BUILDING SCIENCE LIVE

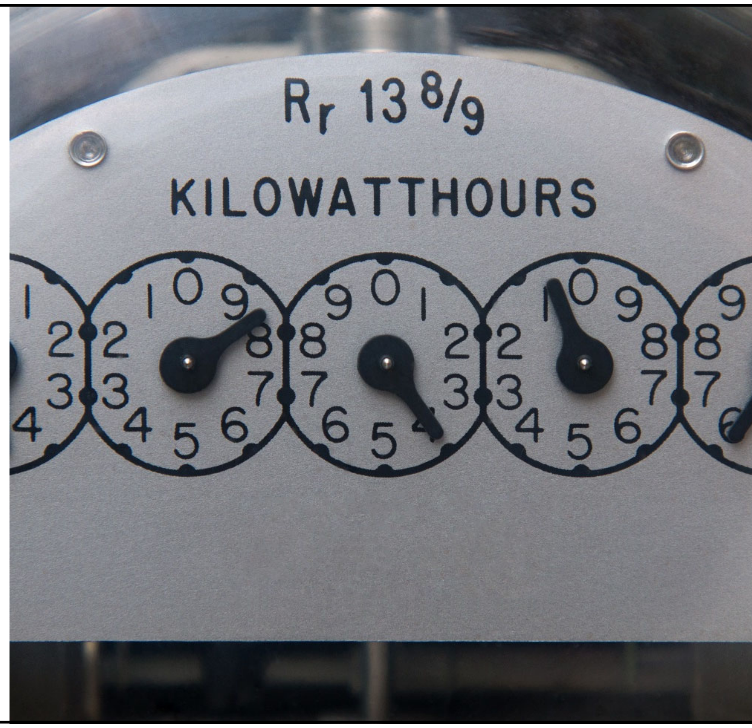
AUG 5, 2020

Mind the Gap:

Achieving Measured Energy Performance

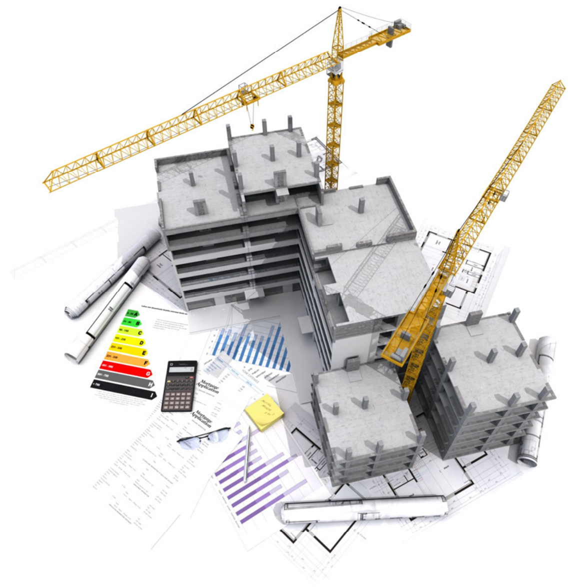
Brittany Coughlin, M.A.Sc., P.Eng.
Steve Kemp, M.A.Sc., P.Eng., LEED® Fellow

RDH

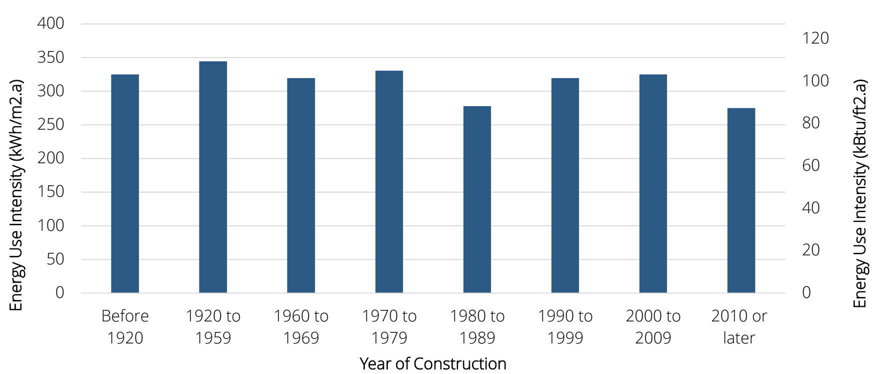


Agenda

- The Concern
- Models in General
  - Empirical
  - Theoretical first principles
- How Well Do We Know the Inputs?
  - Known knowns
  - Known unknowns
  - Unknown unknowns
- Weaknesses in Building Systems
  - Controls and sensors
  - Operators
- Summary of Where We Are
  - What matters, what doesn't
- Closing the Gap
  - Final thoughts

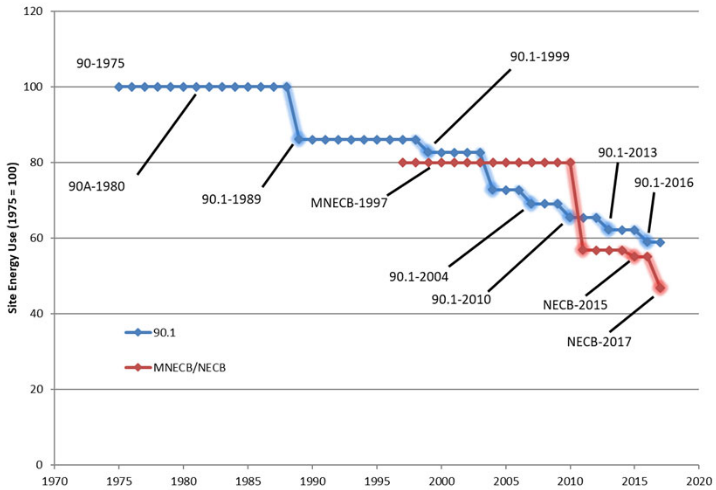


Building Energy Use Trends?



