

# Screening system design elements for optionality

Presentation in ESD.71

Thursday, December 2, 2004  
Konstantinos Kalligeros

## Overview

- ✍ Flexibility and options overview: options “on” projects

- ✍ Options “in” projects

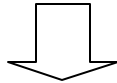
  - ✍ Linking option variables to physical variables

  - ✍ Case studies:

    - ✍ Parking garage

    - ✍ BWB aircraft family

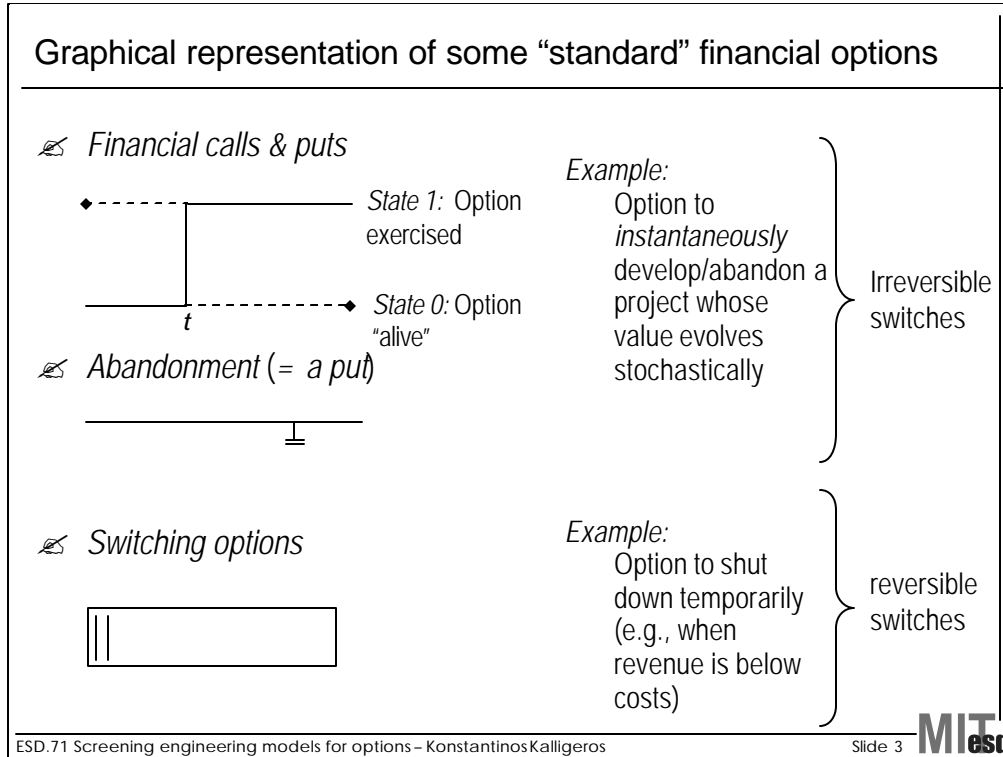
    - ✍ BP headquarters



- ✍ Where is the option?

  - ✍ Simulation-based screening models

  - ✍ Deterministic screening models



For details on this graphical representation, see

- Vollert, A., A stochastic control framework for real options in strategic valuation, Birkhauser Boston, MA, 2003

For valuation of such options on projects, there are multiple references. See, e.g.,

- Dixit, A. and Pindyck, R., Investment under uncertainty, Princeton University Press, New Jersey, 1994

- Copeland, T. and Antikarov, V., Real Options, A practitioner's guide, Texere LCC, New York, NY, 2001

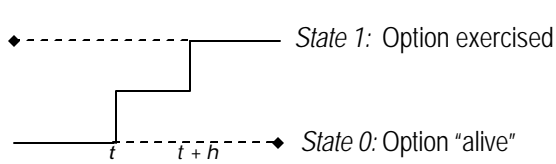
for two diametrically different approaches to real options.

