Performance-Risk Methodology for the Design of High-Performance Affordable Homes

Building Enclosure Science & Technology Conference
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Rodrigo Mora, British Columbia Institute of Technology (BCIT)
Fitsum Tariku, British Columbia Institute of Technology (BCIT)
Girma Bitsuamlak, Florida International University (FIU)
Building Performance Assessment
Motivation: Easy to miss the forest...

A Tree Analogy

People
- Age/Gender/Preferences
- Behavior/Habits
- Adaptation

Lighting
- Daylight distribution
- Daylight autonomy
- Glare index
- Contrast
- Uniformity

MEP/services
- Load
- Capacity
- Efficiency
- Automation

Indoor Environmental Quality
- Occupants’ activities
- Indoor contaminants
- Humidity
- Ventilation

Thermal Environment
- Draughts
- Asymmetric radiation
- Temperature swings
- Space overheating

Architectural form
- Window-wall-ratio (WWR)
- Orientation
- Exposure/protection
- Interior materials/finishes

Service life
- Durability
- Damage models
- Mold, Fungi
- Maintenance

Economy

Natural environment
- Energy consumption
- Peak demand
- Service life performance
- Life-cycle assessment

Adapted from Mora et al., 2011
Building Performance Assessment

Premises

- Building Science experts possess intuitive knowledge
- Such knowledge is difficult to communicate to non-experts: students, clients, other practitioners
- Building Science Knowledge is scattered
- Good sources of knowledge available over the Internet
- However, such sources do not facilitate learning & are often:
  - Ad-hoc structured based on source priorities
  - Static: open documents & read...
Overall Project Goals

• Formulate building science knowledge-framework to improve **Education, Communication & Dissemination**
• A core with **Product ↔ Process** knowledge models
• Generic → Specific: agreed knowledge to facilitate extensibility as new knowledge becomes available
• Concepts/Principles → Details: help users move freely between levels of abstraction in order not to miss the forest through the trees
• Intuitive: make intuitive knowledge explicit
• Intelligent & dynamic: uncover knowledge & establish knowledge connections based on user input for improved learning guidance
Sample Generic Knowledge

- Climate
- Building
- Performance
- Structure
- Occupancy
- Risks
- Process

[1] degrees & types of performance “coupling”

The leaves at the end of the Hierarchy branches are external documents/references
Knowledge of Specific Cases

Climate
- Cold climate
- Night cooling

Building
- Residential
  - Attic
  - Ventilated

Performance
- HAM

Structure
- Underside of roof sheathing

Occupancy

Risks
- Moisture accumulation

Process
- Design
- Construction
- Commission
- Retrofit & Renovation

Graphically browse the Knowledge-Base…
Knowledge of Specific Cases

- Climate
  - Cold climate

- Structure
  - Wall & floor construction

- Building
  - Residential
    - Basement
    - Wall
    - Floor

- Occupancy

- Performance
  - Energy
  - Comfort
  - HAM

- Risks
  - Moisture accumulation

- Process
  - Energy retrofit
Knowledge of Specific Cases

Climate
- Dynamic
  Wind loading

Building
- Envelope
  - Window
  - Wall

Structure
- Interface
  - Materials
  - Details

Occupancy

Process
- Design

Performance
- Structural

Risks
- Integrity
- Seal pull apart
Elaborate Generic Knowledge

Climate → Microclimate

Environmental parameters
- Outdoor temperature
- Outdoor humidity
- Wind speed and direction
- Solar radiation
- Rainfall
- Topography, vegetation
- Nearby buildings

Structural parameters
- Geometry, size, orientation
- Layers, interfaces, details
- Materials, connections
- Construction

Occupancy parameters
- Number of occupants
- Type of indoor activities
- Age group
- Demography

Serviceability parameters
- Indoor air temperature
- Indoor humidity
- Indoor air quality
- Thermal radiation
- Indoor air circulation
- Energy efficiency
- Lighting & acoustic quality
- Durability

Performance/Physical Models

Performance Functions
Performance Indicators/Metrics
- Relating physical & functional aspects of a system being analyzed

Serviceability limits
- Structural integrity
- Health & comfort
- Productivity, etc...

