Flexibility in Engineering Design

Using Flexibility to Creating Value

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Engineering Systems + Civil and Environmental Engineering

Author: Flexibility in Engineering Design MIT Press, 2011

with Prof. Stefan Scholtes, University of Cambridge UK

(about $30; ebook also available)

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Theme for Flexibility

A Change in Paradigm from designing to
- a specified requirements;
- to actual conditions using flexibility!

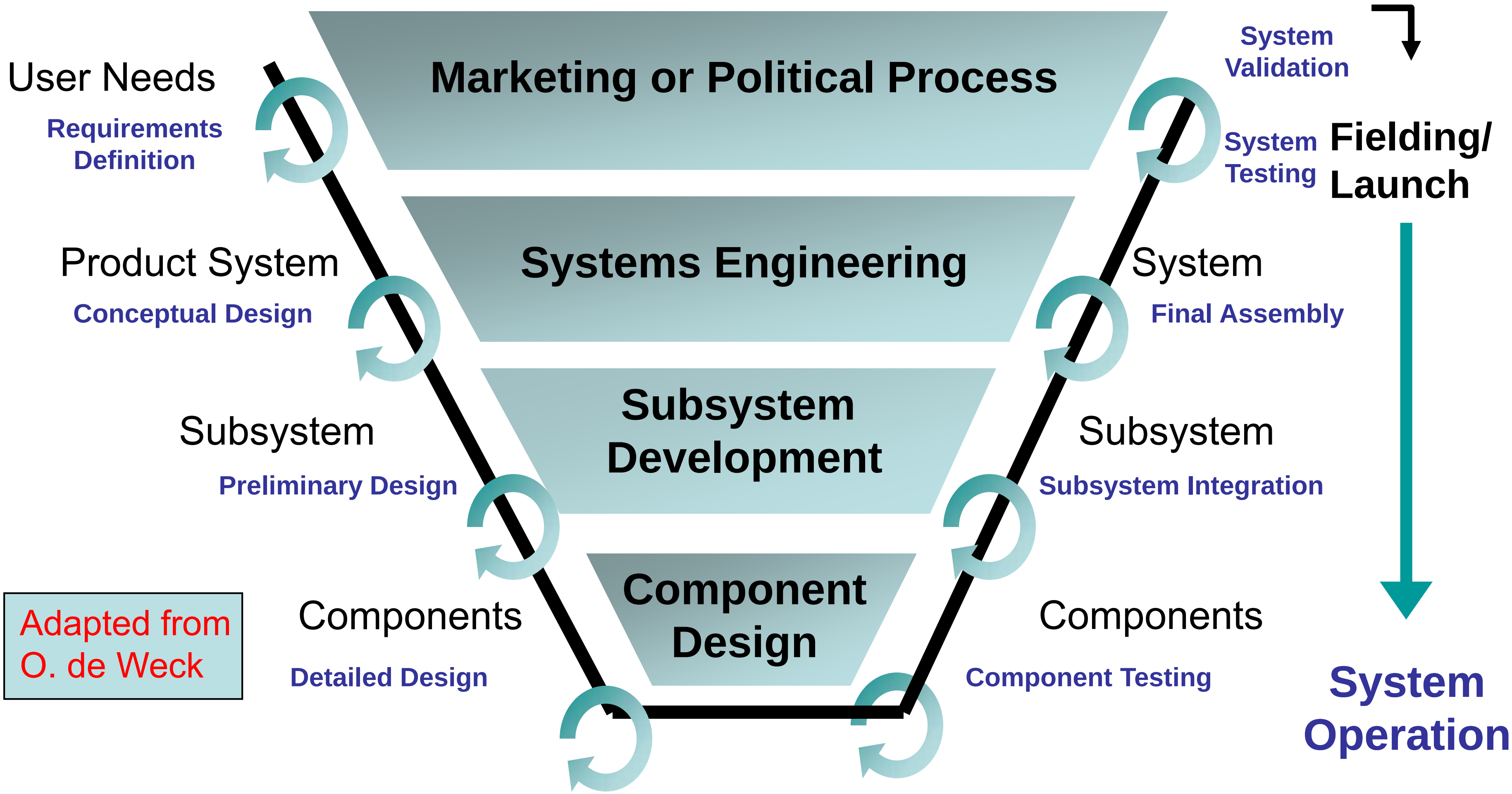
Flexibility:
- Leads to 20 to 30% increase in value
- Using a win-win approach
- Mitigates risk (downside) -- a win
- Opens opportunities (upside) – more win

