threshold, I will expand production capacity
Design Problem Description

Introduction

Thanks for being here!

Personal background

About design experiments
- Test under different contexts
- Might wonder: “why this procedure?”
- Can’t answer all questions… unfortunately!

Example Project: Cambridge, MA

http://www.northpointcambridge.com

Setup

You are lead design team at renown real estate development firm:

Specialize in multi-family residential real estate
- Condo and apartment buildings
- Firm’s objective: sell building at highest profit
- Performance metric: Net Present Value (NPV)

Land already bought
- Zoning allowed for either condos and/or apartments
- Building permit for 310 units maximum over 3 years

Data and Assumptions

Current demand expectations:
- 100 condo units
- 100 apartment units

Current selling price expectations:
- $205,000/unit as condo
- $200,000/unit as apartment

Current construction cost estimate per unit (not inclusive of land):
- $152,000/unit as condo
- $150,000/unit as apartment

Demand, price, and construction cost all projected to increase linearly at 3%/year with annual volatility ~20%

Market Projections

Fig. 4 Introduction and design problem description slides 1-6
Analysis and Suggested Design
Go with condo building design
\[ \text{NPV} = 12.4M > 11.6M \] (8% discounting)
All 309 units developed in phase 1 (incl. 3% growth)
Sold over 3 years (1 year/phase)

The Situation
Management wants design offering best expected (or average) future performance over range of possible scenarios
Not convinced suggested design is best
Market demand and price may change; differ from projections
Costs may increase, construction delayed
Your team is asked to investigate alternative designs that can improve overall performance compared to current design

Your Task
Brainstorm collectively about design alternatives in this simplified infrastructure project
Only conceptually, no quantitative assessment necessary
Not much time, Management wants suggestions by the end of business day!
Plan two 25 minutes sessions using Group Support System software
GOOD LUCK!

Fig. 5 Introduction and design problem description slides 7-9
Survey Questions

Answer scale for each question (1 to 7): 1 = Strongly disagree 4 = Neutral 7 = Strongly agree

Process Satisfaction (PS)
- I feel satisfied with the way the first/second session was conducted.
- I appreciated the techniques we used in the first/second session.
- I liked the way the first/second session progressed today.
- I feel satisfied with the methods we used in the first/second session.
- I feel satisfied about the way we carried out activities in the first/second session.

Results Satisfaction (RS)
- I feel happy with what we achieved in the first/second session.
- I feel satisfied with the things we achieved in the first/second session.
- I am happy with the results of the first/second session.
- Our accomplishments in the first/second session give me a feeling of satisfaction.
- When the first/second session was over, I felt satisfied with the results.

Quality Assessment (QA)
- The result of the first/second session had the required quality.
- What we achieved in the first/second session met the goal.
- We achieved what we intended to achieve in the first/second session.
- The result in the first/second session has the quality we intended to achieve.
- The result in the first/second session was in line with the goal set for this workshop.
- I feel confident the top five (5) design alternatives recommended in the first/second session provide better anticipated performance than the current benchmark design.
**Computer Model Assumptions**

### Multi-Family Residential Development Project: All input parameters on this page... Assume zero time-to-build

#### Years per Phase

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#### Construction Cost Expected Growth Rate (each phase) (g)

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#### Construction Cost Expectations (as of completion, each phase):

### Phase 1

- **Base Cost (BC)**: 130,000 per unit

### Phase 2

- **As Condos (C_C)**: 22,000 per unit
- **As Apts (C_A)**: 20,000 per unit
- **Total Construction and Sales Cost Expectations (C_CT)**: 152,000 per unit

### Phase 3

- **Land Cost Expectation**: 0 per unit
- **Up-front Cost Expectation to Enable Switching Flexibility (C_switch)**: 0 per unit
- **Up-front Cost Expectation to Enable Expansion Flexibility (C_expand)**: 0 per unit
- **Selling Price Expected Growth Rate (each phase) (g)**: 0.03

### Selling Price Expectations:

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<tbody>
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<td>217,485</td>
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<tr>
<td>Apts (P_A)**: 200,000</td>
<td>206,000</td>
<td>212,180</td>
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#### Units Demand Expected Growth Rate (each phase) (g)