Adapted from
Pietrzyk & Hagentoft, 2008
The concepts of **redundancy & load sharing** are fundamental but rarely explicitly/formally explained in building science education.
Case Study
Habitat for Humanity of Greater Miami

• Climate Zone & Reference Years for Simulation:
  • Energy: TMY3 climate zone 1 (hot & humid)
  • Moisture: Moisture Design Reference Year (MDRY)
Case Study

Design Priority: Hurricane Safety
Case Study
Habitat for Humanity of Greater Miami

BUILDING ENERGY RATING GUIDE

$732

Reference
$995

0 MBtu

30.3 MBtu

41 MBtu

Proposed Home

Cost Basis:

EnergyGauge Default

Electric Rate: $0.083

EnergyGauge Default

Gas Rate: $1.729 /Therm

Statewide Price

Oil: $1.50/gal

LP Gas: $1.75/gal

This Home may Qualify for EPA's Energy Star Label

This Home Qualifies for an Energy Efficient Mortgage (EEM)

HESS Index: 76

Certified Florida Green Home

Certificate of Validation

This Home was built by
Habitat for Humanity
at 5135 NW 88th street, Miami, FL

satisfies the ENERGY STAR® for Homes criteria of the
U.S. Environmental Protection Agency.

HESS Index calculated in accordance with 2006 RESNET standard, Section 303.2 (Reference Home = 100. Zero energy use = 0).

21/2/2010 16:02:35
EnergyGauge® / USRRPE v2.8
Page 1/1
Case Study
Habitat for Humanity of Greater Miami

- Climate
  - Hot-humid

- Building
  - Residential
  - Affordable

- Performance
  - Energy
  - Cost

- Structure
  - CMU construction

- Occupancy
  - High occupancy

- Risks
  - Life-cycle costs
  - Durability
  - IAQ
  - Comfort
  - Safety

- Process
  - Design
Performance-Risk Methodology
Design Process Model

1. State Vision Goals & Objectives
2. Select Targets & Identify Viable Alternatives
3. Optimize Design Objectives
4. Select Strategies Identify Risks
5. Evaluate Risks

End

Knowledge Base
Performance models
Risk Evaluation
Risk Process Model

- Initiating Events
- Scenario Development
- System Analysis
- Risk Analysis
- Consequences

Knowledge Base
Risk models

Serviceability parameter: Moisture content
Serviceability limit = MC_{crit}
Probability density

h(MC)
Probability of un-serviceability
Probability of serviceability

Step 1 - Project Vision & Objectives

Primary Objectives
- Energy
- Economy Affordability

Constraining Objectives
- Architecture
- Environment
- IEQ
- Construction

Adapted from Deru et al. 2005

Note: IEQ = Indoor Environmental Quality
Step 1 - Vision, Objectives
Transformed into Performance Targets

Vision

“To build energy efficient affordable homes in the Greater Miami area that meet the Energy Star incentive requirements, while maintaining the indoor environmental health, comfort, & construction safety & durability standards.”

Objectives & Performance Targets

- **Energy**
  - **Goal:** to minimize home energy consumption.
  - **Performance objective:** to reduce annual energy consumption by as much as 50% by 2015 based on a typical HFH home built in 2010, with enclosure performance ready for net-zero energy by 2020.

- **Affordability**
  - **Goal:** to improve or at least maintain affordability
  - **Performance objective:** to improve home affordability or maintain cost neutrality based on a typical home built in 2010, using an annualized mortgage plus utility costs method over a period of 30 years.
### Step 2 - Alternatives