Source: NRCan, Survey of Commercial & Institutional Energy Use (SCIEU) – Buildings (2014)

Energy Codes Are Changing Rapidly



National Research Council's Goal for Canada's National Energy Code for Buildings

Net Zero Ready by 2030

RDH

Performance Gap - Modelled vs. Measured

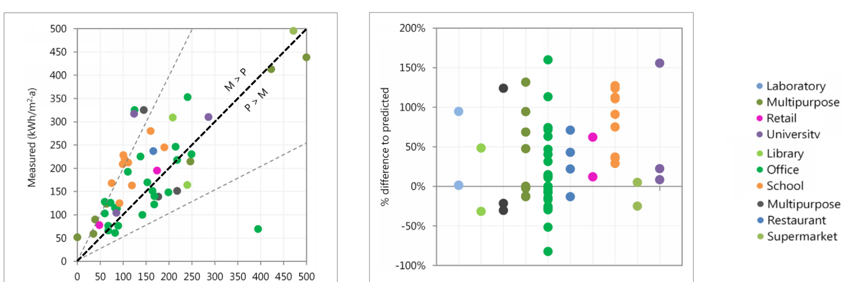


FIGURE 2 | Predicted and measured energy use intensities of reviewed case studies for different building functions.

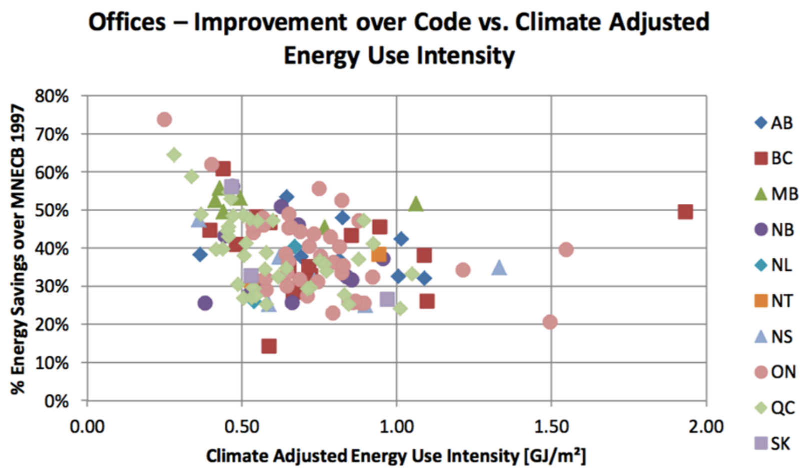
FIGURE 3 | Difference in percentages of measured to predicted energy use of reviewed case studies for different building functions.

---- Line representing Measured (M) = Predicted data (P)

Source: A review of the Energy Performance Gap and its Underlying Causes in Non-Domestic Buildings, Van Dronkelaar et al. 2016

RDH

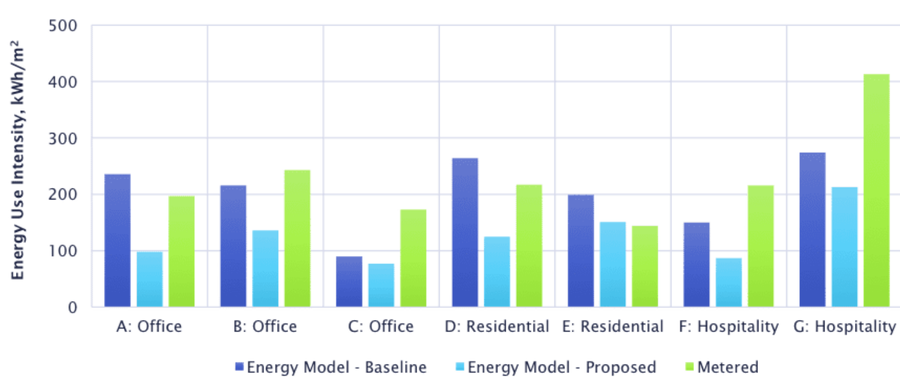
Energy Model Correlation between Relative and Absolute – NRCan Analysis



RDH

M&V of 7 LEED Developments

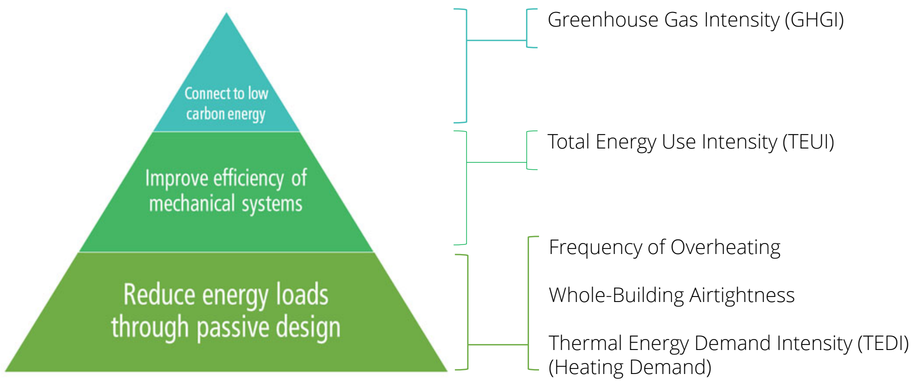
→ Significantly higher EUIs



Absolute Performance Targets

→ Measure what you want to manage

→ Passive House, BC Step Code, Toronto Green Standard



Why Model

Models are always wrong – they are necessarily approximations of reality, and inputs into the model are always the weakest link.

However… some models are useful.