A standard textbook for the theory is also

- Hull, J., Options, futures and other derivatives, Fifth edition, Prentice Hall International editions, ISBN 81-203-2237-1, 2000

# Options “on” projects: reality beyond finance

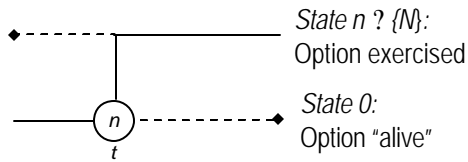
✍ Irreversible switches with lag time



Example:

Option to develop a project whose value evolves stochastically and which takes time to complete

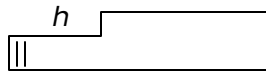
✍ Choice among  $\{N\}$  states



Example:

Option to choose the capacity of the project upon development

✍ Reversible switches with lag time

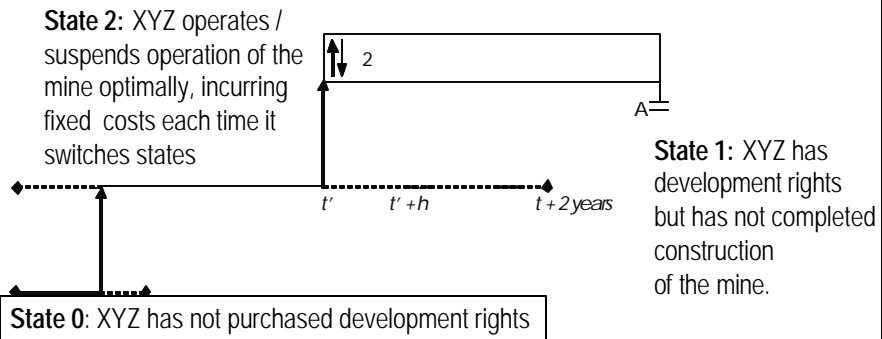


Example:

Option to suspend production with time lag to restart

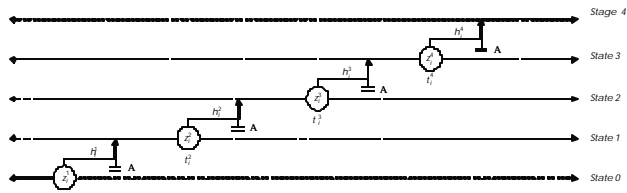
## Options in systems usually come in *contingency structures*

- ✍ Seldom are real options seen individually
- ✍ Example: Antamina mine
  - ✍ Purchase development rights to a mine is an option to develop mine
  - ✍ Developed mine is an option between operating/mothballing mine
  - ✍ AND to abandon mine or its development for a salvage value (if any)

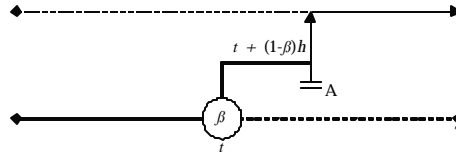


# Most common patterns of flexibility in engineering systems

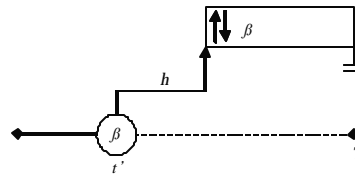
✍ Staging flexibility



✍ Time-to-build flexibility



✍ Switching flexibility



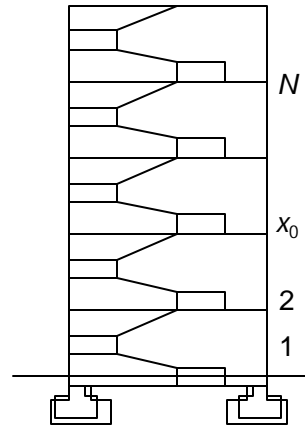
## Real systems: barriers to implementation

- ✍ Related to the systems:
  - ✍ Complexity in real systems obscures insight on these flexibility modes
  - ✍ Design variables & models used do not usually reveal flexibility modes
- ✍ Related to people & organizations:
  - ✍ Traditional engineering training does not promote “options thinking” or actively accounting for uncertainty
  - ✍ Mindset required for engineering is different than that required for management
  - ✍ Skills to implement options analyses are sophisticated, even for managers
- ✍ To follow:
  - 3 examples of options “in” systems,  
to **show complexity** and **introduce the problem**
  - ✍ Garage example
  - ✍ BWB aircraft family development
  - ✍ Office building development

## Options in projects: Parking garage example

Zhao & Tseng (2003) ; de Neufville, Scholtes, Wang (2004)

- ✍ Simple example of **staging flexibility**
- ✍ Uncertain demand for parking spots
- ✍ Tradeoff between
  - ✍ Large foundations and columns, able to support  $N$  levels
  - ✍ Small foundations, enough to cover today's demand,  $x_0$  levels
- ✍ Design problem:
  - ✍ How many levels should the foundations and columns be able to support?
  - ✍ How many levels to build today?