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<td>Apts (D_A)**: 100</td>
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</table>

#### Planned capacity deployment strategy (each phase)

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<th>Phase 2</th>
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</thead>
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<tr>
<td>Apts (K_A)**: 309</td>
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#### Maximum capacity allowed (K_Cmax)

|   | 309 |

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**OCC Built Property (r_P)**: 8.00% (Note: Should include spec premium)

**OCC Construction Costs (r_C)**: 8.00% (Note: Should be near risk-free rate)

**Resulting Canonical OCC (r)**: 8.00% (Note: Discount project contains operational leverage. This rate will be used as discount rate (see GM Ch 29).)

**Overall Volatility Factor**: 20%

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**Uncertainty Factor in Cost (CC)**:

- **Condos (CC)**: 20%
- **Apts (CC)**: 20%

**Uncertainty Factor in Price (P)**:

- **Condos (P)**: 20%
- **Apts (P)**: 20%

**Uncertainty Factor in Units Demand (D)**:

- **Condos (D)**: 20%
- **Apts (D)**: 20%

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Fig. 6 DCF model assumptions
Flexible Design Concept Examples

These examples summarize flexible design concepts elicited in experiments. They are all subject to the same uncertainty sources: demand, price, and construction costs. Only enablers and decision rules are summarized.

Phase the development planning from one phase to another
- Enablers: phase horizontally by keeping land or preparing land, developing modular “blocks” of units, keeping cash reserves for future expansion, and/or contracting agreements to have workers easily hired/laid off if needed.
- Decision rule: if demand (price) is higher than planned capacity (observed cost) in this phase, build next phase.

Expand unit capacity
- Enabler: expand vertically by reinforcing the structure, starting with small capacity to add more units, preparing shared infrastructures (e.g. laundry, power, water, ventilation) for expansion, hedging materials costs for expansion.
- Decision rule: expand if demand (observed price) is higher than capacity (observed cost) within the same phase.

Reduce unit capacity
- Enabler: because this is managerial flexibility “on” the project, one can always reduce or slow down unit capacity allocation. No specific enabler was needed.
- Decision rule: reduce capacity if demand (observed price) was lower than capacity (observed cost) within the same phase.

Adjust unit capacity “just in time”
- Enabler: given this flexibility is very difficult to implement in practice, teams had to demonstrate sufficient understanding of how to implement this in practice. This was typically a mixture of enablers listed in the phasing and expansion strategies.
- Decision rule: if demand is different than planned capacity, match capacity to demand exactly.

Temporarily abandon the project
- Enabler: because this is managerial flexibility “on” the project, one can always stop it, however with the stated goal of resuming at some point.
- Decision rule: do not develop a phase if demand in the previous phase was lower than planned.

Completely abandon the project
- Enabler: because this is managerial flexibility “on” the project, one can always stop it.
- Decision rule: abandon the project if demand in phase 1 is lower than a minimum threshold.
3. Provocation CoP

2. Uncertainty
2.1. What are the major sources of uncertainty affecting the future performance of this system?
2.2. Examples:
2.2.1. Exogenous uncertainties (e.g. demand markets, natural catastrophes, etc)
2.2.2. Endogenous uncertainties (e.g. technology failure rates, etc)
2.2.3. Scenarios where things go really bad (e.g. prices drop, economic crisis, etc)
2.2.4. Scenarios where things go really well (e.g. demand rises suddenly, etc)
2.3. Market demand
2.4. Volatility in the cost and demand. A sharp rise in the cost can affect the bottom line of the firm. Changes in market scenarios like new competitor coming in the market.
2.5. New technology for construction
2.6. New technology in the real estate industry making demand depend on either condo and apartment obsolete.
2.7. Development of new public transportation system or building a new road may make the value of the location increase or decrease, which will change the demand and market price.
2.8. If the area is creating more job opportunities, more people will move here, thus increase the demand and vice versa.
2.9. If the government is increasing real estate tax, more people may just prefer to rent an apartment instead of buying one, thus decrease the demand.