"If we had observations of the future, we obviously would trust them more than models, but unfortunately…

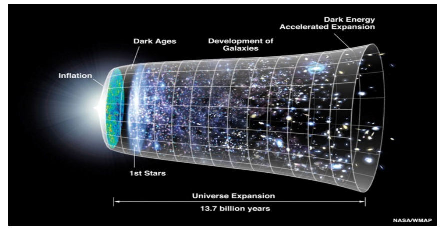
… observations of the future are not available at this time."

Tom Knutson and Robert Tuleya

(climate modelers)

Models in General

All of modern science and engineering is built on mathematical models



RDH

First Principle Models

- Newton's Law of Gravity
  - Can get you to the moon, but cannot explain the precession of Mercury's orbit
- Einstein's General Relativity
  - An improved model of gravity
  - Model predicts singularities (black holes and beginning of the universe), needs to be reconciled with a "quantum theory of gravity"—100 years later we still haven't discovered one
- Laws of Thermodynamics
  - Underpins much of building energy modeling
  - Perfect model, no known exceptions!

$$Force(M1, M2, r) = \frac{M1 \times M2}{r^2} G$$

$$R_{\mu v} = \frac{\partial \Gamma_{\mu\lambda}{}^{\lambda}}{\partial \chi^{v}} - \frac{\partial \Gamma_{\mu v}{}^{\lambda}}{\partial \chi^{\lambda}} + \Gamma_{\mu\lambda}{}^{\beta} \Gamma_{\mu\beta}{}^{\lambda} \text{-} \Gamma_{\mu v}{}^{\beta} \Gamma_{\beta\lambda}{}^{\lambda} = 0$$

where $\Gamma_{\mu v}{}^{\lambda} = \frac{1}{2} g^{\lambda\beta} \left(\frac{dg_{\mu\beta}}{d\chi^{v}} + \frac{dg_{v\beta}}{d\chi^{\mu}} + \frac{dg_{\mu v}}{d\chi^{\beta}} \right)$

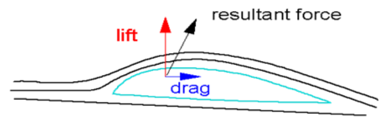
Energy and matter must be conserved

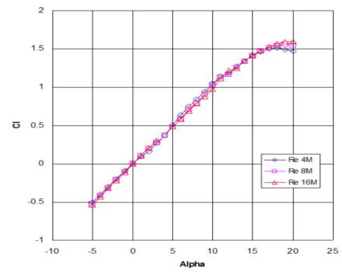
$$\sum E = 0$$

RDH

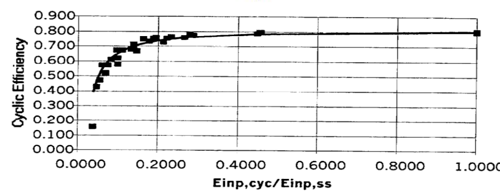
Empirical Models

- Measure and correlate outputs to inputs where inputs have a known causation
  - Lift on an airplane wing
  - Part-load efficiency of boilers, chillers, pumps and motors
- Every airplane wing design is unique and the risk is great (death, dismemberment) so we measure all of them
- Every boiler design is unique, low risk thus we can't afford to measure them all!





Lift Coefficient Curve for Wing



Generic Boiler Efficiency Curve

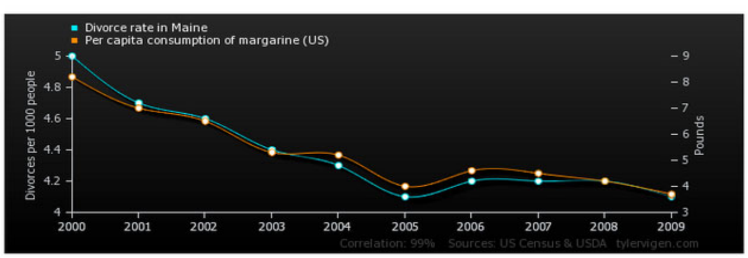
RDH

Empirical Models – Correlation Does Not Mean Causation

Divorce rate in Maine

correlates with

Per capita consumption of margarine (US)



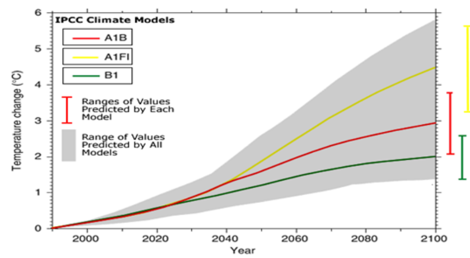
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Divorce rate in Maine *Divorces per 1000 people (US Census)*	5	4.7	4.6	4.4	4.3	4.1	4.2	4.2	4.2	4.1
Per capita consumption of margarine (US) *Pounds (USDA)*	8.2	7	6.5	5.3	5.2	4	4.6	4.5	4.2	3.7

Correlation: 0.992558

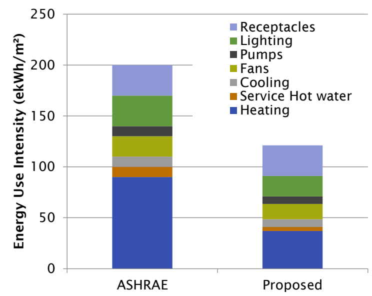
RDH

Complex Models

- Combine multiple models into a large interacting system
  - Climate change models
  - **Building energy models**
  - Thousands of inputs
  - Incomplete data
  - Many more assumptions made by user and the software



Climate Model Predicting Increased Global Temperatures



Building Energy Model Predicting:

- 35% energy cost savings (90.1-2007)
- 12 LEED points
- 135 ekWh/m²-a

RDH

Accuracy of Model Predictions

Depends on the accuracy of the underlying model

- Theoretical model
  - How well does it represent observation?
    - **General Relativity** supplanted **Law of Gravity** as a better representation of gravity
- Empirical model
  - Accuracy of measurements to develop model
  - Strength of correlation of inputs to outputs
- Complex models
  - All of the above

Depends on accuracy of the inputs (garbage in = garbage out)

- Mass of the earth
- Ambient temperature
- Conductivity of materials and assemblies
- Part load curves for boilers and chillers
- Control algorithms
- Etc.