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### References:

- T. Zhao and Tseng C. *Valuing flexibility in infrastructure expansion*. Journal of Infrastructure systems, 9(3):89–97, September 2003.
- Valuing Options by Spreadsheet: Parking Garage Case Example  
Richard de Neufville, Stefan Scholtes and Tao Wang -- submitted to ASCE Journal of Infrastructure Systems, August 2004



# Options “in” projects: reversible switching factory

Kalligeros (last night :-)

- Consider an option to build a factory producing widgets, with characteristics

$$X_0 \in \{Q_{max}, K_{react}, C_2\}$$

where

$K_{react}$  = lump cost of reactivation / capacity

$C(Q) = c_1Q + c_2Q^2$  is the operating cost

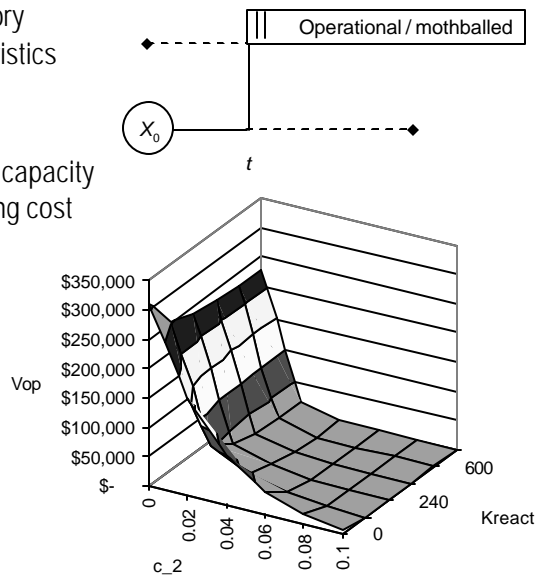
$Q_{max}$  = maximum capacity

- Design problem: What is the optimal design that accounts for the flexibility to temporarily shut down?

- Solution: Obviously, the design with

$$\min c_2$$

$$\text{and} \quad \min K_{react}$$



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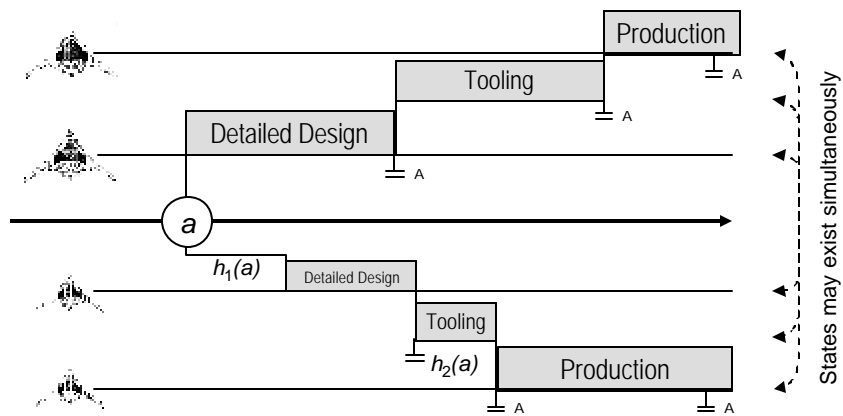


Notice 2 important (but rather “advanced”) issues:

- The design decision,  $X_0$ , is made NOW, not when the option is exercised. (If it was made at the exercise of the option, the circle with  $X_0$  in it should have been shown where the vertical arrow is). This seems irrational and stupid: why decide on the design of the factory now, if you haven’t decided you will build it now? Under some circumstances, however, the result is the same (in terms of project value). Specifically, we can make the design decision now and not later if:
  - The uncertainty stays the same over time. Assuming a GBM for the underlying uncertainty satisfies this requirement. To intuitively understand why the uncertainty remains the same in GBM, notice that the volatility in the GBM model does not depend on time: The decision-maker is equally unsure for the “stock’s” returns looking forward one period, regardless of whether it is now or in 10 years from now.
  - The life of the project (therefore, the switching option) is infinite. Infinite time horizon problems cannot be accurately solved using either lattices or simulation; quite mathematical approaches are required (continuous-time stochastic dynamic programming). Solving such problems with lattices is a computational as well as (significant) *conceptual* approximation. The reasons for this is beyond the scope of this class; see a book on mathematical finance, such as Thomas Bjork, Arbitrage Theory in Continuous Time, ISBN: 0199271267
- The plot shows the value of the completed project, which has the flexibility to shut down and re-open. It DOES NOT refer to the value of the option to build the project. Again, for an infinite time horizon and constant uncertainty, the value of the completed, operational project ( $V_{op}$ ) is independent of WHEN it is built (i.e., when the first call option on the graph is exercised).

