Flexibility in Engineering Design
with examples from electric power systems

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Reference to text

“Flexibility in Engineering Design”
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Theme of Presentation

A Change in Paradigm of Design
• Back to ‘common sense’ approach
• Increasingly used in industry

Essence of Paradigm:
• As we cannot predict future, we must design for adaptability, so as to
• Take advantage of upside opportunities
• Avoid downside problems
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 Applications
6. Wrap-up and Questions
Standard Procedure for Design of Engineering Systems
Traditional Systems Paradigm

Adapted from O. de Weck

User Needs
- Requirements Definition

Product System
- Conceptual Design

Subsystem
- Preliminary Design

Components
- Detailed Design

Marketing or Political Process

Systems Engineering

Subsystem Development

Component Design

Fielding/Launch

System Validation

System Testing

System Final Assembly

Subsystem Subsystem Integration

Components

Component Testing

System Operation
Implicit Assumptions of TSE

- Customers, public know what the needs are
- These requirements are time-invariant
- The system or product can be designed as one coherent whole and is built and deployed in one step
- Only one system or product 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!

- Customers know the needs? New ones emerge!
- The requirements are fixed? These change with needs and new regs, etc, 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 systems are in the middle of uncertainties

➤ Economic Financial conditions … Boom and Bust
➤ Technological change … fracking, wind, nuclear…
➤ Regulatory… New Rules: Environmental, economic…
➤ Shape of Industry… deregulation, merchant suppliers …
➤ Political… will there be a carbon tax? …
➤ Other … 3-mile island, Sandy, climate change? …

Bottom Line: Outcomes only known probabilistically
The Flaw of Averages
Further Crucial Reality: Flaw of Averages

• Design to “most likely”, “average” or “requirement” scenario is BAD – gives wrong results

• benefits of better scenarios “never” equal losses of poorer scenarios (a few theoretical exceptions)

Example:

Design plant to most likely capacity
20% Higher sales => lost sales -- can’t deliver demand
20% Lower sales => losses

Systems are non-linear, need to examine range

• We need to analyze scenarios
Flaw of Averages


It is a pun. It integrates two concepts:
- A mistake => a “flaw”
- The concept of the “law of averages”, that things balance out “on average”
- Flaw consists of assuming that design or evaluation based on “average” or “most likely” conditions give correct answers
Mathematics of Flaw

- Jensen’s law:
  \[ E [ f(x) ] \leq f [ E(x)] \] if f(x) is convex function

- Notation: \( E(x) = \) arithmetic average, or “expectation” of x

- In words:
  \( E[f(x)] = \) average of possible outcomes of f(x)
  \( f[E(x)] = \) outcome calculated using average x
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 \( \sqrt{7} + 2 \approx 4.65 \) with equal probability
- \( E[f(x)] = (3 + 4 + 4.65) / 3 \approx 3.88 \leq 4 = f[E(x)] \)
In Words

• Average of all the possible outcomes associated with uncertain parameters,

• generally does not equal

• 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.
Practical Consequences

Because Engineering Systems not linear:

• Unless you work with distribution, you get wrong answer

• 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 infrastructure 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 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.
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
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
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: Process

• Develop screening models
  – Simplified, “mid-fidelity” models of system 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)
Example Analyses for Electric Power Systems

1. Renewables in Texas
2. Technological Innovation
1. Renewables in Texas

**Issue:** Standard planning process is deterministic and simplistic: Capacity planned based on estimates – operations not analyzed

**Analysis:** Combine both capacity planning and operational constraints, along with uncertainty

**Results:**

a. Demonstration that simple process misestimates consequences

b. More flexible, more advantageous design
Long-Term Generation Planning with Operations Constraints

- **Today:** Simple analysis does not tie actual operations into long-term plan
- The “Short Blanket” Problem
- Our analysis (the blanket) does fully cover us

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**Investment Decisions**

**Operations Constraints**

Based on Dr. Bryan Palmintier
Long-Term Generation Planning with Operations Constraints

• Challenge: Short time scale embedded in long-term planning – problem too big
• We get wrong/bad answers – case of RPS
  Renewable Portfolio Standard (e.g.. 20%)

<table>
<thead>
<tr>
<th>Goal</th>
<th>Result with Simple Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimate carbon price</td>
<td>Off by factor of 2</td>
</tr>
<tr>
<td>Design for 45Mt CO2 cap</td>
<td>Infeasible Can’t do RPS + Cap</td>
</tr>
</tbody>
</table>
Long-Term Generation Planning with Operations Constraints

• Root cause of wrong answers
  – Planning model neglects variability of loads, has no “plan b” to deal with them

• Desire: Operational Flexibility
  – Issue: Renewables – production changes rapidly BUT Low CO2 technologies (e.g., Nuke) can’t ramp quickly
  – Need: Unit Commitment (UC) capability, up to a week ahead

Based on Dr. Bryan Palmintier
**What is Driving the Results?**

Based on Dr. Bryan Palmintier

Standard Model implies that old coal plants (left) and combined cycle gas are used (right) – and turned on/off over few hours.