Outline of Presentation

1. Discussion of Standard Procedure for design of Engineering Systems
2. Flaw of Averages
3. Concept of Alternative Paradigm
4. Analytic Procedure
5. Example Application
6. Wrap-up and Questions

Standard Procedure for Design of Engineering Systems

Traditional Systems Paradigm



Adapted from O. de Weck

Implicit Assumptions of TSE

- Companies, public know what the needs are
- These requirements are time-invariant
- The product or facility can be designed as one coherent whole and is built and deployed in one step
- Only one plant or mine designed at a time
- The system will operate in a stable environment as far as regulations, technologies, demographics and usage patterns are concerned

Assumptions of TSE – not Realistic!

- Companies know the needs? New ones emerge!
- The requirements are fixed ?
  No change with new needs and regulations, etc.
- The system can be designed as a coherent whole and built and deployed in one step? Often not
- Only one system being designed? Families likely
- The system will operate in a stable environment as far as regulations, technologies, demographics and usage patterns are concerned? We wish…

Traditional (Systems) Engineering

- Has been very successful, delivering highly complex systems of all sorts
- However, it can now do better…
- If we step outside its "box" of assumptions
- … which are unrealistic!

- **The Reality is**

- Our plants, facilities face great uncertainties
- Outcomes risky
- We need to deal with this

The Flaw of Averages

Flaw of Averages

- Named by Sam Savage ("Flaw of Averages, Wiley, New York, 2009)

It is a pun. It integrates two concepts:

- A mistake => a "flaw"
- The concept of the "law of averages",   that that things balance out "on average"

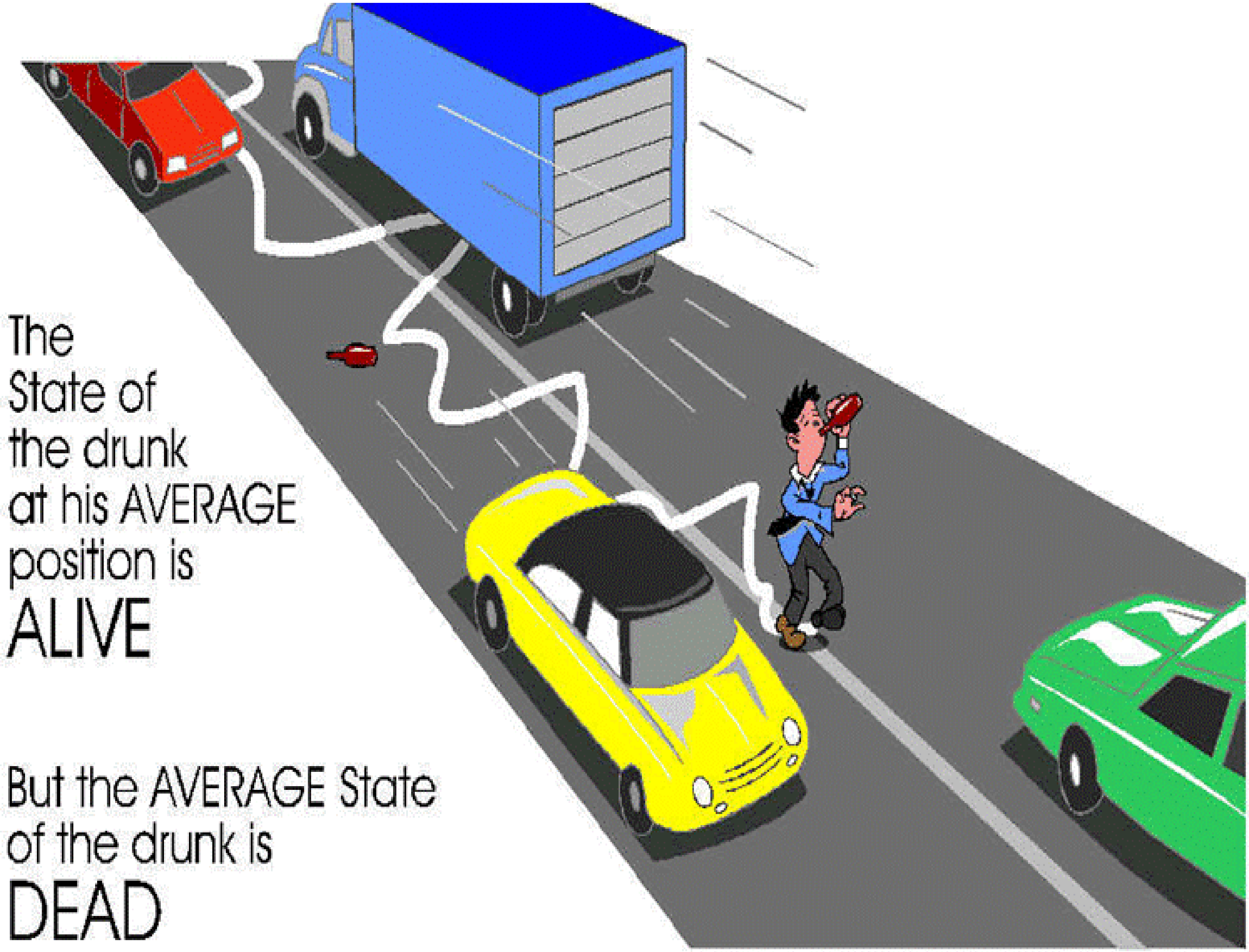
- Flaw consists of assuming that evaluation based on "average" or "most likely" conditions give correct answers **NOT SO!**