## Options in projects: BWB aircraft family example

Markish & Willcox (2002)



- ✍ Parallel, staged development of two aircraft in the same family
- ✍ Existing staging flexibility in the development of each aircraft
- ✍ Additional flexibility from sharing components between the two aircraft (see next)

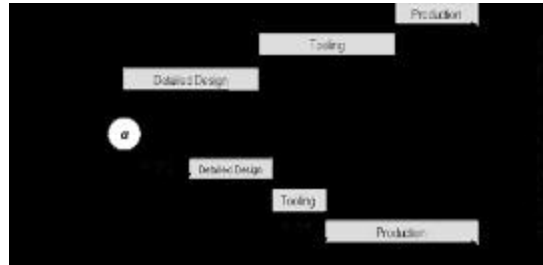
### Reference:

- Jacob Markish and Karen Willcox. *A value-based approach for commercial aircraft conceptual design*. In ICAS, 2002.

## Options in projects: BWB aircraft family example

Markish & Willcox (2002)

- ✍ Design problem:  
What is optimal percentage of components,  $a$  % that 2<sup>nd</sup> aircraft should share with the first?



- ✍ Tradeoff between expected profits and bringing small model to market fast
  - ✍ High  $a$ :
    - ✍ reduce the time lag and development cost for the 2<sup>nd</sup> aircraft
    - ✍ Inferior performance ( ✍ sale price) of one or both aircraft
  - ✍ Low  $a$  :
    - ✍ optimal design for both aircraft
    - ✍ Increased time to market for small model
- ✍ **Combined *time-to-build flexibility* and *staging flexibility***

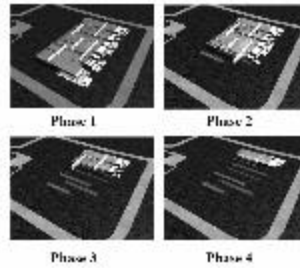
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- Jacob Markish and Karen Willcox. *A value-based approach for commercial aircraft conceptual design*. In ICAS, 2002.

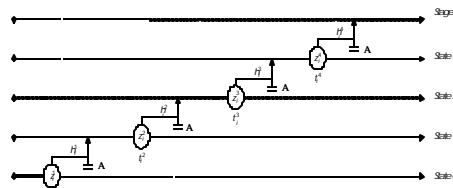
# Options in projects: BP exploration Headquarters

Kalligeros (2004)

- ✍ Uncertainty about:
  - ✍ BP's value of the facility *in use*
  - ✍ Value of land for alternate uses
- ✍ Modular architecture ✍ **staging flexibility**
- ✍ How to design modular building *optimally*?



- ✍ Trade-off between
  - ✍ Durable, monolithic structure;
    - redundant future capacity;
    - commitment of profitable land;
    - inexpensive construction
  - ✍ Modular facility;
    - adapting to future capacity;
    - exploitation of alternative land use;
    - expensive construction



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## Reference:

- Kalligeros, K., de Weck, O. (2004) *Flexible design of commercial systems under market uncertainty: framework and application*. 10th AIAA/ISSMO Multidisciplinary Analysis and Optimization (MA&O) Conference, Albany NY, September 2004

## Options in projects: BP exploration Headquarters example

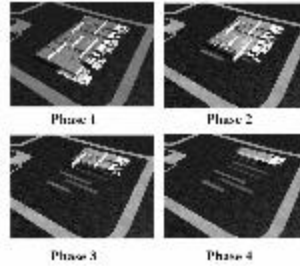
Kalligeros (2004)

✍ Architecture described by *design vector*

$$X_0 = \{N, A(y), F(y), Q(y)\}; \quad y = 1 \dots N$$

where *module (building) y*:

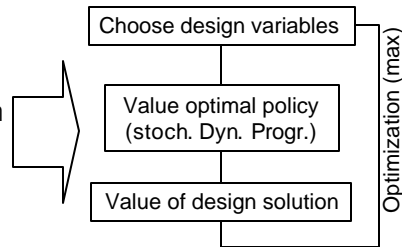
- ✍ has a gross square footage of  $A(y)$
- ✍ is designed to (normalized) quality specifications of  $Q(y)$
- ✍ is  $F(y)$  floors high
- ✍  $N$  is also a design variable!!!