<table>
<thead>
<tr>
<th>Systems</th>
<th>Reference Home</th>
<th>Building America</th>
<th>Various Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walls &amp; Floor</td>
<td>CMU/reflective foil/gap</td>
<td>wood-frame</td>
<td>wood-frame, ICF, SIP</td>
</tr>
<tr>
<td>* Effective R-value (IP units)</td>
<td>R-6 to R-7</td>
<td>R-15</td>
<td>R-19 to R-22</td>
</tr>
<tr>
<td>* Solar absorptance</td>
<td>0.75 exterior</td>
<td>NA</td>
<td>0.5 int./ext.</td>
</tr>
<tr>
<td>* Floor slab</td>
<td>4&quot; slab on grade/6 mil poly</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Windows</td>
<td>Single/impact</td>
<td>double/Low-e</td>
<td></td>
</tr>
<tr>
<td>* Window to floor area</td>
<td>16%</td>
<td>NA</td>
<td>12%</td>
</tr>
<tr>
<td>* U-factor (IP units)</td>
<td>1.09</td>
<td>0.32</td>
<td>0.6</td>
</tr>
<tr>
<td>* SHGC</td>
<td>0.5</td>
<td>0.27</td>
<td>0.27, 0.3</td>
</tr>
<tr>
<td>Ceilings</td>
<td>Fiberglass batt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>* R-value</td>
<td>R-30</td>
<td>R-30</td>
<td>R-38</td>
</tr>
<tr>
<td>Roof/Attic</td>
<td>Shingles light</td>
<td></td>
<td></td>
</tr>
<tr>
<td>* Solar absorptance</td>
<td>0.8</td>
<td></td>
<td>0.3, 0.4</td>
</tr>
<tr>
<td>* Roof deck insulation</td>
<td>NA</td>
<td></td>
<td>Radiant</td>
</tr>
<tr>
<td>* Attic type</td>
<td>Vented</td>
<td>Conditioned</td>
<td>Conditioned</td>
</tr>
<tr>
<td>Space conditioning</td>
<td>Central AC/Heat split</td>
<td>Conditioned</td>
<td></td>
</tr>
<tr>
<td>* SEER / HSPF</td>
<td>14.5/Heat coils @ AHU</td>
<td>15/8.8</td>
<td>17/</td>
</tr>
<tr>
<td>* Capacity/SHR/Airflow</td>
<td>21 Kbtu-h/0.75/630 CFM</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>* Ducts location</td>
<td>Attic</td>
<td>AC conditioned</td>
<td>AC conditioned</td>
</tr>
<tr>
<td>* Ducts leak Qn/CFM</td>
<td>0.05/50 (tested)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>* Ducts insulation</td>
<td>R-6</td>
<td>R-4 to R-8 if in attic</td>
<td>R-6 if in attic</td>
</tr>
<tr>
<td>Air movement</td>
<td>5 (tested)</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>* Mechanical ventilation</td>
<td>Kitchen &amp; bath exhaust fans</td>
<td>Controlled central supply</td>
<td>Controlled central supply</td>
</tr>
<tr>
<td>* Ceiling fans cover - eff.</td>
<td>75% - 130 CFM/watt</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Supplemental</td>
<td>No</td>
<td>stand-alone/humidistat</td>
<td></td>
</tr>
<tr>
<td>dehumidification</td>
<td>Energy Star 1.2 - 1.5 l/kwh</td>
<td>Stand-alone</td>
<td></td>
</tr>
<tr>
<td>Water heating</td>
<td>Heat pump/52 Gal tank</td>
<td>Solar/tank 64 sf cl-loop</td>
<td>Solar</td>
</tr>
<tr>
<td>Lighting</td>
<td>10% CFL</td>
<td>100% CFL</td>
<td>-</td>
</tr>
</tbody>
</table>
Step 3 - Optimization

- Boundary Conditions: TMY3 / Indoor Occupancy Schedules

Region 2: Cost neutral strategies with PV

(PV in hurricane region!)

Region 1: Maximum source energy & cost savings without PV
# Step 4 - Parametric Analysis → Strategies