RDH

Building Energy Models

- Inputs
  - Material conductivity, assembly construction, infiltration, equipment efficiency, pressure drops, airflow rates, temperature set-points, wall dimensions, window U-values, window dimensions, window SHGC, window visible transmittance, building orientation, control set-points, ventilation rates, equipment size, lighting, lighting controls, operating schedules, temperature set-backs…

    10,000 inputs is not an unreasonable estimate

- Inherent Assumptions
  - Building will be constructed as modelled
  - Workmanship and quality control
  - Building will be **operated** and **people will behave** as per the modeling assumptions
    - Schedules, receptacle loads, operable windows, temperature set-points, turning lights off at the end of the day

RDH

Reliability of Inputs

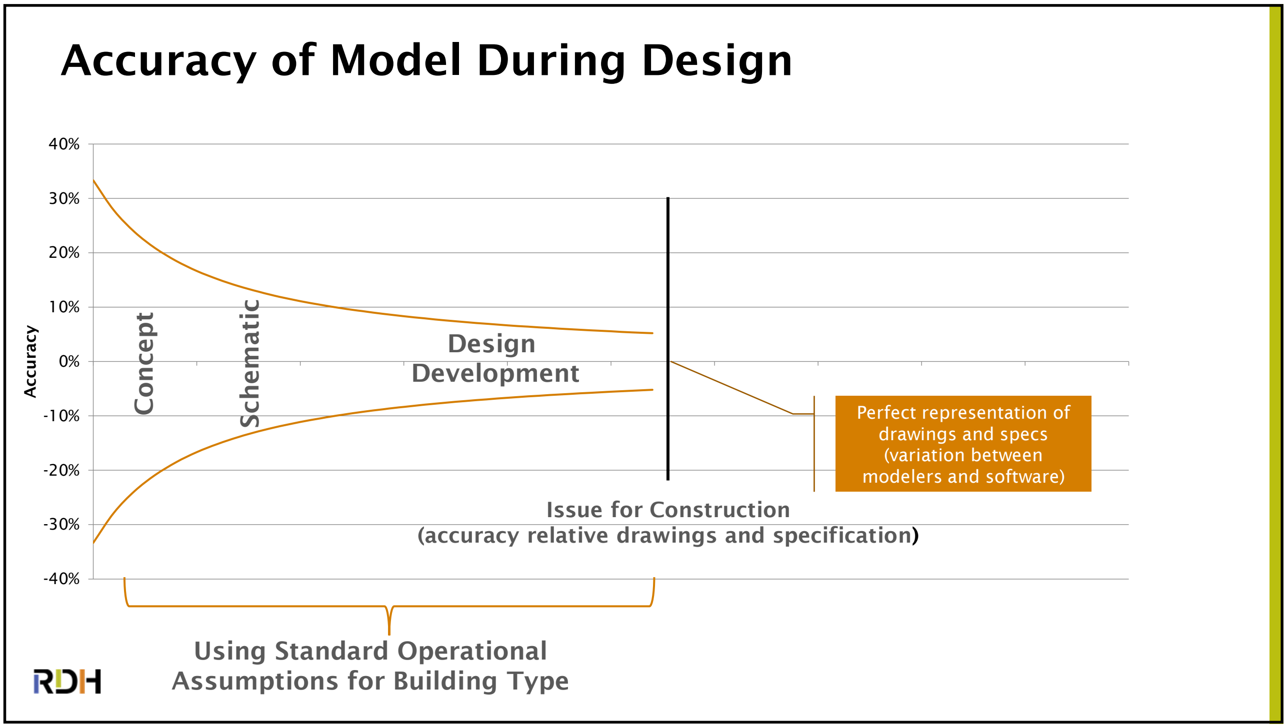
Examples

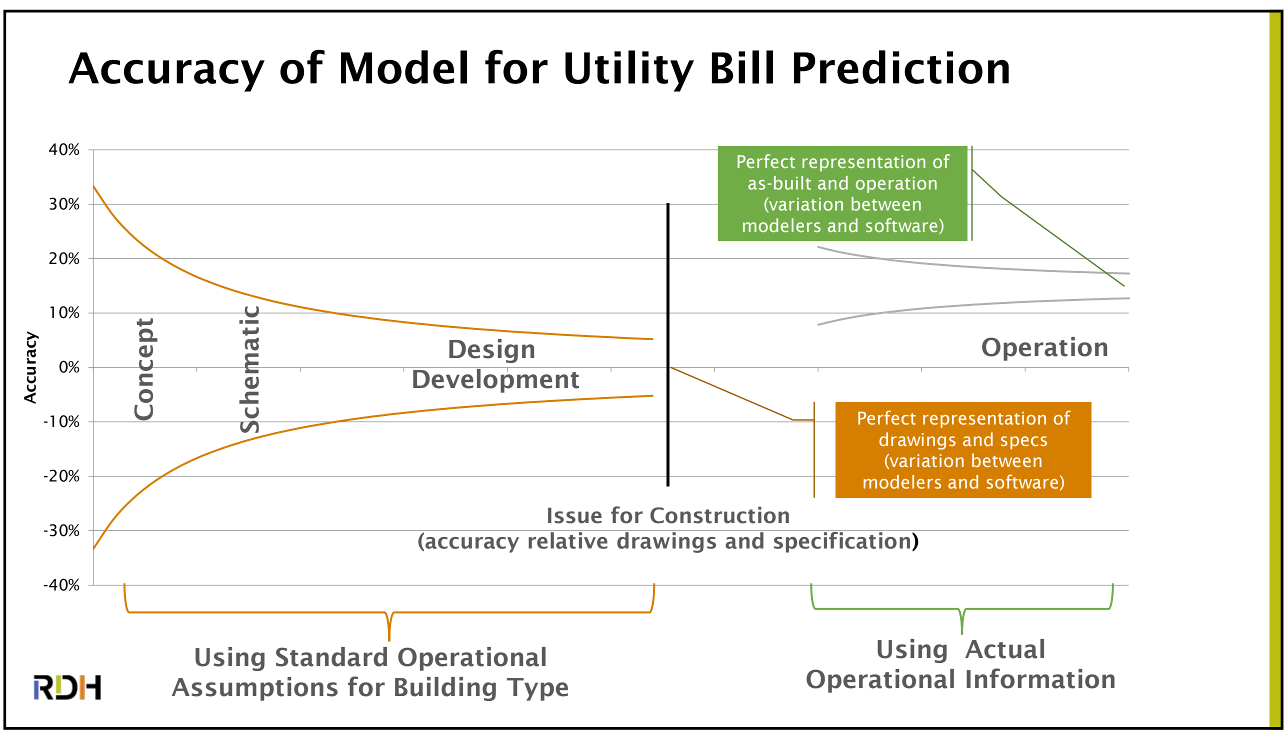
- R-value of an opaque wall
  - Conductivity of materials
    - Well known for most materials
    - Lots of scatter for other materials (e.g.: polyisocyanurate 5.5 to 7.5 R/inch)
  - Assembly conductivity
    - Thermal bridging, 2-D and 3-D effects
    - Contact resistance! (not well understood)
  - Minimum firing rate on plant equipment
    - EE4 default uses 10% minimum firing, actual is 5:1 (or 20%)
  - How well does the modeler interpret the information?
    - What are the big levers?

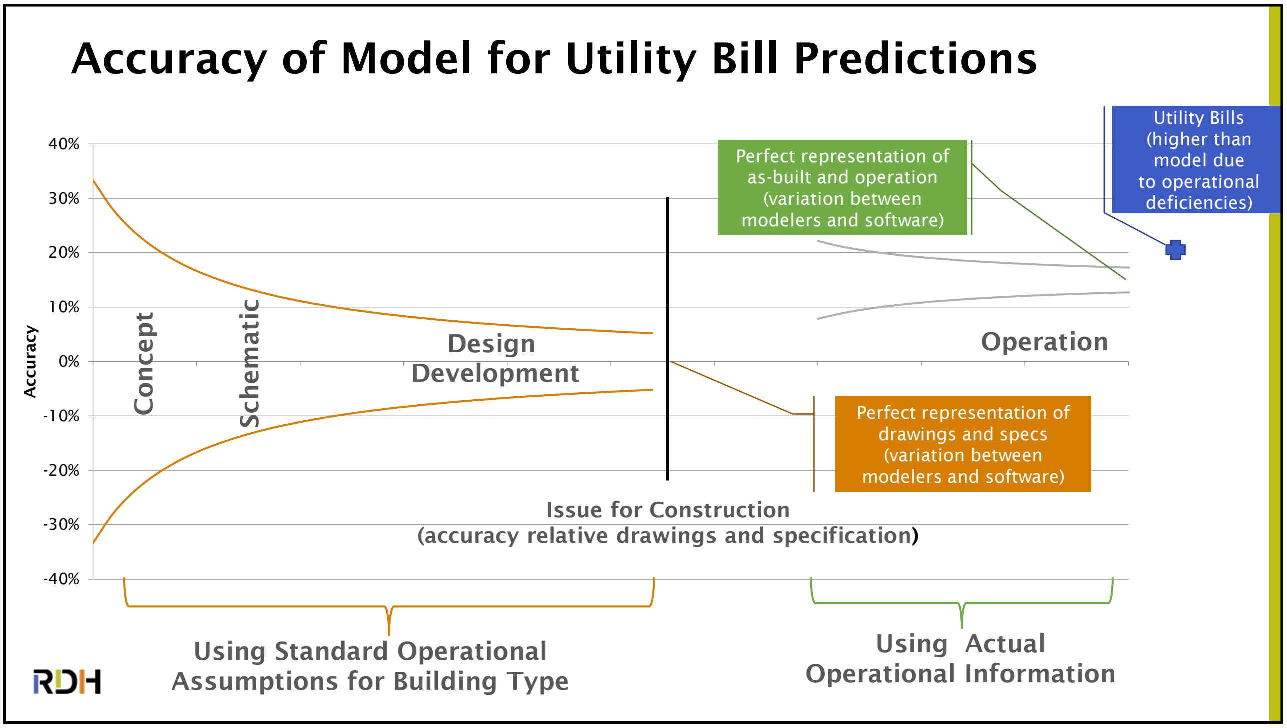
Typically not a large effect, we have good material property data