In Words

- **Average of all the possible outcomes associated with uncertain parameters,**

- **does not equal** (except if system linear)

- **the value obtained from using the average value of the parameters**


The
State of
the drunk
at his AVERAGE
position is
ALIVE
But the AVERAGE State
of the drunk is
DEAD

Example

Given: $f(x) = \sqrt{x} + 2$

And: $x = 1, 4,$ or 7 with equal probability

- $E(x) = (1 + 4 + 7) / 3 = 4$
- $f[E(x)] = \sqrt{4} + 2 = 4$
- $f(x) = 3$, 4, or $[\sqrt{7} + 2] \sim 4.65$
  with equal probability
- $E[f(x)] = (3 + 4 + 4.65) / 3 \sim 3.88 \leq 4 = f[E(x)]$

Flaw of Averages: A Real Example

- Background: Review of evaluation of a mine in Chile
- Model: The spreadsheet on revenues and profits of mine
- Deterministic valuation: NPV calculated for plant with capacity limited by crusher mill
- Valuation with Uncertainty: Used variation in ore quality given by owners – results very different !

Source: Esteban Montero

Difference due Flaw of Averages

NPV	$
Original NPV without variability	1,875.00
@Risk with variability and Production Rate constrained to 52 M tons/year	1,072.46
Difference (>43%)	**816.4**

Practical Consequences

Because Engineering Systems not linear:

- **Unless you work with distribution, you get wrong answer – and wrong choice of design**
- design from a realistic description differs – often greatly – from design you derive from average or any single assumption of "requirements"
- This is because gains when things do well, do not balance losses when things do not (sometimes they're more, sometimes less)

Concept
of
Alternative Paradigm

New, Flexible Approach to Design

- Recognizes Uncertainty
- Analyses Possible Outcomes of Designs
- Chooses Flexible Designs to
  - Reduce, eliminate downside risks (in general, less ambitious initial projects – less to lose)
  - Maximize Upside opportunities (that can expand or change function, when, if, and how seems desirable given future circumstances)

20 to 30 % Increases in Expected Value Routine!

The Concept

- Flexible design recognizes future uncertainty. The economy, technology, regulations all change.
- Flexible design creates systems easily adaptable to actual futures. It differs from the traditional approach, which defines a future and creates a design for that situation – which has little chance of occurring!
- Traditional design often leaves us with plants and operations poorly suited to actual conditions, and thus inefficient..