## Region 1

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>ref</td>
<td>Reference</td>
<td>Attic</td>
<td>Shingles light</td>
<td>HPWH</td>
<td>R-6</td>
<td>Single tinted</td>
<td>18%</td>
<td>SEER15</td>
<td>Standard</td>
<td>Kitchen/bath Test 5 ACH50</td>
</tr>
<tr>
<td>p1</td>
<td>Ducts in AC</td>
<td>Inside</td>
<td>Shingles light</td>
<td>HPWH</td>
<td>R-6</td>
<td>Single tinted</td>
<td>18%</td>
<td>SEER15</td>
<td>Standard</td>
<td>Kitchen/bath 5ACH@50Pa</td>
</tr>
<tr>
<td>p2</td>
<td>White tile</td>
<td>Inside</td>
<td>White metal</td>
<td>HPWH</td>
<td>R-6</td>
<td>Single tinted</td>
<td>18%</td>
<td>SEER15</td>
<td>Standard</td>
<td>Kitchen/bath 5ACH@50Pa</td>
</tr>
<tr>
<td>p3</td>
<td>Solar HW</td>
<td>Inside</td>
<td>Shingles light</td>
<td>Solar</td>
<td>R-6</td>
<td>Single tinted</td>
<td>18%</td>
<td>SEER15</td>
<td>Standard</td>
<td>Kitchen/bath 5ACH@50Pa</td>
</tr>
<tr>
<td>p4</td>
<td>Wall R-14</td>
<td>Inside</td>
<td>Shingles light</td>
<td>HPWH</td>
<td>R-14</td>
<td>Single tinted</td>
<td>18%</td>
<td>SEER15</td>
<td>Standard</td>
<td>Kitchen/bath 5ACH@50Pa</td>
</tr>
<tr>
<td>p5</td>
<td>Window</td>
<td>Inside</td>
<td>Shingles light</td>
<td>HPWH</td>
<td>R-6</td>
<td>High perform</td>
<td>18%</td>
<td>SEER15</td>
<td>Standard</td>
<td>Kitchen/bath 5ACH@50Pa</td>
</tr>
<tr>
<td>p6</td>
<td>Window+</td>
<td>Inside</td>
<td>Shingles light</td>
<td>HPWH</td>
<td>R-6</td>
<td>High perform</td>
<td>12%</td>
<td>SEER15</td>
<td>Standard</td>
<td>Kitchen/bath 5ACH@50Pa</td>
</tr>
<tr>
<td>p7</td>
<td>AC efficiency</td>
<td>Inside</td>
<td>Shingles light</td>
<td>HPWH</td>
<td>R-6</td>
<td>Single tinted</td>
<td>18%</td>
<td>SEER17</td>
<td>Standard</td>
<td>Kitchen/bath 5ACH@50Pa</td>
</tr>
<tr>
<td>p8</td>
<td>Ceiling fans</td>
<td>Inside</td>
<td>Shingles light</td>
<td>HPWH</td>
<td>R-6</td>
<td>Single tinted</td>
<td>18%</td>
<td>SEER15</td>
<td>Standard</td>
<td>Kitchen/bath 5ACH@50Pa</td>
</tr>
<tr>
<td>s1</td>
<td>CMU+</td>
<td>Inside</td>
<td>Shingles white</td>
<td>HPHW</td>
<td>R-14</td>
<td>High perform</td>
<td>12%</td>
<td>SEER17</td>
<td>Occupancy +4°F setp</td>
<td>Kitchen/bath 3ACH@50Pa</td>
</tr>
<tr>
<td>s2</td>
<td>CMU++</td>
<td>Inside</td>
<td>Shingles white</td>
<td>HPHW</td>
<td>R-14</td>
<td>High perform</td>
<td>12%</td>
<td>SEER17</td>
<td>Occupancy +4°F setp</td>
<td>Supply ASHRAE 62.2</td>
</tr>
<tr>
<td>s3</td>
<td>ICF++</td>
<td>Inside</td>
<td>Shingles white</td>
<td>HPWH</td>
<td>R-20</td>
<td>High perform</td>
<td>12%</td>
<td>SEER17</td>
<td>Occupancy +4°F setp</td>
<td>Supply ASHRAE 62.2</td>
</tr>
</tbody>
</table>
Step 4 - Strategy Selection
Region 1: uncertainties

Solar HW
$ government incentives??
$ maintenance??
Step 4 – Strategy Selection
Wall Insulation Improvements

- Stucco
- 8” concrete block wall (grouted cells @ 48” c/c)
- 3/4” wood furred air space
- Reflective foil insulation (hi-perm: 8.67 perms)
- Gypsum board / latex paint

- Stucco
- 8” concrete block wall (grouted cells @ 48” c/c)
- 2” vapour semi-permeable rigid insulation > 1 perm
- 3/4” wood furring
- Gypsum board / semi-permeable interior finish
Step 4 - Wall Insulation Improvements

Diminishing Returns
### Step 5 - Risk Evaluation

**Initiating Events \(\rightarrow\) Scenario Development**

<table>
<thead>
<tr>
<th>Initiating events</th>
<th>(1) High-performance envelope</th>
<th>(2) Occupant density / behaviours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduced uncontrolled air flows (air-tightness)</td>
<td>Rigid insulation at wall interior</td>
<td>Reduced sensible heat gain through the envelope</td>
</tr>
<tr>
<td>Under-ventilation for actual occupancy</td>
<td>Reduced wall drying potential to the interior</td>
<td>High latent load indoors (lower SHR)</td>
</tr>
<tr>
<td>Poor IAQ</td>
<td>Solar driven inwards moisture transport</td>
<td>High indoor RH</td>
</tr>
<tr>
<td>Moisture accumulation</td>
<td>Condensation</td>
<td>High indoor RH</td>
</tr>
</tbody>
</table>

**Consequences**

- Health effects
- Health effects
- Reduced durability
- More energy for cooling
- Health effects
- Reduced durability
Step 5 – Risk Evaluation: System Analysis

- Boundary Conditions: MDRY / Indoor Moisture Generation Schedules
Step 5 – Risk Evaluation: System Analysis

