Technical and non-technical uncertainties in operational energy performance

Nick Doylend
Research Engineer
CREST, Loughborough University
Overview

- Quick summary of the problem
- Identifying the key issues:
  - Improving simulation techniques
  - Accounting for uncertainty
  - Incorporating non-technical factors
- Proposing a way forward:

  *A due diligence framework for energy performance risk management*
Drivers

- **Climate Change Act 2008**
  - Net 80% reduction on 1990 emissions by 2050
  - At least 26% reduction on 1990 emissions by 2020

- **Low Carbon Transition Plan 2009**
  - Emission cuts of 18% on 2008 levels by 2020
  - Over a one third reduction on 1990 levels

- **Zero carbon new non-domestic construction by 2019**

- **Changes to Building Regulations**
The big picture

**Energy Consumption**

- **Opposition to Generation**
- **Security of Supply**
- **Cost**
- **Environmental Pollution**
- **Resource Depletion**

- CO₂ Balloon

- Images:
  - Opposition to Generation
  - Security of Supply
  - Cost
  - Environmental Pollution
  - Resource Depletion

---

**Energy Consumption**
CO$_2$ emissions by end use

- Transport: 32%
- Buildings: 47%
- Industrial Process: 20%
- Agriculture: 1%
- Domestic: 28%
- Commercial And Public: 15%
- Industrial: 4%

BRE Report 442 2002
## Energy benchmarks

<table>
<thead>
<tr>
<th>ECON19</th>
<th>Office Type 1</th>
<th>Office Type 2</th>
<th>Office Type 3</th>
<th>Office Type 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-electric (kWh/m².yr)</td>
<td>79</td>
<td>151</td>
<td>79</td>
<td>151</td>
</tr>
<tr>
<td>Electricity (kWh/m².yr)</td>
<td>33</td>
<td>54</td>
<td>54</td>
<td>85</td>
</tr>
<tr>
<td>Total CO₂ (kgCO₂/m².yr)</td>
<td>32</td>
<td>57</td>
<td>43</td>
<td>73</td>
</tr>
</tbody>
</table>

**EEBP Energy Consumption Guide 1998**

<table>
<thead>
<tr>
<th>National Trust</th>
<th>Good Practice</th>
<th>Best Practice</th>
<th>Innovative</th>
<th>Pioneering</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-electric (kWh/m².yr)</td>
<td>79</td>
<td>47</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>Electricity (kWh/m².yr)</td>
<td>54</td>
<td>43</td>
<td>35</td>
<td>25</td>
</tr>
<tr>
<td>Total CO₂ (kgCO₂/m².yr)</td>
<td>40</td>
<td>30</td>
<td>15</td>
<td>0</td>
</tr>
</tbody>
</table>

**Gething & Bordass 2006**

<table>
<thead>
<tr>
<th>CIBSE</th>
<th>General Office</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-electric (kWh/m².yr)</td>
<td>120</td>
</tr>
<tr>
<td>Electricity (kWh/m².yr)</td>
<td>95</td>
</tr>
<tr>
<td>Total CO₂ (kgCO₂/m².yr)</td>
<td>75</td>
</tr>
</tbody>
</table>

**CIBSE TM46 2008**
DEC data

- Operational i.e. ‘real’
- Distribution of ratings

Source: http://www.cse.org.uk/pages/resources/open-data
DEC data analysis

- Wider variation in non-electric than electricity energy use
- Mean electricity use close to benchmark
- Mean non-electric use lower than benchmark

<table>
<thead>
<tr>
<th>CIBSE TM46 Benchmarks (used for DECs)</th>
<th>Schools and seasonal public buildings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-electric (kWh/m².yr)</td>
<td>40</td>
</tr>
<tr>
<td>Electricity (kWh/m².yr)</td>
<td>150</td>
</tr>
<tr>
<td>Total CO₂ (kgCO₂/m².yr)</td>
<td>50.5</td>
</tr>
</tbody>
</table>
The performance gap

Adapted from Bordass 1999
• Smallest difference: -33%
• Biggest difference: 401%
• Median difference: 71%

Source: http://www.carbonbuzz.org
● Ambitious CO$_2$ targets for new build
● Demonstrating operational performance
● Use of typical/good practice benchmarks
● DEC dataset illustrates variability
● CarbonBuzz illustrates performance gap
Uses of simulation

