Outline

- **Issue:**
  - Too many combinations to analyze
  - Traditional Approach: very simplified

- **Analytic Problem:** How do we take more realistic approach, within available analytic resources (time, modeling complexity)

- **Proposed Solution:**
  - Concept: Use of “Catalogs” of Conditions
  - Implementation: Depends on Nature of Industry

- **Example:** Analysis for a Garage, Copper Mine
The Analytic Issue

- A complete analysis of an engineering system involves modeling and optimizing:
  - The basic infrastructure (the plant, the 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 the many modes of operating the infrastructure (routing of vehicles on network, allocation of production lines to products, etc)
  - To provide a range of measures of merit (Net Present Value, Amount of Capital expense – Capex, Return on Investment)

IMPRACTICAL TO DO COMPLETELY!

Graphical View: the full problem

<table>
<thead>
<tr>
<th>Stage for System</th>
<th>Element</th>
<th>Possibilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Design</td>
<td>Configuration of Infrastructure</td>
<td>Many</td>
</tr>
<tr>
<td>Periodic Data on Context Factors</td>
<td>Price, Demand, Quantity, etc</td>
<td>Many, over many periods</td>
</tr>
<tr>
<td>Periodic Management Adjustments</td>
<td>Work Plans for Existing and New Facilities</td>
<td>Many, over many periods</td>
</tr>
<tr>
<td>Performance Metrics</td>
<td>NPV, ROI, Capex, etc</td>
<td>Many</td>
</tr>
</tbody>
</table>
Traditional Design Approach

Although Complex, Very Simplified Overall

<table>
<thead>
<tr>
<th>Stage for System</th>
<th>Element</th>
<th>Possibilities</th>
<th>Traditional Design Practice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Design</td>
<td>Configuration of Infrastructure</td>
<td>Many</td>
<td>Many</td>
</tr>
<tr>
<td>Periodic Data on Context Factors</td>
<td>Price, Demand, Quantity, etc</td>
<td>Many, over many periods</td>
<td>One Vector (Each 1 value)</td>
</tr>
<tr>
<td>Periodic Management Adjustments</td>
<td>Work Plans for Existing and New Facilities</td>
<td>Many, over many periods</td>
<td>None Not considered</td>
</tr>
<tr>
<td>Performance Metrics</td>
<td>NPV, ROI, Capex, etc</td>
<td>Many</td>
<td>One (the focus)</td>
</tr>
</tbody>
</table>

Analytic Problem

- We know that we can increase value by
  - Recognizing Uncertainty
  - Dealing Proactively with it, by creating options
  - ... and Enabling Management to Adjust

- How do we take this more realistic approach, within available analytic resources (time, modeling complexity)?
- Specifically, how do we
  - Focus effort on most productive parts? (Phd by Bartolomei and other theses – next session)
  - Expand Variables considered – and stay within limits of capability (this session)
Size of Problem: Astronomical

- A full analysis of variations is impractical

- Example 1: possible price variations over 20 periods, if the price could be low, medium or high. The total number of combinations would be $3^{(exp\ 20)} \sim 2^{1/2}$ billion… And this is for only 3 price levels!

- Example 2: possible decisions rules for expanding a facility (as in parking garage). One could expand with 1, 2, or 3 units (say); at different times; under different conditions. Over 20 periods, the possibilities are orders of magnitude greater than above.

Concept of Solution

We want a

- Middle ground between
  - the simplest possible assumption typically used (e.g., price of copper 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
Outline of solution

- Use “Catalogs” of possible conditions

- The “Catalogs” would provide scenarios intended to describe relevant patterns designers might wish to anticipate

- Thus, instead of $3^{20}$ combinations of 3 price levels over 20 periods, we might consider a “handful” of scenarios such as:
  - Steady rising and falling prices
  - High prices at beginning, low at end
  - Low prices at start, surge in prices at end
  - High volatility of prices around trend
  - Etc..

Graphical view of “Catalog” Approach

<table>
<thead>
<tr>
<th>Stage for System</th>
<th>Element</th>
<th>Possibilities</th>
<th>“Catalog” Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Design</td>
<td>Configuration of Infrastructure</td>
<td>Many</td>
<td>Many</td>
</tr>
<tr>
<td>Periodic Data on Context Factors</td>
<td>Price, Demand, Quantity, etc</td>
<td>Many, over many periods</td>
<td>10 to 20 Representative Scenarios</td>
</tr>
<tr>
<td>Periodic Management Adjustments</td>
<td>Work Plans for Existing and New Facilities</td>
<td>Many, over many periods</td>
<td>10 to 20 possible responses</td>
</tr>
<tr>
<td>Performance Metrics</td>
<td>NPV, ROI, Capex, etc</td>
<td>Many</td>
<td>Several E(NPV), Capex, Value at Risk and Gain, etc</td>
</tr>
</tbody>
</table>
Benefits of “Catalog” approach

- Enables consideration of major scenarios

- Encourages deeper investigation of situations with greatest impact on performance
  - Additional Scenarios easily be added to Catalog

- Can be tailored to design problem; Catalog can be larger or smaller, focused on specific uncertainties, etc.