✍ Solution by

1. Valuation of options "created" by the design
2. Optimization of total value over all designs

✍ **Mapping of design variables to option parameters *already not very obvious***



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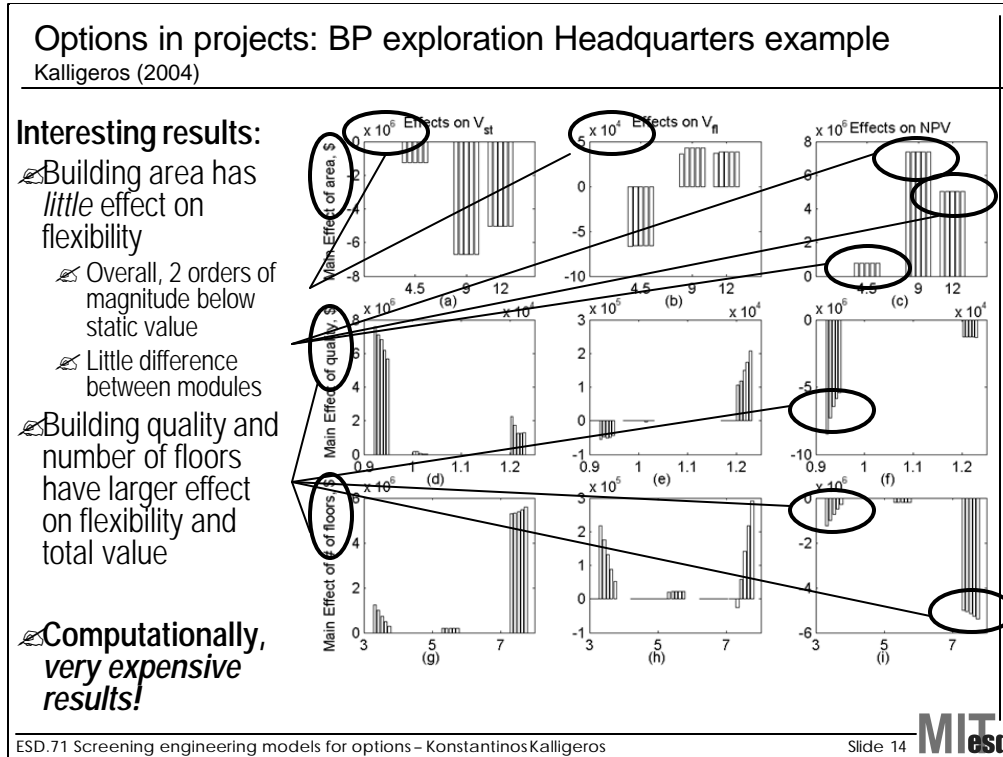


### Reference:

- Kalligeros, K., de Weck, O. (2004) *Flexible design of commercial systems under market uncertainty: framework and application*. 10th AIAA/ISSMO Multidisciplinary Analysis and Optimization (MA&O) Conference, Albany NY, September 2004

The beauty of this optimization scheme is that it is deterministic: If we believe that the sources of uncertainty fulfil some necessary requirements (market completeness, absence of arbitrage etc.) then the value of each design is no longer stochastic, and the options value is NOT an expectation, at least no more than the underlying sources of uncertainty. Deterministic optimization tools, such as gradient or evolutionary methods can be used.

This method is similar in its implementation, but conceptually very different, to the so-called *2-stage approach* in stochastic optimization. See any standard book on stochastic optimization for details (e.g., Kall and Wallace 1994).