Great increase in Expected Value

- systems with flexibility to adapt to new conditions can greatly increase expected value.
- With flexibility we can
  - avoid future downside risks (by building smaller with confidence that can expand as needed)
  - profit from new opportunities by appropriate actions
- Reduce initial capital expenditure (CAPEX).
  - Lower initial CAPEX because less complex at start
  - Lower Present Values, because costs deferred many years (and maybe even avoided)

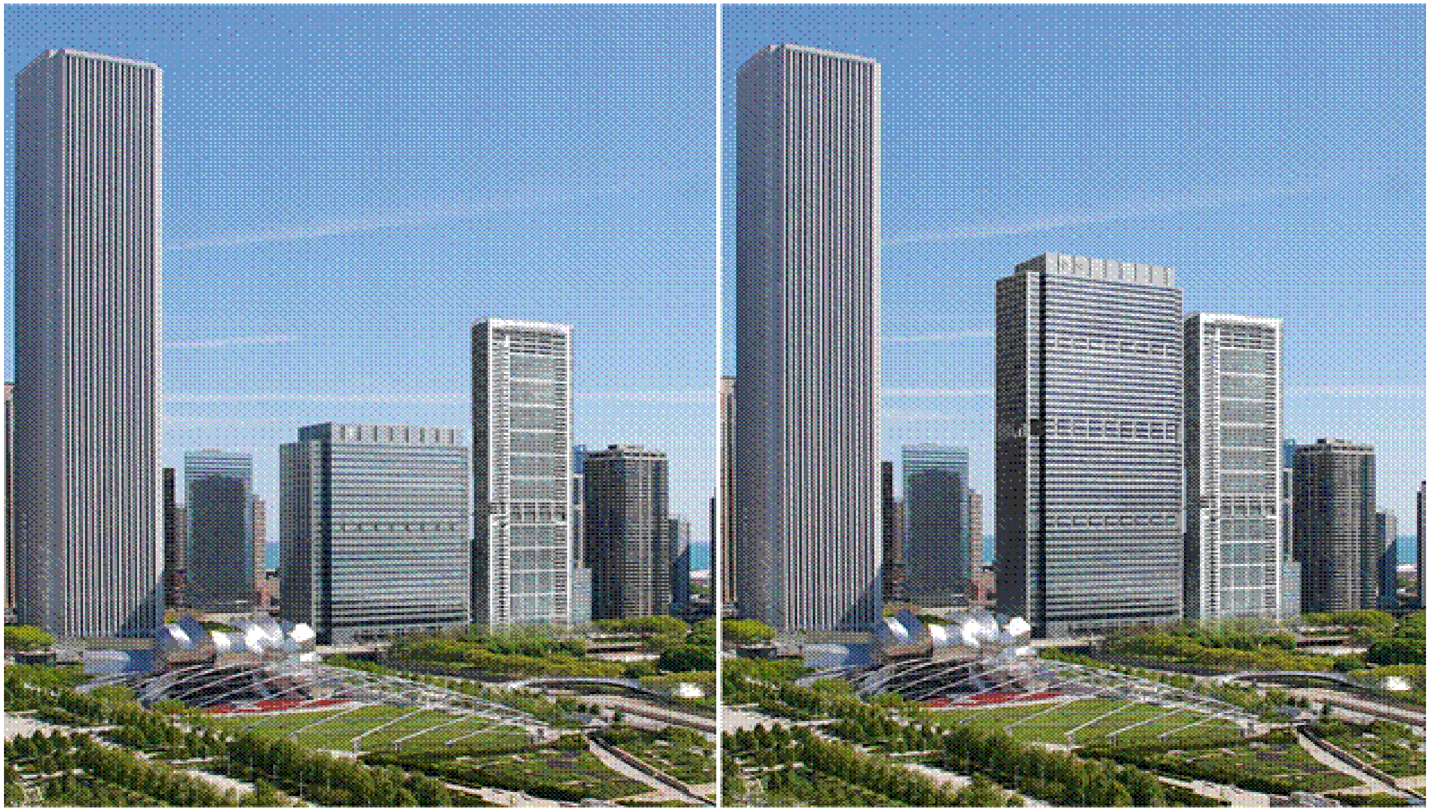
Higher returns, lower cost = A Great Formula

HCSC Building in Chicago

- In 2007-2009, 3000 people were coming to work in the 30-story HCSC building in Chicago,
- … and a 27-story addition was being built right on top of them!