- Using modern computers, expanding analysis effort factor of 100 or so is easy.

Unknows about approach

- **Validity**: Only a few applications so far. Seems promising, but more validation needed

- **Definition of Catalog**: How is this best done?
  - All at once at start?
  - Incrementally? from a starter set to more scenarios determined according to their effect on performance

- **Detailed Characteristics**: What level of detail appropriate to this approximate approach?

A RESEARCH TOPIC!

See Cardin discussion of his thesis next time
Conceptual Application to Garage (1)

- The traditional definition of the design problem for “Garage Case” is:

<table>
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<th>Possibilities</th>
<th>Traditional Design Practice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural Design</td>
<td>Number of Floors</td>
<td>Many</td>
<td>Many</td>
</tr>
<tr>
<td>Periodic Data on</td>
<td>Price, Demand, Quantity, etc</td>
<td>Many, over</td>
<td>One Price, Demand Profile</td>
</tr>
<tr>
<td>Context Factors</td>
<td></td>
<td>many periods</td>
<td></td>
</tr>
<tr>
<td>Periodic Management</td>
<td>Price Changes; More Floors</td>
<td>Many, over</td>
<td>None</td>
</tr>
<tr>
<td>Adjustments</td>
<td></td>
<td>many periods</td>
<td>Not considered</td>
</tr>
<tr>
<td>Performance Metrics</td>
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<td>Many</td>
<td>One (the focus)</td>
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Conceptual Application to Garage (2)

- We expanded analysis, and looked at:
  - many different possible demands
  - Expansions with a simple decision rule
  - Looked at Value at Risk and Gain (VARG)

<table>
<thead>
<tr>
<th>Stage for System</th>
<th>Element</th>
<th>Possibilities</th>
<th>&quot;Garage Case Design&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural Design</td>
<td>Number of Floors</td>
<td>Many</td>
<td>Many</td>
</tr>
<tr>
<td>Periodic Data on</td>
<td>Price, Demand, Quantity, etc</td>
<td>Many, over</td>
<td>One Price, 1000s of</td>
</tr>
<tr>
<td>Context Factors</td>
<td></td>
<td>many periods</td>
<td>Demand Profiles</td>
</tr>
<tr>
<td>Periodic Management</td>
<td>Price Changes; More Floors</td>
<td>Many, over</td>
<td>Some Simple decision</td>
</tr>
<tr>
<td>Adjustments</td>
<td></td>
<td>many periods</td>
<td>rule</td>
</tr>
<tr>
<td>Performance Metrics</td>
<td>NPV, ROI, Capex, etc</td>
<td>Many</td>
<td>Several NPV, VARG</td>
</tr>
</tbody>
</table>
Conceptual Application to Garage (3)

- As a next step, Cardin looked at range of decision rules beyond one assumed:
  - Sensitive to amount by which demand > capacity
  - Stage in Life of project
  - Relative size of addition relative to capacity, etc...

<table>
<thead>
<tr>
<th>Stage for System</th>
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<th>“Garage Case Design”</th>
</tr>
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<td>Number of Floors</td>
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<td>Periodic Management</td>
<td>Price Changes, More Floors</td>
<td>Many, over many periods</td>
<td>CATALOGS of decision rules</td>
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Research Questions

- What is a good way to define members of catalog?
- How should search be expanded to more members of catalog?
- When should search be terminated?
- Others?
Initial Application to Codelco

- Codelco is the National Mining Company of Chile (COMpania nacional DEL CObre)

- It owns the biggest copper mines in the world, near Calama, in North Chile
  - Chuquicamata ("Chuqui") is 4 km long, 2 km wide, and 800 m deep - a hole as big as Cambridge and half a mile deep
  - Is known to have enough copper to produce for 90 years at current rate
  - More deposits anticipated, but not proven by drills

- This project concerns secondary potential mines – "Cluster Toki"

Recognition of Help

- This work was done in collaboration with

  - Gerencia de Recursos Mineros y Desarrollo, Codelco Norte
    - Miguel Romero Casanova
    - Juan Carlos Peña

  - Gerencia Corporativa de Recursos Mineros, Codelco Casa Matriz
    - Felipe Azócar H.
    - Cristián Barrientos Parant
    - Miguel Cabrera Reyes
Site Map

Cluster Toki consists of the mines in the lower left side of the photograph

Outline for Codelco case

- Placing “Catalog Methodology” into context
- Presenting the Analysis
  - Part 1: Staged Analysis, designed to provide a transparent view of process
  - Part 2: Preliminary Results from full analysis
Traditional Evaluation of Mine

- Design of basic infrastructure is simple:
  - Crushing Mill,
  - Fleet of BIG trucks

- Crux of design lies in “mine plan” the optimization of sequence of excavations into body of sterile overburden and mineral
  - Huge combinatorial problem ~ 50,000 blocks of 20m to 30m on a side, each with estimate of its mineral content, etc.
  - Takes time, effort, money

An Open Pit Mine

Source: www.codelco.com
Blasting

Source: www.codelco.com

Moving the rock

Source: www.codelco.com
Big Trucks!