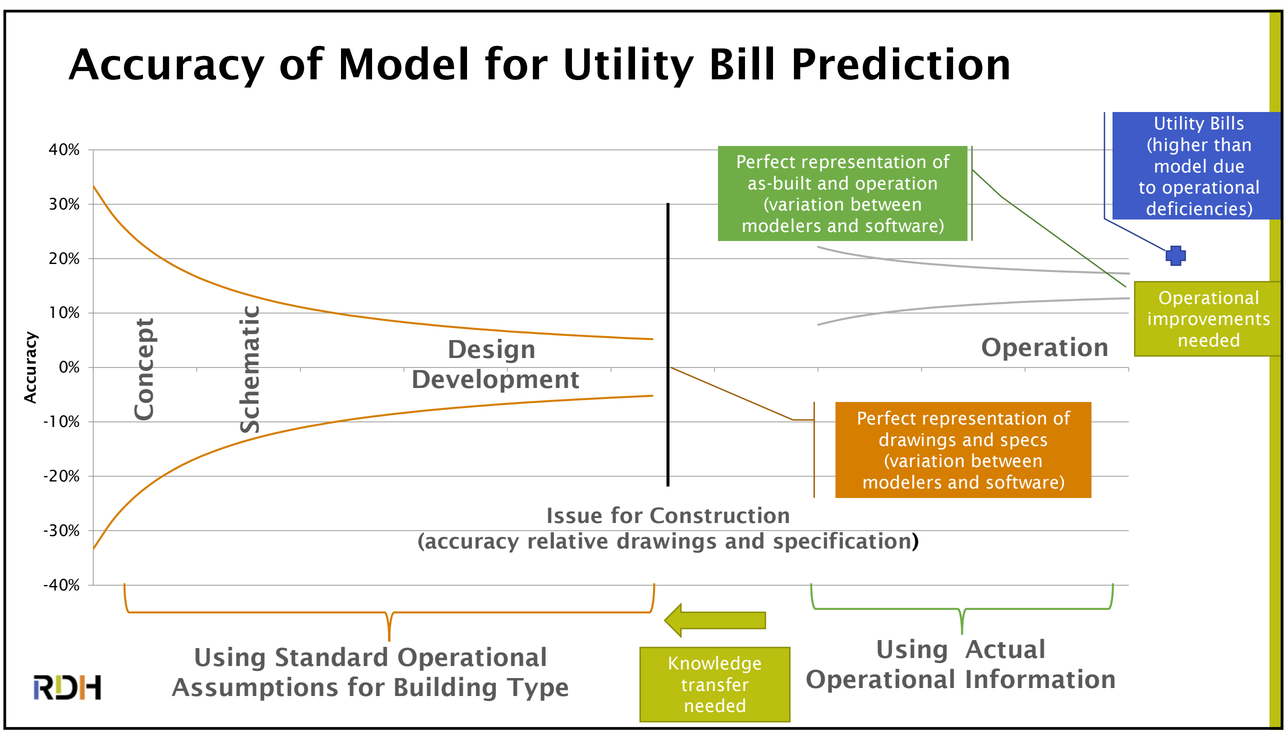
Critical effect in opaque walls

RDH


Accuracy of Model During Design
40%
30%
20%
10%
0%
-10%
-20%
-30%
-40%
Accuracy
Concept
Schematic
Design Development
Perfect representation of drawings and specs (variation between modelers and software)
Issue for Construction (accuracy relative drawings and specification)
Using Standard Operational Assumptions for Building Type


Accuracy of Model for Utility Bill Prediction
40%
30%
20%
10%
0%
-10%
-20%
-30%
-40%
Accuracy
Perfect representation of as-built and operation (variation between modelers and software)
Concept
Schematic
Design Development
Operation
Perfect representation of drawings and specs (variation between modelers and software)
Issue for Construction (accuracy relative drawings and specification)
Using Standard Operational Assumptions for Building Type
Using Actual Operational Information

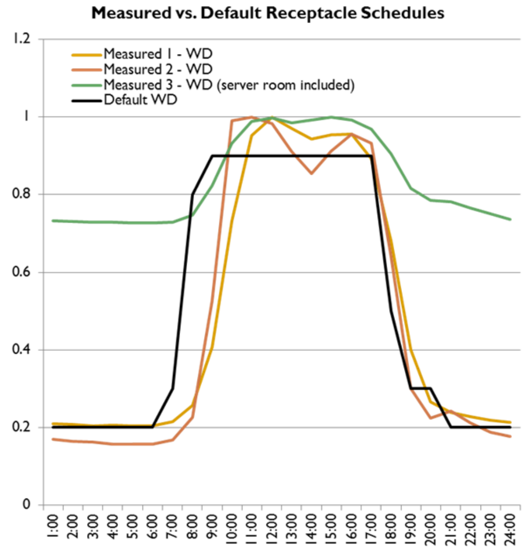

Accuracy of Model for Utility Bill Predictions
40%
30%
20%
10%
0%
-10%
-20%
-30%
-40%
Accuracy
Concept
Schematic
Design Development
Operation
Perfect representation of as-built and operation (variation between modelers and software)
Utility Bills (higher than model due to operational deficiencies)
Perfect representation of drawings and specs (variation between modelers and software)
Issue for Construction (accuracy relative drawings and specification)
Using Standard Operational Assumptions for Building Type
Using Actual Operational Information
RDH


Accuracy of Model for Utility Bill Prediction
40%
30%
20%
10%
0%
-10%
-20%
-30%
-40%
Accuracy
Concept
Schematic
Design Development
Operation
Perfect representation of as-built and operation (variation between modelers and software)
Utility Bills (higher than model due to operational deficiencies)
Operational improvements needed
Perfect representation of drawings and specs (variation between modelers and software)
Issue for Construction (accuracy relative drawings and specification)
Using Standard Operational Assumptions for Building Type
Knowledge transfer needed
Using Actual Operational Information
RDH

Simple Calibration

Calibrate building energy model with measured independent variables

- Weather
- Operational schedules
- Receptacle loads
  - Office default schedules reasonable for "office spaces"
    - Doesn't include printer rooms, data closets, kitchens or kitchenettes, etc.
  - Measured peak load: 6-10 W/m²
  - Measured peak load with server: 26 W/m²
  - Default peak load: 7.5 W/m²
- Most commonly missed process loads:
  - Server rooms, data closets, kitchens, printers, etc.



RDH

What are the Known Unknowns?