- No longer a niche technique
- Part L / EPC NCM calculations
  comparison of design against 'notional' / 'typical'
  under standard scenarios; no unregulated loads
- Inappropriate for energy prediction
- Does the industry get this?
Calibration

- Good results are possible
  ...for a specific building
- But what to calibrate against?
- Can improve input data
- Leading to better benchmarks
- Of limited use in improving energy prediction generally
Uncertainty

- Do benchmarks reflect future building?
- How do you account for this uncertainty?
  - Sensitivity analysis
    (impact of individual parameters)
  - Monte Carlo analysis
    (repeated simulations using parameter values drawn from probability distributions)
  - Stochastic models
    (probabilistic variation in input data)
- Techniques should become mainstream
  (a plea to tool developers)
What's the problem?

What the user really wanted

How the analyst saw it

As the contractor built it

What the user asked for

How the system was designed

How it actually works (Mondays)
We just can't predict!

- Complex socio-technical systems
- Many non-technical factors:
  - How do we account for these?
Robust design (1)

- Technical complexity itself is not the problem
- Needs careful design to ensure robustness
- Vigilance is the price of (technical) complexity
- Robustness can help reduce uncertainty

Bordass, Leaman, Ruyssevelt 1999
Robust design (2)

- A outperforms B in theory
- B outperforms A in practice
- Technical sophistication may increase uncertainty
- Robustness can reduce uncertainty

**CO₂ Emissions Intensity**

2010 DEC Data (Filtered, Schools)

- A outperforms B in theory
- B outperforms A in practice
- Technical sophistication may increase uncertainty
- Robustness can reduce uncertainty
Risk management

- Performance-gap represents risk
- Simulation models need to consider uncertainty
- Also need to integrate non-technical factors
- Compare designs on the basis of performance and risk
- How to evaluate this risk (rigorously)?
What other techniques?

- Regression models
  - Great for predicting the past \((given\ suff cient\ data)\)

- Neural networks
  - Great given sufficient training

- Bayesian networks
  - Based on probabilistic inference
  - Allow reasoning with incomplete data
  - Integrate quantitative and qualitative data
Probability

- **Objective (frequentist) probability**
  - The long-run or limiting frequency of an event
  \[
  Pr(A) = \lim_{n \to \infty} \frac{n_a}{n}
  \]

- **Subjective (Bayesian) probability**
  - Can be used with degrees of belief
  - Derived from Bayes’ Rule
  \[
  Pr(A|B) = \frac{Pr(B|A) Pr(A)}{Pr(B)}
  \]
  - \(Pr(A)\) represents *prior* probability
  - \(Pr(A|B)\) represents *posterior* probability given some evidence B.
Bayesian inference

- Allows reasoning under uncertainty
- Updating initial beliefs in the light of new observations
- Pragmatic approach applicable to real-life problems:
  - Cracking the Enigma
  - Medical diagnosis
  - Spam filtering
  - Reliability prediction
Bayesian networks (1)

- Model cause and effect relationships
- Use Bayesian inference techniques
- Allow reasoning from cause to effect (prognosis) and vice versa (diagnosis)
- Graphical models are transparent and auditable
Bayesian networks (2)

- "directed acyclic graphs and associated probability tables"
  - Nodes represent uncertain variables
  - Edges represent causal or influential links
  - Tables describes the probabilistic relationship between parent and child nodes
Causal relationships

Example Project Performance Network
Probabilistic relationships

Example Project Performance Network

<table>
<thead>
<tr>
<th>Project Team Integration</th>
<th>Project Team Experience</th>
<th>Technological Complexity</th>
<th>Availability of Field Trial Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Project Team Ability</th>
<th>Project Resources</th>
<th>Technical Risk</th>
<th>Technical Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Potential Project Outcome</th>
<th>Technical Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Success</td>
<td>High</td>
</tr>
<tr>
<td>Failure</td>
<td>Low</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Technical Risk</th>
<th>Availability of Performance Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Technical Risk</th>
<th>Availability of Performance Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Technical Risk</th>
<th>Availability of Performance Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Technical Risk</th>
<th>Availability of Performance Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>
Empirical data