- The structure was designed in 1990s with extra steel, utilities, elevator shafts, etc. to permit doubling of height.
- This flexibility was exploited a decade later

Here's the Picture



Vertical Expansion of Health Care Service Corporation Building, Chicago.
Phase 1 (left) and Phase 2 (right) in center of image.

Source: Goettsch Partners, 2008 and Pearson and Wittels, 2008.

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The Paradox

- 30-story building with capacity to expand
  - costs more than one without expansion capacity
  - Yet saves money!
- Why is this?
- The fair comparison is between
  - 30-story expandable building and
  - what HCSC would build otherwise to meet its long-term needs – such as a 40-story building
- Flexible design saves money 2 ways:
  - Lower initial Capital Expenditures (CAPEX)
  - Deferral, possible avoidance, of expansion costs

Analytic Procedure

Main Elements of Procedure

1. Recognition of Uncertainty …
   and its characterization

2. Simulation of Performance for Range of Scenarios

3. Evaluation… necessarily multi-dimensional, one number not enough to describe a distribution

4. Implementation … needs planning

Recognition of Uncertainty

- Best estimates of established trends and procedures – what is the record? Error rate? Standard deviation?

- Judgment about important, possible but unprecedented scenarios. For example, new environmental regulations, technological change, mergers of competitors, etc.

Analysis of Scenarios: Issues

- Issues:
  - Number of possibilities immense, Example of Copper mine: 3 states over 20 years => 3^{20}
  - Decision points where intelligent management would exercise flexibility – changes spreadsheets
  - Stochastic Optimization not practical in foreseeable future

Analysis of Scenarios: Process

- Develop screening models
  - Simplified, "mid-fidelity" models of situation that run quickly (minutes, not hours or a day)
- Simulate system performance under range of scenarios
  - Sample distribution hundreds or more times
- Identify "plausible sweet spots" for detailed analysis

Evaluation

- Analysis results are distributions
  - This is as it should be; if future is a distribution, results must be also
- Evaluation must be multi-dimensional
  - Because several numbers needed to characterize distributions
- Useful metrics
  - Average expectation
  - Extremes such as P_5 , P_{95}
  - Others: Initial Capex (capital expenditure)

Implementation – Needs Planning

- Many obstacles can arise
  - Failure to monitor environment to identify conditions when flexibility should be used
  - Loss of knowledge about flexibility
  - Stakeholders may selfishly block changes
- System designers and managers need a "game plan" for implementation
  - Monitoring conditions
  - Maintaining knowledge and capability
  - Coalition of stakeholders