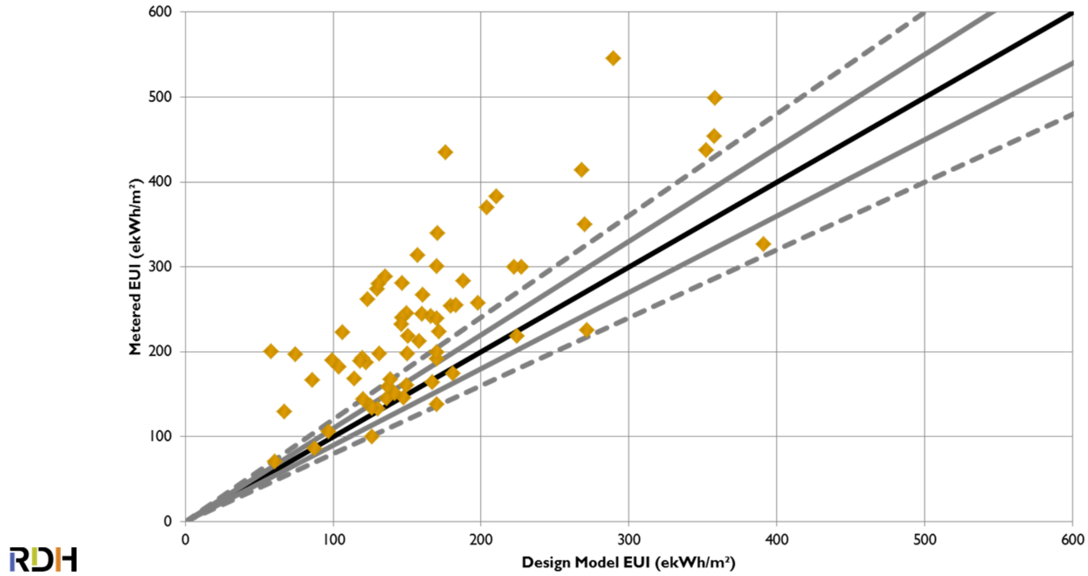
- Receptacles
  - Neither schedules nor peak values typically assume (MNECB-1997 or ASHRAE 90.1 user manuals) match reality… and they don't include:
    - 24/7 Data closets
    - 24/7 Networking and telephony
- Controls not functioning properly
  - Occupancy controls, setback, control sequences, thermostats in wrong locations, humidity sensors

Phone display that is useful as a coffee hot plate

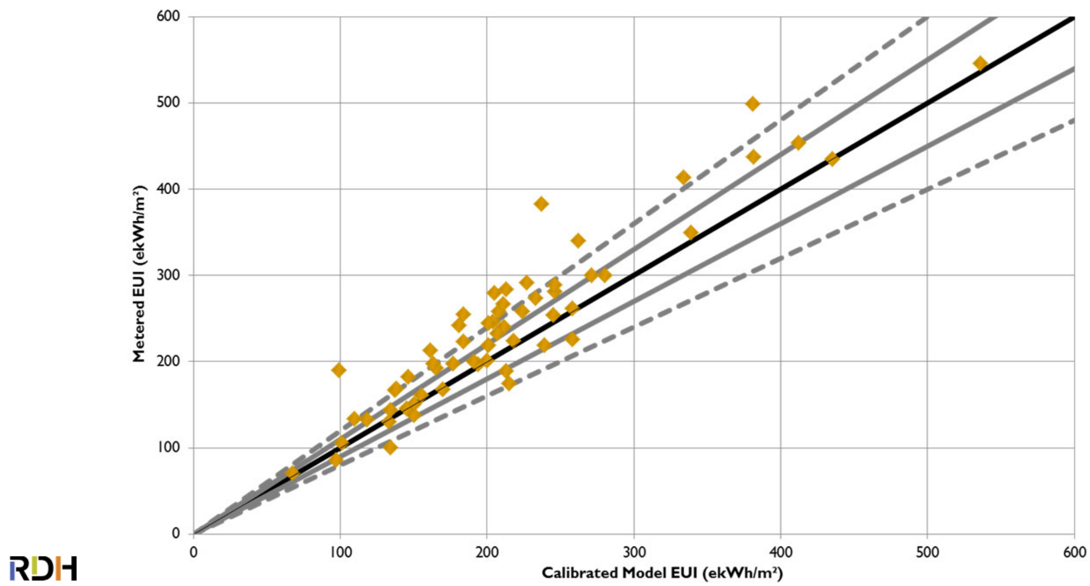
- Residential buildings service hot water consumption
  - Much higher and lower than we assume – wide distribution of results
  - Few measured data points, appears to be related to social-economic status