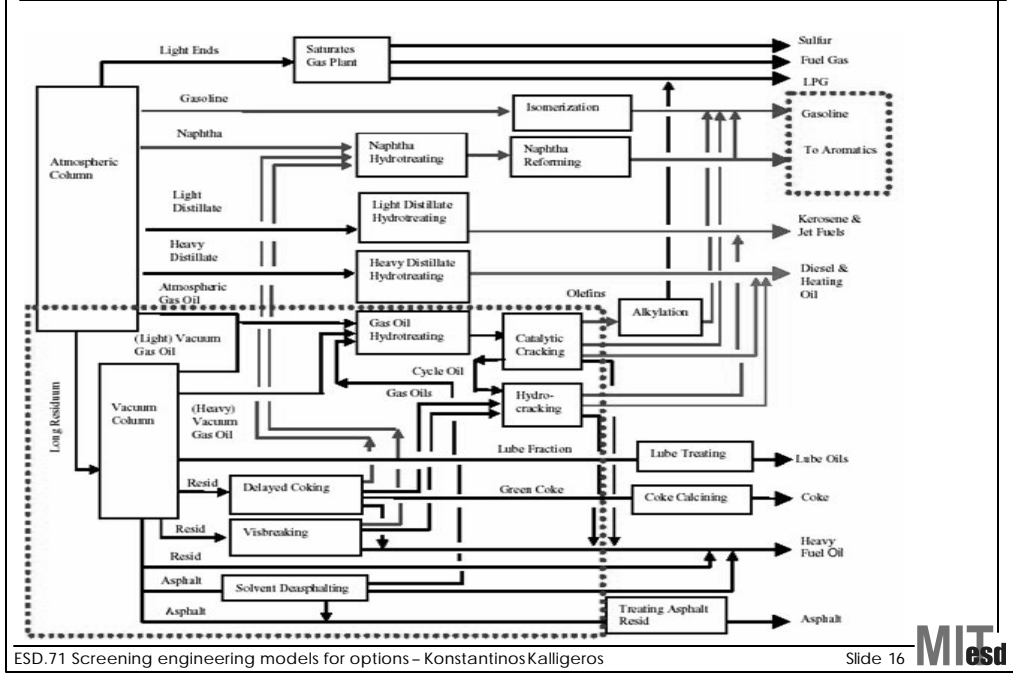
**NOTES:**

- $V_{st}$  is computed as the “static” value of a configuration (set of buildings), if the uncertain parameters remained at their current level indefinitely, i.e., there is no uncertainty
- $V_{fl}$  is the value of being able to follow the optimal policy of abandoning modules as you go, given the uncertainty. It is calculated using binomial lattices on two underlying assets.
- $NPV = V_{fl} + V_{st} - [\text{construction cost of a design}]$
- For every plot, the horizontal axis represents design variables (building area, number of floors and construction quality), while the vertical represents value (\$).
- Each thin bar in each plot corresponds to a building. Each group of bars in each plot corresponds to the change in the respective value for a small variation of the design variable (for each building). It is like the derivative of value ( $V_{fl}$ ,  $V_{st}$  or  $NPV$ ) with respect to a change in each design variable (for each building), calculated at the level shown on the horizontal axis.
- For example, the plot in the 2<sup>nd</sup> row and 3<sup>rd</sup> column of plots represents the effect of marginally varying design quality at three levels (0.85, 1.0 and 1.2, normalized to some standard, see paper), on the  $NPV$ , for each building.
- This is the result of a Design of Experiments analysis, following a one-at-a-time sampling method. See the paper for details.

## Where is the option?

- ✍ Parking garage  
Obvious option to build capability to expand      ✍  $X_0$  = size of foundations
- ✍ BWB deployment  
Flexibility to speed up production at lower cost      ✍  $X_0$  = shared components  
(but which components?)
- ✍ BP Headquarters  
Flexibility to respond to changes in space demand and value of alternate use ✍  
 $X_0$  = number of modules, quality, area and height for each
- ✍ However, we saw that **area had insignificant effect on flexibility**
- ✍ It would be nice to have a quick and dirty way of **screening the design elements** with impact on total value, *including flexibility*
- ✍ Especially on systems such as the following:

# Process flowsheet: refinery level



You are MEANT to be overwhelmed here. I am!

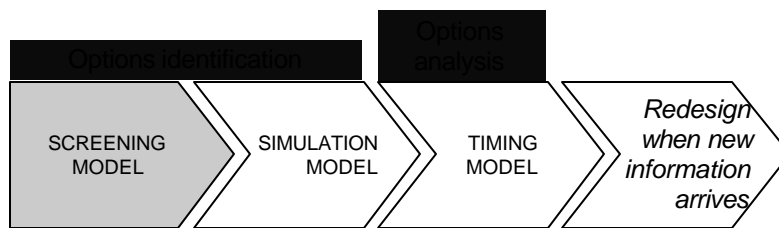


# Simulation-based screening methodology

de Neufville R. & Wang, T. (2004)

## 1. Screening model

- ✍ Run deterministic optimization model for various levels  $\tau_i$  of the uncertain parameters ✍ obtain optimal designs  $\{d_0, y_0\}_{\tau_i}^*$
- ✍ Compare the optimal designs  $\{d_0, y_0\}_{\tau_i}^*$  for common elements (integer decision variables and/or approximately equal continuous variables)
- ✍ partition the design vector as  $\{d_0, y_0\}_{\tau_i}^* \{d_0^B, y_0^B; d_0^F, y_0^F\}$  where  $F$  denotes *flexible* and  $B$  denotes *base*



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Slides 17 to 22 refer to a methodology developed by R. de Neufville and Tao Wang for the latter's PhD thesis.