Source: Briony Hall, BBC News, 10 Dec. 2003 "Monster Trucks Transform Mining" (in Botswana)
http://news.bbc.co.uk/2/hi/business/3293889

Crushing Mill

Source: www.codelco.com
Smelting

Source: www.codelco.com

The Product: copper sheets

Source: www.codelco.com
### Graphical View of Traditional Analysis

- The key analytical effort lies in the Mine Plan

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<tbody>
<tr>
<td>Initial Design</td>
<td>Size of Crushing Mill and Truck Fleet</td>
<td>A Few</td>
<td>A Few</td>
</tr>
<tr>
<td>Periodic Data on Context Factors</td>
<td>Price, Demand, Quantity, etc</td>
<td>Many, over many periods</td>
<td>One Vector (Each 1 value)</td>
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<tr>
<td>Periodic Management Adjustments</td>
<td>Change in the “Mine Plans”</td>
<td>Many, over many periods</td>
<td>One Mine Plan</td>
</tr>
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<td>Performance Metrics</td>
<td>NPV, ROI, Capex, etc</td>
<td>Many</td>
<td>One (VAN = NPV)</td>
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Note: VAN = Valor Anual Neto = NPV

### Graphical View of “Catalog” Analysis

- Innovation: use of representative Mine Plans and Price Vectors over time, not using entirely new ones for each detailed variation

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<td>Several (VAN = NPV) and VARG</td>
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</tbody>
</table>
Part 1: Staged Application

Objective of this exercise:
- To demonstrate contribution of proposed analysis method …
- … to the understanding of the sources of value in the project
- … and thus improve the overall value of a project
Concept of Staged Analysis

- Starts from simplest situation: base case with no fluctuation in the price over time, and with only one long-term price

- Step by step increases factors being considered, for example
  1. considering effect of fluctuations in price, 
  2. then, possible variations in average price, etc

- Until show comprehensive analysis

Object of Staged Procedure

- To provide a transparent way to see how the method works

- … by indicating clearly the individual effects of each change in the analysis

- … and thus improve the understanding of the sources of value for a project
Application Inspired by Toki

- Data can be improved, examples only
- Drawn from estimates prepared for other analyses
- Not yet suitable for any investment planning...

Step A: Base Case

- Description:
  - Single design (Crushing Mill, Capacity) = (36,120)
  - Average Price = 130 (historical average in $2005)
  - No fluctuations in price over time
  - No uncertainty about average price level

- $NPV_A = 396$
Step B: Includes Fluctuations

- Description:
  - Single design (Crushing Mill, Capacity) = (36,120)
  - Average Price = 130 (historical average in $2005)
  - Price varies around the average in a set pattern
  - No uncertainty about average price level

- $\text{NPV}_B = 541$
- $\text{NPV}_B - \text{NPV}_A = +145$ (~ +38%)

Lessons from Step B

- Analysis with a constant price over time does not reflect reality
- Differences large (example: 38%) and should not be ignored
- Note: this particular difference due to cash flow with early peak. Difference could be negative.
Step C: with Price Level Uncertainty

- **Description:**
  - Single design (Crushing Mill, Capacity) = (36,120)
  - Average Price = 130 (historical average in $2005)
  - Fluctuations in price over life of mine
  - Uncertainty about price level: +/- 30 = +/- 23%

- **NPV^c** (high price = 160) = 933 (~ + 72%)
- **NPV^c** (average price = 130) = 541
- **NPV^c** (low price = 100) = 230 (~ - 57%)

- Note: Select mine plans according to price!

Lessons from Step C

Changes in NPV
- not proportional to Change in price
  (a standard result, due to fixed costs)
- not symmetric – management chooses mine plan depending on price level
- do not balance: + 392 – 311 = + 81 (~ +15%)
- Must be better – management chooses operations that improve performance

- Differences large and should not be ignored
Summary from Staged Analysis

- Standard Analysis, with known price without variations over time, gives unrealistic view

- Fluctuations over time must be considered – offer important sources of improved value through faster development with high prices

- Uncertainty in long-term average prices must be considered – offers important source of value through choice of better mine plan

Part 2: Full Simulation Analysis

- Description of Main Elements:

  - Variation in Copper Prices over time
  - Distribution is “log normal”
    - negative prices are not permitted
  - With “regression to the mean”
    - Mean is forecast long-term of US $1/pound CuF
      (Cobre Fino = Refined Copper)
  - Same Mine Plan for all cases
    - Analytically difficult to change plans with prices
Results: Comparison with Base Case

- Recognizing Uncertainty => Greater Value

![Graph showing VAN (%) against Uncertainty]

Explanation of Final Result

- Prices can go up more than they go down
  - $1 up to over $3 / pound
  - $1 down to only about $0.70
- Benefits of higher prices proportionately greater than disbenefits of low prices
- These factors combine to explain why the recognition of variability in prices leads to greater expected NPV
Discussion of Methodology

- Methodology is a significant improvement on current practice which is simplistic as regards price levels and other outside factors.

- It is not complete. It does not use a different mine plan for each simulation. This would
  - take far too long
  - Be very expensive

- Method uses a “catalog” of mine plans prepared ahead of analysis. These are designed to be “representative”