Comparing measured and simulated building energy performance data

Tobias Maile, Ph.D.
Measured ≠ simulated building energy performance
Measured ≠ simulated building energy performance

1) How many performance problems cause this difference?

2) Total building data is not enough to determine performance problems – How much data is needed? (e.g., Gillespie et al. 2001)

3) Today’s building energy performance evaluation is
   • missing a link to design (compare measured and simulated)
   • inconsistent
   • time-consuming

Domain: performance assessment of commercial buildings

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Observed problem in practice

Theoretical limitations (point of departure)

Research questions

Research results

Research tasks

Legend:

→  Leads to

←  Compare

Agenda – CIFE “Horseshoe”
Intuition - The big idea

A performance assessor can evaluate building energy performance by **comparison** of measured and simulated performance data.

**Building object hierarchy**
- Measured data
- Simulated data
- Comparison (Salsbury and Diamond 2000)

**Assumptions**
- e.g., spot measurement

**Limitations**
- e.g. constant speed thermal box (versus 2 speed)

**Real world Building**

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Example comparison at the system level

Difference during unoccupied hours

Is this a performance problem?
POD - Existing performance evaluation concepts

- **Design**
  - Building energy simulation (e.g., EnergyPlus)
  - Rule based fault detection (e.g., Santos and Rutt 2001)
  - Semi-automated fault detection (Xu et al. 2005)

- **Commissioning**
  - Traditional commissioning

- **Operation**
  - Rule based fault detection (e.g., Santos and Rutt 2001)
  - Calibrated models (e.g., Reddy 2006)

- **Retrofit**

**Legend**
- Model based
- Measurement based
- Rule based
POD - Existing calibration methods

1. Compensating errors can mask modeling inaccuracies at the whole building level
   (Clarke 2001)
   → need for “calibration” on component level
   → need for bottom-up comparison

2. Model “validated” if difference within predefined error margin (e.g., 5 %)
   a. “trial-and-error” approach (until within 5%)
   b. Multiple and arbitrary solutions (Reedy et al. 2006)
   c. Solutions include undocumented limitations
   → Better understanding of underlying measurement assumptions simulation approximations is necessary
Research questions

• How can a comparison of measured and simulated energy performance data identify performance problems based on HVAC design models and actual measured data?
  – How can components in a building be represented to support this comparison?
  – What measurement assumptions help to explain differences between measured and simulated data?
  – What simulation approximations, assumptions and simplifications (AAS) help to explain differences between measured and simulated data?
Energy Performance Comparison Methodology

Step 1: Preparation
- Create or update energy model
- Establish component hierarchy
- Set up data collection

Step 2: Matching
- Update input
- Simulated data
- Simulation AAS
- Measurement assumptions
- Measured data
- Create data pairs via hierarchy

Step 3: Evaluation
- Detect differences
- Identify performance problems
- Estimate impact
- Adjust energy model
- Improve building operation
- Feedback to HVAC design

Legend:
- Performance data
- Tasks
- Approximations
- Assumptions
- Actual building
- Contributions
Example comparison at the system and component level

Difference during unoccupied hours

Is this a performance problem?
Example comparison continued

Difference during unoccupied hours

Simulation approximation
Active chilled beam is constant volume (not two speed)

Is this a performance problem?
NO
Building object hierarchy (O’Donnell 2009)
- Missing relationships between components
- Missing spaces
→ relationships are needed to link components
All HVAC systems are linked to the zone. There are no relationships between components and no spaces in the hierarchy. Embedded in HVAC energy model (O’Donnell 2009).
Two interlinked building object hierarchies

Hierarchical structures for spatial and HVAC perspectives:
- To represent needed relationships for comparison
- To establish data pairs

HVAC object hierarchy:
- Building
- System
- Component
- Zone
- Space
- Floor

Spatial object hierarchy:
- Building
- Floor
- Space
- Zone
- Component

Relationships between components and zone/spaces:
Research methods and tasks

Research methods
- Case study investigation
- Literature review

Research tasks
- Observe measurement systems
- Observe simulation models
- Identify and characterize assumptions, approximations and simplifications (AAS)
- Develop formal representation
- Develop energy performance comparison methodology
- Assess measurement data set guidelines
- Show number of identified problems of methodology compared to current practice