Indoor Temperature Profile

![Graph showing indoor temperature profile over time with reference and setpoints marked.](image-url)
Step 5 – Risk Evaluation: System Analysis
Indoor Relative Humidity Profile
### Step 5 - Risk Evaluation
Performance criteria & metrics

<table>
<thead>
<tr>
<th>Performance Aspect</th>
<th>Performance Criteria</th>
<th>Performance Serviceability Limits</th>
</tr>
</thead>
</table>
| Durability (moisture related)    | • Limit excessive moisture accumulation \(f(\text{exposure time, severity, & materials})\)  
• Damage functions                                                                                       | ANSI/ASHRAE Standard 160-2009                   |
| Indoor Air Quality (IAQ)         | • Substantial majority of occupants do not express dissatisfaction with respect to odor & sensory irritation  
• No known contaminants at harmful concentrations  
• Ventilation requirements: cfm, ACH                                                                 | ASHRAE Standard 62.2-2010                       |
| Thermal Comfort                  | • Satisfactory thermal indoor conditions for at least 80% of the occupants:  
• Uniform conditions: minimize thermal asymmetries, drafts, vertical air temperature differences, drifts & ramps | ANSI/ASHRAE Standard 55-2010                   |

• 30-day running average surface RH < 80% when the 30-day running average surface temperature is between 5°C (41°F) and 40°C (104°F)
• 7-day running average surface RH < 98% when the 7-day running average surface temperature is between 5°C (41°F) and 40°C (104°F)
• 24-h running average surface RH < 100% when the 24-h running average surface temperature is between 5°C (41°F) and 40°C (104°F)
Step 5 – Risk Evaluation
Durability Risk Analysis

Relative Humidity at the back of the Gypsum board
Step 5 – Risk Evaluation

IAQ Performance

Performance Criteria: ASHRAE Standard 62.2-2010

<table>
<thead>
<tr>
<th>Case</th>
<th>cfm</th>
<th>ACH natural</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infiltration-based ventilation (current)</td>
<td>18</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>(Sherman &amp; Grimsrud)</td>
<td></td>
</tr>
<tr>
<td>ASHRAE 62.2-2010</td>
<td>45</td>
<td>0.31</td>
</tr>
</tbody>
</table>

- It is clear that infiltration-based ventilation is not sufficient
- Plus: higher occupation density expected in affordable homes
- Safety concerns window opening unfeasible, particularly for night cooling
- Need controlled ventilation/dehumidification
Step 5 - Risk Evaluation
Thermal Comfort Performance

Performance Criteria: ASHRAE Standard 55-2010

<table>
<thead>
<tr>
<th>Season</th>
<th>Winter</th>
<th>Summer</th>
<th>Winter</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>70</td>
<td>70</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>80%</td>
<td>40%</td>
<td>95%</td>
<td>85%</td>
</tr>
<tr>
<td>Clothing</td>
<td>1 clo</td>
<td>0.5 clo</td>
<td>1 clo</td>
<td>0.5 clo</td>
</tr>
<tr>
<td>PMV</td>
<td>-0.42</td>
<td>-2.43</td>
<td>0.79</td>
<td>-0.5</td>
</tr>
<tr>
<td>PPD</td>
<td>8.76</td>
<td>91.87</td>
<td>18.31</td>
<td>10.24</td>
</tr>
<tr>
<td>Thermal sensation</td>
<td>Neutral</td>
<td>Cold</td>
<td>Slightly warm</td>
<td>Neutral</td>
</tr>
</tbody>
</table>

- As long as there is AC, thermal comfort is not an issue
- Occupants change set-point temperature to remain comfortable, thus overriding the benefits of the energy analysis
- Not explored: local solar heat gain & use of ceiling fans
Case Study Conclusions

- Controlled supply ventilation & dehumidification required
- Improve analysis to consider:
  - localized solar heat gains: orientation, shading, comfort
  - use of ceiling fans: manual/sensor-operated (elevated set-point temperature needs dehumidification)
- Survey to homeowners on occupancy, schedules, habits, perceptions of comfort & indoor environmental quality
- Monitor the indoor environment: RHT
- Consider cost-effective & energy-efficient options for dehumidification
Overall Conclusions & Future Work

- There is a need to better communicate building science knowledge to non-experts
- Formalize process & product knowledge models
- Incorporate risk-evaluation models
- Need for Building Science **Ontologies** “meta-knowledge”
- Envisioned Outcome:
  - Building Enclosure Science & Technology Knowledge-Base
  - Dynamic & collaborative like “Wikipedia”
  - But more focused & structured: from generic knowledge → fundamental principles → case study applications
Thank you!