Example Application:
Deep Water Oil Platform

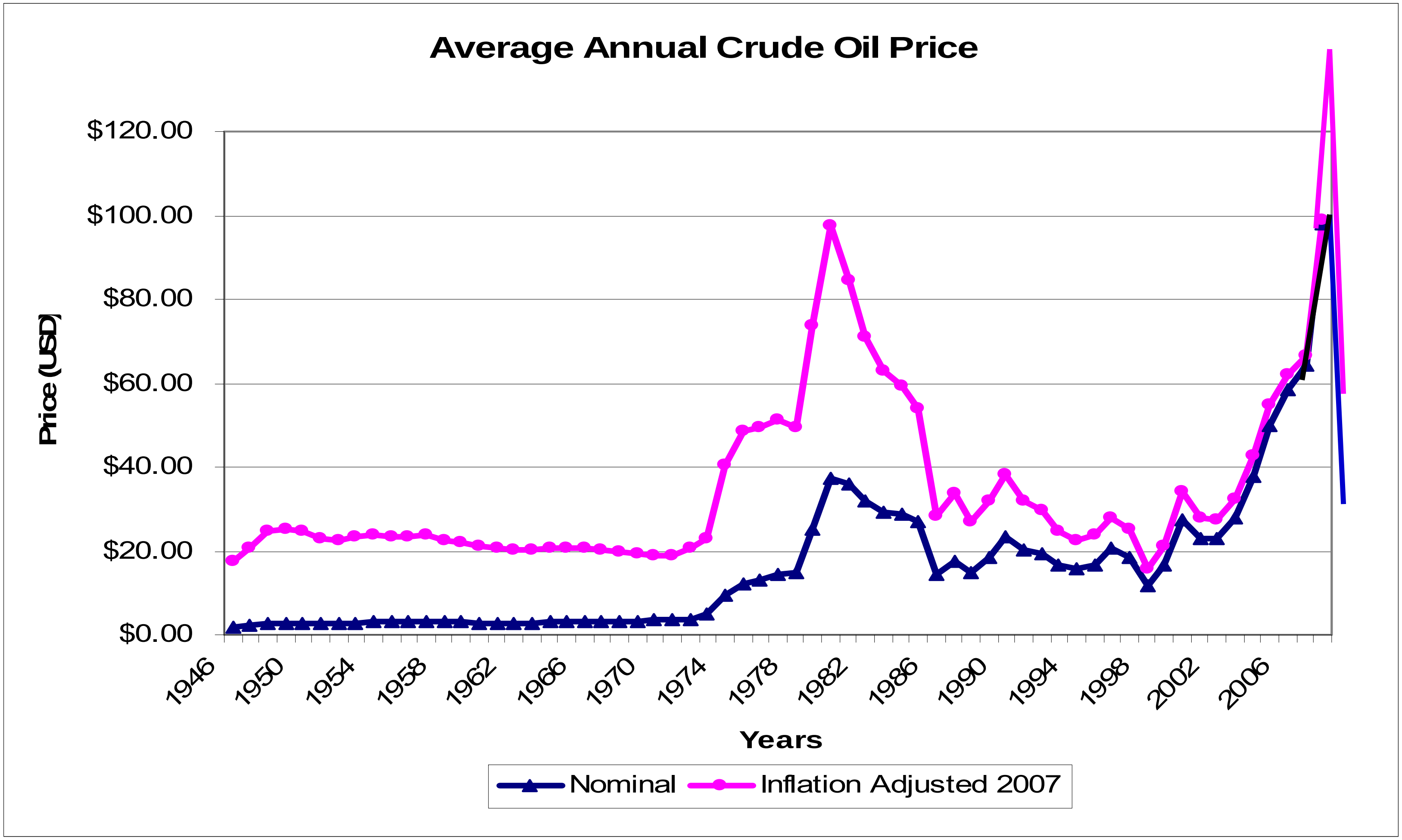
Example: Deep Water Oil Platform

Details of Case

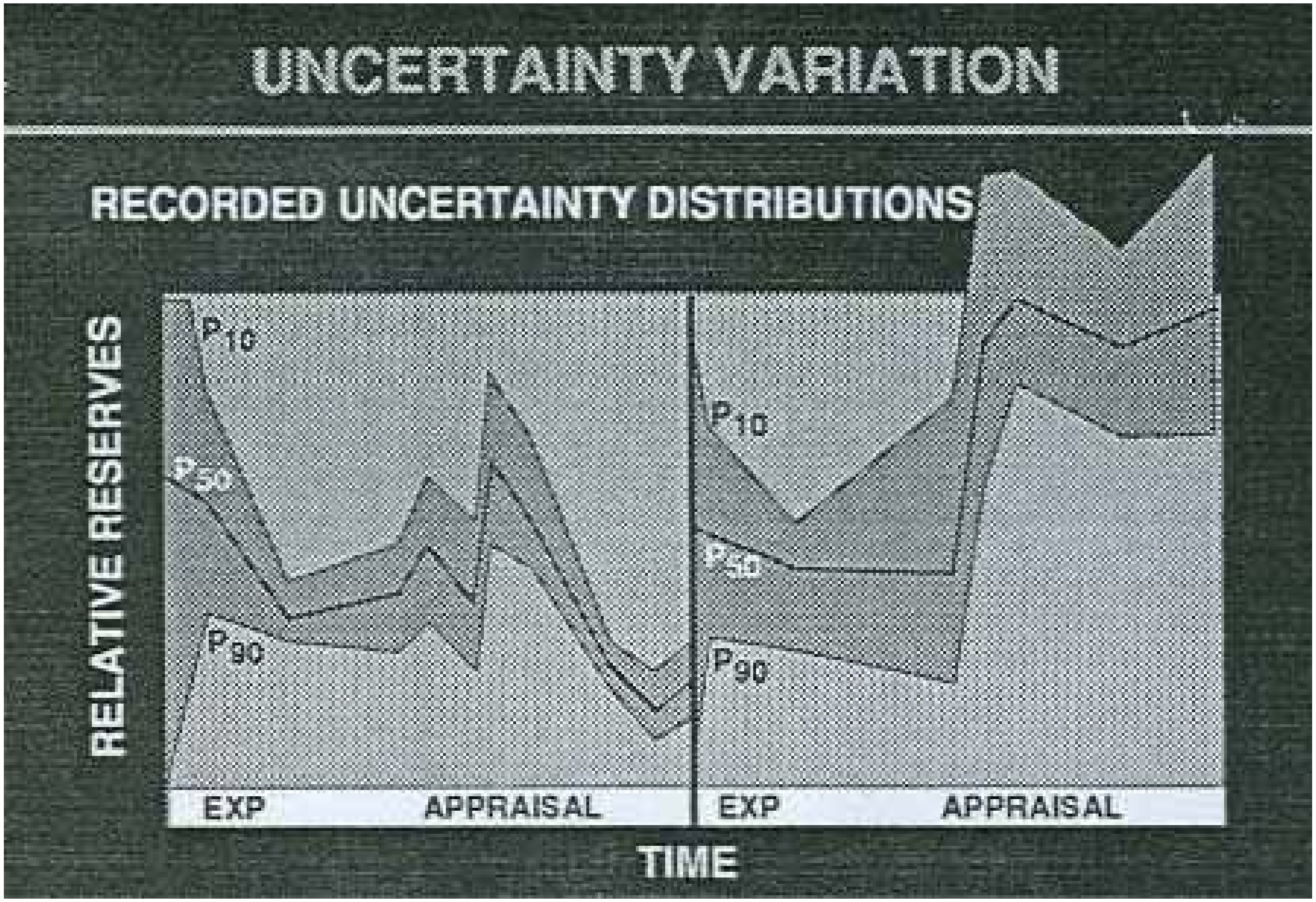
- Reservoirs in deep water, far from Country ***
- Design team taking traditional approach – optimizing for "best estimates of conditions"
- Preliminary design: **Single large facility**

- Note Uncertainties:
  – Price of Crude Oil highly volatile
  – Recoverable quantities of oil and gas difficult to determine during design stage – will only be known after more wells sunk and production begins.

Historical Prices of Crude Oil



Example Uncertainty in Oil Recovery



Source: Lin, 2009 (from BP sources)