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## Case studies

<table>
<thead>
<tr>
<th>Building</th>
<th>Existing simulation model</th>
<th>Ventilation</th>
<th>Building use</th>
<th>Notes</th>
</tr>
</thead>
</table>
| SF Federal Building      | E+                        | Natural                  | • Office                          | • temporary measurements  
  • only thermal comfort                                              |
| Global Ecology Center    | DOE2                      | Natural and mechanical   | • Office  
  • Academic  
  • Labs               | • archiving very unreliable  
  • no comprehensive analysis possible                              |
| Y2E2                     | eQUEST                    | Natural and mechanical   | • Office  
  • Academic  
  • Labs               | • students identified “known” set of performance problems in class |
| SCC                      |                           | Mechanical               | • Jail                            | • due to several project delays comparisons just started            |
Mechanism to identify performance problems from differences

Data pair graph

- Difference?
  - Yes
  - Performance Problem?
    - Yes
      - Identified performance problem
    - No
      - No
      - No
      - OK

- No
  - Yes
  - Measurement assumptions
  - Simulation assumptions, approximations and simplifications
POD – measurement assumptions

Measurement assumptions:
Project-specific assumptions only (e.g., Reddy et al. 1999)

Measurement limitations:
Multiple inconsistent measurement data set guidelines (e.g., Gillespie et al. 2007)
- Assessment of the different guidelines is missing
POD - Existing measurement data sets

No validation of data sets (comparative to other sets or to actual case studies)

Ideal data set
O’Donnell 2009

Gillespie et al. 2007

Neumann & Jacob 2008

Barley et al. 2005
Validation of measurement data set guidelines with known Y2E2 problems

-O’Donnell covers all sensors needed to find all problem
-Gillespie et al. (most detail) cover - 35% with ALL sensors
- 55% with SOME sensors
Data acquisition systems
Example of use of measurement assumption

Difference between measured and simulated data

**Sensing assumption:** Temperature set point is for occupied hours only

No difference between measured and simulated data during occupied hours

⇒ no performance problem

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POD – simulation approximations

Simulation approximations: Project-specific assumptions only (e.g., Salzburg and Diamond 2001)

Simulation limitations:
Project-specific limitations (e.g., Morrissey 2006)
### Category and Assumption

<table>
<thead>
<tr>
<th>Category</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensing</td>
<td>15</td>
</tr>
<tr>
<td>Transmitting</td>
<td>4</td>
</tr>
<tr>
<td>Archiving</td>
<td>5</td>
</tr>
</tbody>
</table>

**List of 24 assumptions**

### Assumption and AAS

<table>
<thead>
<tr>
<th></th>
<th>Assumption</th>
<th>Approximation</th>
<th>Simplification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input data</td>
<td>4</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Model</td>
<td>9</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Usage</td>
<td>13</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

**List of 39 AAS**
Limitations of EnergyPlus - example

Return air flow is divided into two streams  
Return air flow cannot be divided

Actual HVAC system configuration cannot be modeled

→ need to use a simplified model representation with consequences for

• exhaust flow of heat exchanger (50% vs. 100%)
• conditions in atria (return air passes atria vs. does not pass)
Example of use of simulation approximation

**Model simplification:** Pressure drop is not part of the model

**Difference between measured and simulated data**

Simulation model cannot capture changes due the pressure based control

⇒ No performance problem

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Bottom-up simulation model adjustment

Existing calibration methods

Assumptions and approximations

Iteratively adjust model to reflect actual building conditions and identify problems

Compare building performance

Compare system/floor performance

Compare space/zone performance

Compare component performance

Compare set points

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Validation of EPCM with Y2E2

<table>
<thead>
<tr>
<th>Problem categories</th>
<th>Instances of identified problems</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Operator</td>
</tr>
<tr>
<td>Incorrect mapping of sensors</td>
<td>1</td>
</tr>
<tr>
<td>Scaling issues</td>
<td>None</td>
</tr>
<tr>
<td>Incorrect design assumptions</td>
<td>1</td>
</tr>
<tr>
<td>Incorrect control strategy</td>
<td>None</td>
</tr>
<tr>
<td>Sensor problems</td>
<td>None</td>
</tr>
<tr>
<td>Total</td>
<td>2</td>
</tr>
<tr>
<td>Time effort (estimated hours)</td>
<td>-</td>
</tr>
<tr>
<td>Time effort per problem</td>
<td>-</td>
</tr>
</tbody>
</table>

- Student achieved 90% consistency with EPCM results for a data subset (~25%)
- 27% of differences could be explained with measurement assumptions
- 38% of differences could be explained with simulation approximations

ECPM detects most performance problems - Time effort per problem is best
Contributions to knowledge

• Energy Performance Comparison Methodology based on whole building design simulation models and real life building performance measurements

• Concept of two interlinked building object hierarchies to represent relationships between different levels of detail of components

• List of measurement assumptions and a mechanism of their use to identify performance problems

• List of simulation assumptions, approximations and simplifications (AAS) and a mechanism of their use to identify performance problems
Practical significance