Bottom Model is what would actually happen realistically – to account for start-up and ramping constraints.

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**MIT ESD**

*Engineering Systems Division*
2. Technological Innovation

**Issue:** Standard planning process is deterministic and simplistic: It does not account for R&D uncertainty—example of Flaw of Averages

**Analysis:** Combine: capacity planning + economic model of R&D + stochastic R&D results

**Results:**
a. Demonstration that simple process misestimates consequences
b. Amount of incremental R&D depends on technology’s role in system (nuclear vs wind)
Modeling Framework

Environmental Policy

R&D$

Technology Change Module
“Innovation Possibilities Frontier”

\[ h_t = aRD^bH^d \]

Knowledge Stock \((H)\)

New Knowledge \((h)\)

Generation Planning Inputs

- Generation Technology Costs ($/MWh)
- Electricity Demand (MW/time)
- Generation Technology Availability (Year)

Learning by Researching

Learning by Experience

Generation Planning Model

New Power Plant Additions (GW)

Production (GWh)

CO₂ Emissions (Million Metric Tons)

By Dr. Nidhi Santen
**Deterministic Results : Reference Case**

Assume there is a carbon cap.

Spend on wind research early, to make it cheaper and start using it soon. Compared to coal with C capture – too expensive now.
Stochastic Results: Carbon Cap

First Period Optimal R&D Investments (with Carbon Cap)

- Coal with CCS: 31%
- Wind: < 2%

By Dr. Nidhi Santen
Stochastic Results: CARBON CAP

Coal with CCS R&D Investment Under Uncertainty
(with Carbon Cap)

R&D Investment (Millions)

Period

1 2 3 4 5 6

0 100 200 300 400 500 600 700 800 900

Deterministic
Stochastic (plus p05 and p95)

By Dr. Nidhi Santen
Summary

• Flexible design can greatly increase expected value from projects

• New paradigm -- Not traditional approach

• Requires research on how best to analyze and implement flexible design in practice
Thanks for your attention!

Questions and Comments?
Long-Term Generation Planning with Operations Constraints

• Use for Policy: Project CO₂ Emissions

Emissions for $90/ton CO₂

Simple: 50% Error In Emissions Estimate

Energy Production (TWh) (RPS=20%, CO₂=$90/ton)

UC-Predict, Actual (UC), Simp-Predict

By Dr. Bryan Palmintier
Long-Term Generation Planning with Operations Constraints

- Scenario assumed:
  - 20% RPS
  - $90/ton CO2
- Different Capacities
- UC: More Flexible NG-CT to balance Nukes

Based on Dr. Bryan Palmintier
Long-Term Generation Planning with Operations Constraints

By Dr. Bryan Palmintier

- **Total Annual Cost ($Billions)**
  - Predict: UC 39, Actual: UC 37
  - Predict: Simple 3367, Actual: Simple 37

- **Non-served Energy (GWh)**
  - Predict: UC 0, Actual: UC 2
  - Predict: Simple 66461, Actual: Simple 0

- **Wind Shedding (GWh)**
  - Predict: UC 0.5, Actual: UC 0.5
  - Predict: Simple 14, Actual: Simple 0
Deterministic Model

Structural Details

- Centralized, social planning model
- 50-year planning horizon, 5-year time steps
- Representative technologies and demand: U.S. system

Objective

\[
\min \sum_{t=1}^{t=5} NPV = \min \sum_{t=1}^{t=5} \delta_t (FixedCosts_t + VarCosts_t + RD_t)
\]

Decision Variables (per period)

1. R&D $ (by Technology)
2. New Power Plants (by Technology)
3. Generation Operation
4. Carbon Cap (per Period)

Constraints

1. Cumulative carbon cap
2. Cumulative R&D funding spending account
3. All traditional generation expansion constraints (e.g., demand balance, reliability, non-cycling nuclear technology, etc.)

Generation Technologies

- Old Conventional Coal
- New Advanced Coal
- Coal with CCS*
- Old Steam Gas
- Gas Combined Cycle
- Gas Combustion Turbines
- Hydro
- Nuclear*
- Wind*
- Solar*

*Learning Technologies

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**Stochastic Modeling Framework**

*Decisions* $R&D_i$: R&D investments (continuous)

*Uncertainty*: R&D investment efficiencies (continuous)

**State Variable**: Cumulative Knowledge Stocks (continuous)

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**Deterministic Results : Reference Case**

**R&D Investment by Technology**

- **R&D Investment (Millions)**
- **Period**
- **Technologies**:
  - solar
  - wind
  - coal_ccs
  - nuclear

**Installed Capacity by Technology**

- **GW**
- **Period**
- **Technologies**:
  - solar
  - wind
  - gas_ct
  - gas_ccgt
  - gas_ogs
  - coal_ccs
  - coal_new
  - coal_old
  - hydro
  - nuclear