Flexible Approaches to Design

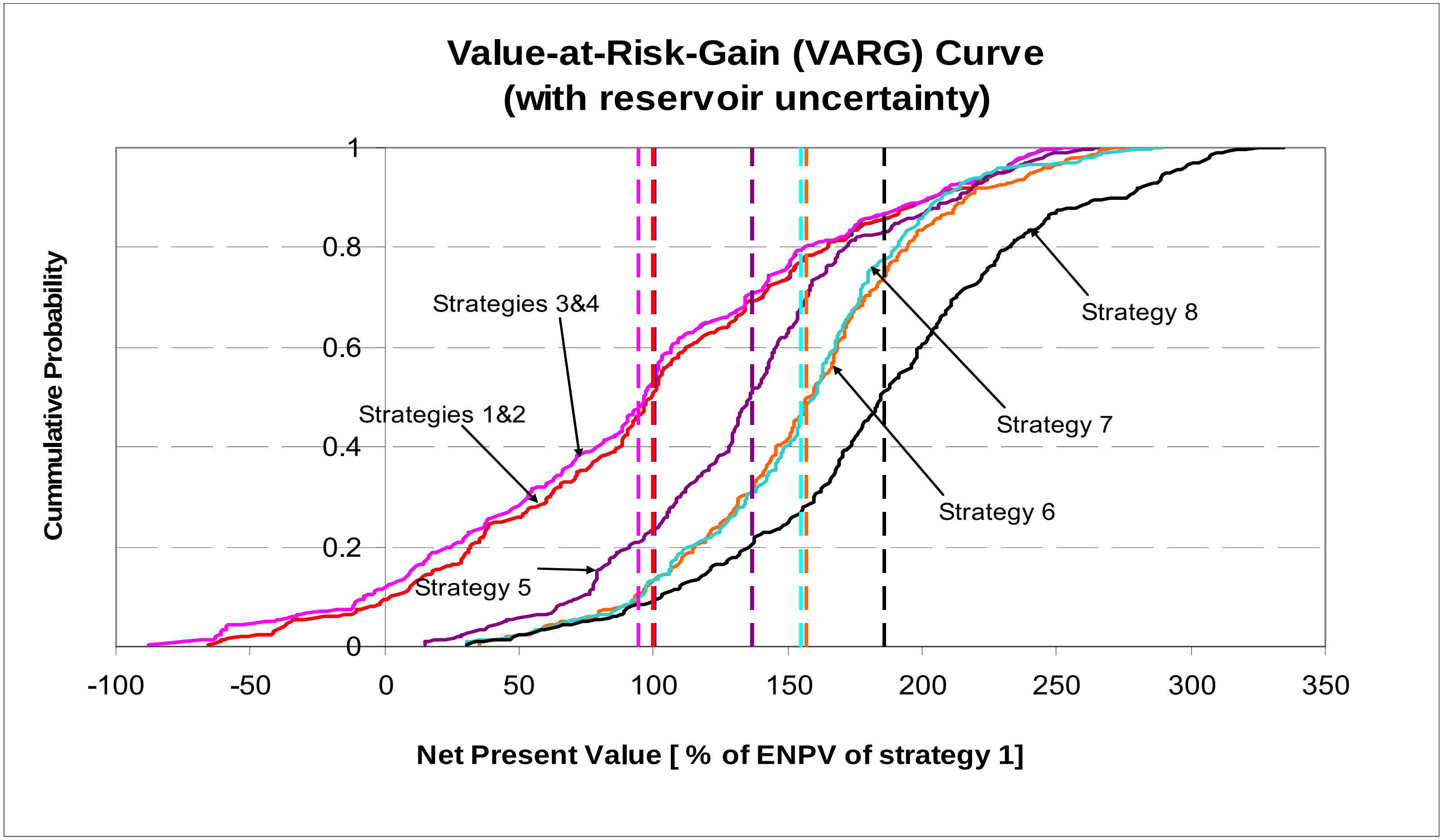
- Platform concept
  - Not a single large platform, smaller modular initial platform that can be expanded as, and when needed, even beyond traditional design
  - Much less invested, much lower risk of losses
  - Much greater profit if quantity high
- Sub-sea concept
  - Multiple "tie-back" interconnections, to adjust flow depending on size of fields, viscosity of crude, need for pressure injections
  - Flexibility to manage range of flows maximizes quantity

Cumulative Effect of Flexible Design

- Great advantages compared to traditional design around "most likely" scenario
- Fixed design subject to
  - large losses if extractable quantity and price of oil is low
  - Cannot expand production economically if reservoirs larger and richer than "best estimate" (likely half the time!) and thus misses out on good opportunities.
- Flexible design improves
  - Much lower exposure to losses
  - Ability to take advantage of good conditions

Moves Cumulative distribution of outcomes higher

Analysis Results



Source: Lin et al, 2009

Bottom Line Improvement

Flexible design for oil platform

- increased expected value 78%,
- lowered CAPEX about 20%

- These were real results

Flexible design more realistic and profitable

Summary

- Flexible thinking can greatly increase expected value from projects
- New paradigm -- Not traditional approach
- A “must” for future system designers and managers!

Thanks for your attention! Questions?

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