• Ability to evaluate building energy performance against building design
• Savings in operation costs through improved building performance
• Improvement of design predictions through feedback about design assumptions and simplifications
<table>
<thead>
<tr>
<th>Limitations</th>
<th>Future research</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commercial buildings</td>
<td>Residential and other buildings</td>
</tr>
<tr>
<td>Four case studies</td>
<td>More case studies</td>
</tr>
<tr>
<td>Measurement guideline validation is based on number of problems</td>
<td>Include severity of problems</td>
</tr>
<tr>
<td>Comprehensive lists based on literature and four case studies</td>
<td>Extend list as new systems, components and sensors are developed</td>
</tr>
</tbody>
</table>
| Partial automation of some tasks | Automate the EPCM including
• a graphical user interface
• an expert system based on assumptions |
| Case studies are missing some measurements | More case studies with more measurements (e.g., occupancy) |
| Support for performance assessor only | Support for building operator |
Questions?
References (1)


References (2)


References (3)


Backup slides
Energy performance of Y2E2

- Actual operation is close to design baseline model (minimum code requirement)
- Actual operation is far away from original design goal
- Calibrated models show about 50% improvement compared to calibrated baseline
An example of a performance problem at Y2E2: Incorrect control strategy for natural ventilation

Regular open/close pattern versus open/close pattern only for **specific conditions** (as defined by control strategy)

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Example of sensor additions

Identified *(30)* new sensors to be installed *(420 existing sensors)*

Example: Condenser Loop
Water flow rate and return water temperature are missing to calculate energy supplied by condenser loop (Energy = flowrate * const * temperature difference)

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Creating an EnergyPlus model

Architectural drawings → 3D CAD → IFC Geometry → IDF Generator → EnergyPlus

IDF
Set points and schedules
HVAC systems and controls
Internal loads and schedules

Field surveys
Manufacturer product data
Mechanical drawings

Legend
Data source
Software tool
File

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Updating an EnergyPlus model

Legend

Data source
Software tool
File

Observed data (Y2E2)

- Space Air Temp Setpoint
- Estimated plug loads and lighting
- Outside Air Temp
- Wind direction and speed
- Wetbulb Temp or Relative Humidity
- Direct and diffuse solar radiation

IDF

- Geometry
- Internal loads and schedules
- HVAC systems and controls
- Set points and schedules
- Weather file

EnergyPlus

Simulated data

Compare

Measured data

- Zone Air Temp
- Ceiling Temp
- Velocity
Weather file converter

Legend
- Database
- Software
- Conversion
- Variable
- File
- Data transfer optional

HVAC database

WeatherToEPW Converter
- IP → SI
- IP → SI
- Pressure difference → Pressure conversion
- Total horizontal radiation
- Diffuse horizontal radiation
- IP → SI
- IP → SI
- IP → SI
- IP → SI

Dry bulb temperature
Wet bulb temperature or Relative humidity
Wind direction
Wind speed
Direct normal radiation
Solar model conversion
Internal loads (lighting, plug loads, occupancy)
Space air temperature set points
Water supply temperature set points
Air supply temperature set points

Weather file *epw
Schedule file *idf

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Reliability measure

Percent of data points

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Macro spreadsheet
Screenshots of macro spreadsheet

Generates EnergyPlus input files (IDF) based on values defined in a spreadsheet
Set up data collection (1)

1. Building point list
2. Generic ideal point list (O’Donnell 2009)
3. Mechanical drawings

- Compile building specific point list
- Compare ideal to actual point list
- Identify missing points
- Identify points to be added based on project constraints
- Add additional points

Legend:
- Data source
- Task
- File

Project-specific point list
Set up data collection (2)

1. Set up data collection system that collects every point on a minute interval automatically.
2. Collect initial data (about a month).
3. Validate that data values are in range based on point type (Friedman and Piette 2001).
5. Validate daily patterns (Friedmann and Piette 2001).
6. Verify continuous data collection (e.g., Seidl 2006).
7. Recalibrate sensors that show problems.

Legend:
- Data source
- Task
- File
Establish Component Hierarchy

- Architectural drawings
  - Create Spatial hierarchy
    - Building, Floor, Space
  - Establish additional relationships
    - Assign generic assumptions to object instances

- Mechanical drawings
  - Create HVAC hierarchy
    - Zone, Component, System, Building
  - Define specific assumptions to object instances

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Relate data pairs via component hierarchy

1. Component hierarchy with assumptions
2. Simulated data
3. Relate data pairs based on hierarchy
4. Measured data
5. Generate comparison graph for each data pair (monthly and weekly)
6. Add assumptions to graphs
7. Graphs of data pairs

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