Example Project Performance Network

### EST Field Trial Results

**Air Source Heat Pumps**

<table>
<thead>
<tr>
<th>COP</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>over 3.5</td>
<td>10%</td>
</tr>
<tr>
<td>3 to 3.5</td>
<td>20%</td>
</tr>
<tr>
<td>2.5 to 3</td>
<td>20%</td>
</tr>
<tr>
<td>2 to 2.5</td>
<td>30%</td>
</tr>
<tr>
<td>1.5 to 2</td>
<td>30%</td>
</tr>
<tr>
<td>1 to 1.5</td>
<td>10%</td>
</tr>
<tr>
<td>below 1</td>
<td>0%</td>
</tr>
</tbody>
</table>

*SAP Benchmark = 2.5*

### Technological Complexity

<table>
<thead>
<tr>
<th></th>
<th>High</th>
<th>Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>Low</td>
<td>0.6</td>
<td>0.4</td>
</tr>
</tbody>
</table>

### Availability of Performance Data

<table>
<thead>
<tr>
<th></th>
<th>High</th>
<th>Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>0.3</td>
<td>0.7</td>
</tr>
<tr>
<td>Low</td>
<td>0.7</td>
<td>0.3</td>
</tr>
</tbody>
</table>

### Availability of Field Trial Data

<table>
<thead>
<tr>
<th></th>
<th>High</th>
<th>Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>30.0</td>
<td>70.0</td>
</tr>
<tr>
<td>Low</td>
<td>70.0</td>
<td>30.0</td>
</tr>
</tbody>
</table>

### Technical Risk

<table>
<thead>
<tr>
<th></th>
<th>High</th>
<th>Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>66.8</td>
<td>33.2</td>
</tr>
<tr>
<td>Low</td>
<td>33.2</td>
<td>66.8</td>
</tr>
</tbody>
</table>

### Technical Risk

<table>
<thead>
<tr>
<th></th>
<th>High</th>
<th>High</th>
<th>Low</th>
<th>Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>0.6</td>
<td>0.95</td>
<td>0.2</td>
<td>0.7</td>
</tr>
<tr>
<td>Low</td>
<td>0.4</td>
<td>0.05</td>
<td>0.8</td>
<td>0.3</td>
</tr>
</tbody>
</table>
Example Project Performance Network

- **Project Team Integration**
  - High: 50.0
  - Low: 50.0

- **Project Team Experience**
  - High: 75.0
  - Low: 25.0

- **Technological Complexity**
  - High: 100
  - Low: 0

- **Availability of Field Trial Data**
  - High: 30.0
  - Low: 70.0

- **Project Team Ability**
  - High: 59.4
  - Low: 40.6

- **Project Resources**
  - High: 100
  - Low: 0

- **Technical Risk**
  - High: 84.5
  - Low: 15.5

- **Potential Project Outcome**
  - Success: 49.6
  - Failure: 50.4
Diagnosis

Example Project Performance Network

- **Project Team Integration**
  - High: 56.1
  - Low: 43.9

- **Project Team Experience**
  - High: 81.2
  - Low: 18.8

- **Technological Complexity**
  - High: 100
  - Low: 0

- **Availability of Field Trial Data**
  - High: 33.7
  - Low: 66.3

- **Project Team Ability**
  - High: 78.3
  - Low: 21.7

- **Project Resources**
  - High: 100
  - Low: 0

- **Technical Risk**
  - High: 77.9
  - Low: 22.1

- **Potential Project Outcome**
  - Success: 100
  - Failure: 0
Creating a useful tool

- Data gathering
  - Literature review
  - Semi-structured interviews
- Derivation of causal maps
- Conversion to Bayesian networks
- Probability encoding
  - Empirical data
  - Structured interviews

Nadkarni & Shenoy 2004
Case study building

- TSB Building Performance Evaluation project
- Wireless energy and environmental monitoring
- Workshops and interviews with design team, tenants and management
Summary

- Simulation isn't the whole story
- Need to consider uncertainty
  - Technical
  - Non-technical
- “Energy Performance Risk Management”
  ...using Bayesian Networks to develop a due-diligence framework for clients and designers
Thank you

For more information:

n.o.doylend@lboro.ac.uk