The paper can be found online at

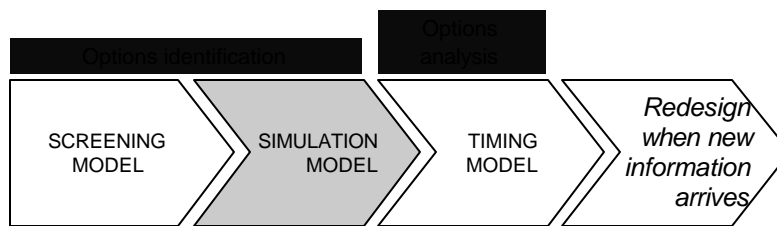
[http://www.realoptions.org/papers2004/de\\_Neufville.pdf](http://www.realoptions.org/papers2004/de_Neufville.pdf)

## Simulation-based screening methodology

de Neufville R. & Wang, T. (2004)

### 2. Simulation model for the extension and validation of screening results

- ✍ Statistically model uncertainty
- ✍ Extend system model (state space) to include transient variables  
e.g., inventory levels
- ✍ Extend model to include control actions and/or non-linear profits.  
e.g., temporarily shut down when not profitable;
  
- ✍ reduced set of designs based on mean value/variability tradeoff

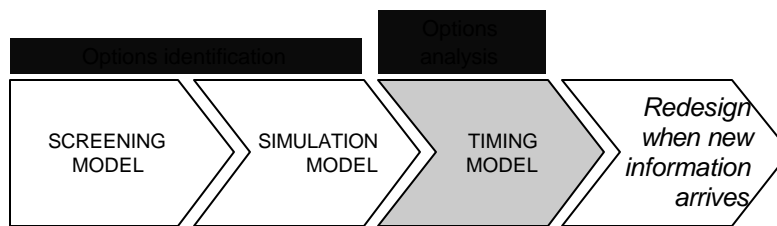


## Optimization-based screening methodology

de Neufville R. & Wang, T. (2004)

### 3. Options model for the exploitation of timing flexibility

- ✍ Elements of the design need not be built all at once provided that the design is operational if partly built
- ✍ Base design  $d_0^B, y_0^B$  will be built regardless, since it is insensitive to uncertainty
- ✍ Flexible elements will be built only contingent on later events
- ✍ Options model optimizes *timing* and *choice* of flexible designs



## Optimization-based screening methodology: application

Development of a river basin involving decisions to build dams and hydropower stations in China, for hydroelectricity production

### 1. Screening

Decision variables:

- ✍ 3 Sites (locations) ; Reservoir storage capacities (9600, 12500, 25)
- ✍ Installed electricity generation capacity (3600, 1700, 3200)

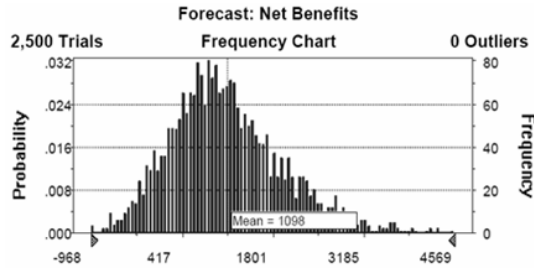
Case	Electricity Price (RMB/kWh)	$H_1$ (MW)	$V_1$ ( $10^6\text{m}^3$ )	$H_2$ (MW)	$V_2$ ( $10^6\text{m}^3$ )	$H_3$ (MW)	$V_3$ ( $10^6\text{m}^3$ )	Optimal Value ( $10^6\text{RMB}$ )
1	0.09	0	0	0	0	0	0	0
2	0.12	3600	9600	1700	25	0	0	367
3	0.15	3600	9600	1700	25	0	0	796
4	0.18	3600	9600	1700	25	1564	6593	853
5	0.22	3600	9600	1700	25	1723	9593	1607
6	0.25	3600	9600	1700	25	1946	12242	2196
7	0.28	3600	9600	1700	25	1966	12500	2796
8	0.31	3600	9600	1700	25	1966	12500	3396