3. Flexibility
3.1. What flexible strategies would enable the system to change and adapt if the uncertainty scenarios you just discussed occur during operations?
3.2. Examples:
3.2.1. Defer the initial capital investment until favorable market conditions
3.2.2. Abandon the project to get out of bad, negative market situations
3.2.3. Invest in R&D to support growth and future opportunities
3.2.4. Phase capacity deployment over time instead of deploying initially all capacity at once
3.2.5. After operating scale by expanding or reducing production capacity depending on market conditions
3.2.6. Switch production output and/or input depending on observed demand
3.2.7. Phase capacity deployment depending on observed demand
3.2.8. Try to build apartment in such a fashion that if required you can convert them into condos.
3.2.9. Do market surveys before starting construction to understand the demand in the market.
3.2.10. Keep cash and inventory in hand to do rapid construction in response to sharp rise in market demand.
3.2.11. Sign in future contracts to overcome the volatility in the market.
3.2.12. Do market research to have a better prediction of demand.
3.2.13. Keep enough cash and make alternative investment to hedge the real estate investment.

Comment [9]: Demand uncertainty source
Comment [10]: Construction cost uncertainty source
Comment [11]: Technology uncertainty source
Comment [12]: Price uncertainty source
Comment [13]: Regulatory uncertainty source
Comment [14]: Phasing strategy
Comment [15]: Switching enabler in design
Comment [16]: Switching enabler in design
Comment [17]: Capacity expansion strategy
Comment [18]: Capacity expansion management/decision rule based on demand

Fig. 7 Example coding analysis for treatment 2 replicate R_i (page 1)
4. Design

4.1. How should you prepare, engineer, and design this particular system to enable the flexibilities you just discussed?
4.2. Think about how to best engineer the system so it can react to:
4.2.1. Negative or bad scenarios (e.g., start with a smaller initial design, and reduce risk of over-capacity and losses)
4.2.2. Positive or good scenarios (e.g., engineer ability to switch product output easily, write legal contract to enable physical expansion later on if needed)
4.2.3. Completely unexpected scenario (e.g., plan ahead for emergency procedure in case of hurricanes)
4.3. I will maintain an inventory to build both condo and apartment.
4.4. I will closely follow the changes in market so that I can change my strategies accordingly to the market.
4.5. Design my apartments such that it is possible to upgrade them to condos if required.
4.6. Sign contracts with the suppliers to safeguard yourself against a sharp price rise in the cost.
4.7. Condo should be the major source of sales but use sales of apartment to supplement that of condo.
4.8. Make alternative investment, such as funds and stock, to hedge the real estate investment. For example, if expecting the raw material cost will go up, we can buy related stock in advance.
4.9. Research on the demand of condo and apartment separately.

5. Management

5.1. How should you manage and decide when it is appropriate to use, or exercise, the flexibilities in this system?
5.2. Examples:
5.2.1. If demand is lower than capacity for two years, I will shutdown operations for 6 months.
5.2.2. If market price gets above a certain threshold, I will expand production capacity
5.3. If you see the price-rise is steady, stick to your strategy.
5.4. If you see a sharp rise in prices of condo and no change in the price of the apartment then think about upgrading your apartment to condo.
5.5. 20% drop in apartment price will mean the selling price is ~$160,000 and 20% rise in cost will mean construction cost is ~$180,000. This will mean loss. So if construction cost goes above $160,000 stop construction for a while unless you are sure that selling price and demand will remain intact.
5.6. React to any change in the government policy.
5.7. If the demand is less than 10% of expected, increase the construction for next year to 80% of original plan.
5.8. If demand is less than expected for a year than it might be possible that demand can overshoot in the next year. We should build up our inventory and plan ourself to face this situation.
5.9. If the demand is increasing, increase the proportion of condo construction, which will bring more revenue.

Fig. 8 Example coding analysis for treatment 2 replicate $R_T$ (page 2)
### Summary of Entire Dataset

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<th>Temp. abandonment</th>
<th>Temp. Justin</th>
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<th>Cost gulf content</th>
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**Fig. 9 Dataset summary**