Nominal price

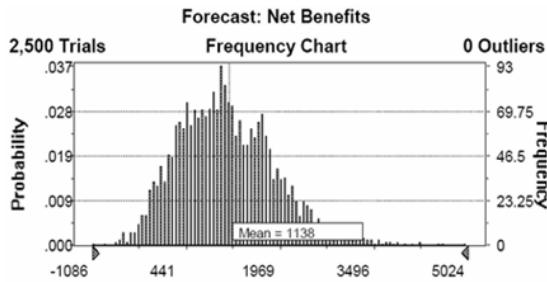
# Optimization-based screening: application

## 2. Monte Carlo simulation

Uncertainties: Electricity price, Seasonal water flow rates



Design #6: Avg. NPV = 1098



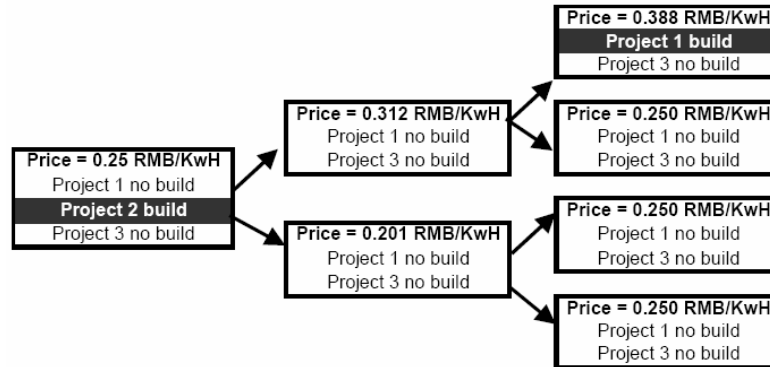
Design #5: Avg. NPV = 1138

Perform timing options analysis on this design

## Optimization-based screening: application

### 3. Timing analysis (real options)

- ✍ Uncertainty: electricity price
- ✍ Non-markovian state-space ✍ path dependencies in evolution of system  
e.g., full upstream reservoirs from previous periods feed downstream ones
- ✍ Solution method: stochastic integer programming  
different than recombining binomial tree that we learned for financial options



## Optimization-based screening: **benefits**

de Neufville R. & Wang, T. (2004)

### ✍ **Simplicity and transparency**

- ✍ Both optimization and simulation are widely implemented and easy to understand in engineering environments
- ✍ Same (or better) results obtainable using obscure and unpopular stochastic optimization “black boxes”
- ✍ Off-the-shelf stochastic optimization software generally unavailable—this is reproducible with existing models and tools

### ✍ **Computational efficiency:**

#### **focus of computational effort where it matters!**

- ✍ Linear program runs quickly, even for dozens of sites, many sizes at each site and hundreds of continuity constraints
- ✍ Timing model computationally expensive generally, but burden considerably reduced by screening model

### ✍ **Improvement over static design**

## Optimization-based screening: **challenges**

### ✍ **Optimality**

- ✍ Indication of the improvement over static design
- ✍ Indication of the sub-optimality of the solution

### ✍ **Utilize knowledge of engineering and management in unified way**

- ✍ Assign engineering to engineers and economics to managers
- ✍ Seam approach into current practice:
  - ✍ existing model utilization
  - ✍ integration with organizational processes
  - ✍ Match accuracy of flexibility optimization with appropriate design stage

### ✍ **Incorporate market-driven uncertainty**

- ✍ Resolve mean/variance trade-off and relate to overall economic system

### ✍ **Controllability, scalability, elegance (?)**

### ✍ **Maintain or improve:**

- ✍ Potential connection to financial markets
- ✍ Computational efficiency: keep it an order of magnitude less than a full stochastic optimization model.



## Option-based screening methodology: **requirements**

my research

### ✍ Problem statement

**Develop a methodology for the identification and quantitative classification of design elements, which are most likely to increase the total expected value of the system, which includes the value of flexibility**

### ✍ Requirements

#### ✍ Optimality

✍ Utilize knowledge of engineering and management in unified way

✍ Maintain or improve:

✍ Controllability, scalability, elegance (?)

✍ Methodology should be developable by late spring, so that I graduate this year!