RDH

Design Stage Modes vs. Utility Bills

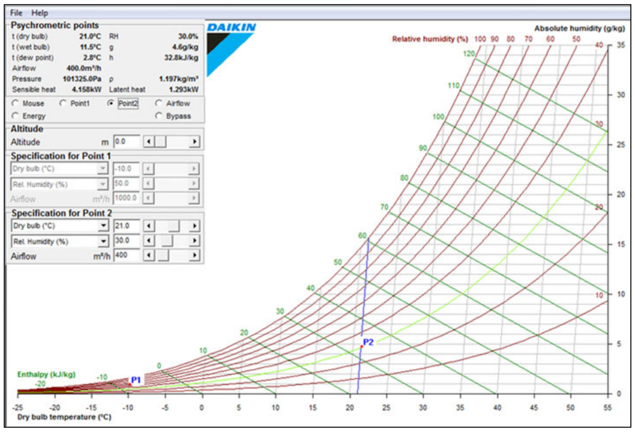


Calibrated Models vs. Utility Bills



Known unknown, model issue: humidity algorithms have room for improvement

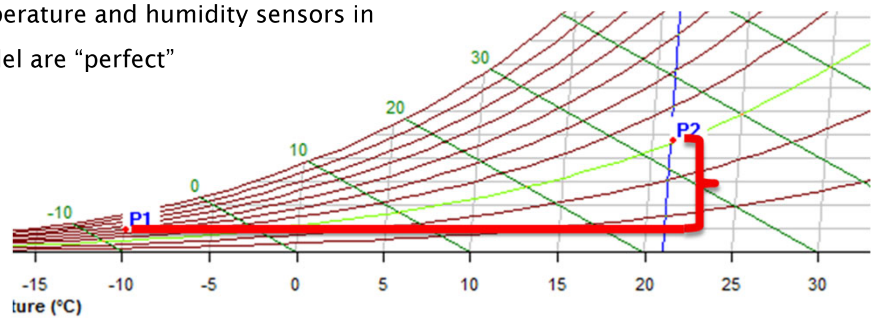
- Humidity
  - Lack of moisture capacitance algorithm in spaces (hygric buffering)
  - Coil wetting, and re-evaporation
  - Florida Solar Energy Center's EnerGuage software uses DOE2.1E engine with improved humidity algorithms



RDH

Known unknown, real world not perfect: real-world humidity sensors

All temperature and humidity sensors in the model are "perfect"



Real world sensors are not that accurate
±10% in senor = -30% to +50% in humidification load @ -10°C

RDH

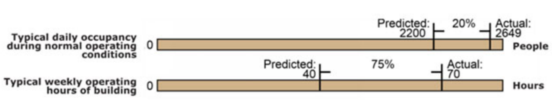
Red River College Innovation Centre

Image Courtesy of Diamond Schmitt Architects

Lessons Learned, Roblin Centre
Completed 2004, Built to Meet C-2000

KEY LESSON:

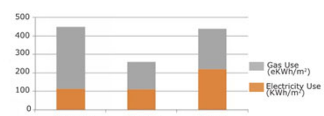
Changes in occupancy can dramatically impact a variety of building performances.



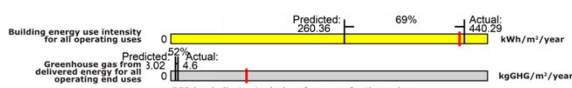
The building is being used beyond design predictions as a result of the owner's changes for general use of the building- common in academic buildings.

KEY LESSON:

A building's energy consumption can be strongly linked to its occupancy hours.



Electricity and natural gas use.



RED bar indicates typical performance for the region.

More energy is being used than predicted.

Process of Estimating Receptacle/Process Loads and Schedule

Datum from Measured Office Buildings

20 to 25 ekWh/m²

Review Program and Spaces → Create Table and Categorize Likely Receptacle Loads → Measure Loads with Surrogates

Review Schedule Assumptions with Client → Compare with Expectations → Refine Assumptions

Re-Review with Client

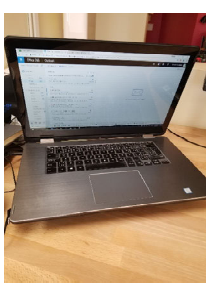
36.5 ekWh/m²

Estimate result from process

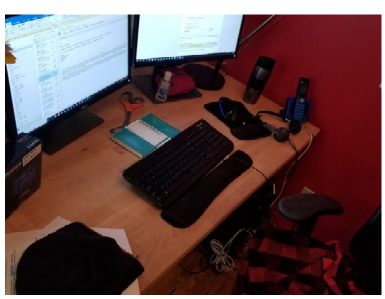
RDH

Measure Loads with Surrogate

Gaming Computer: Avg ~215 W

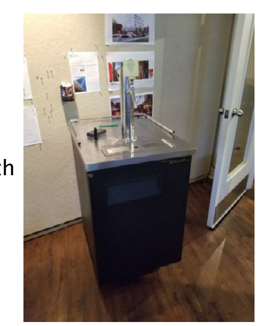


~35 W (charging)
~18 W (charged)

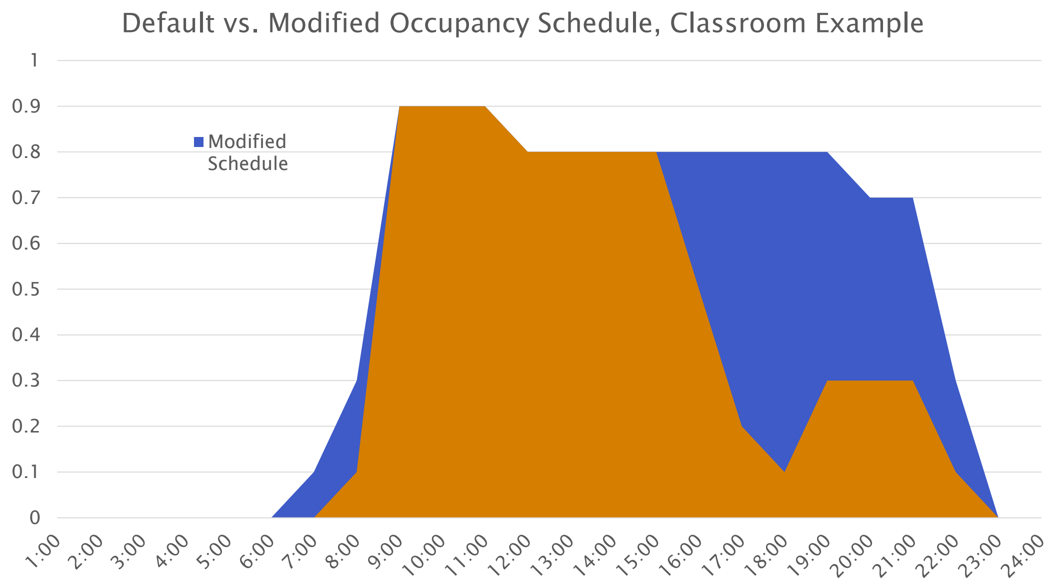


Avg ~63 W

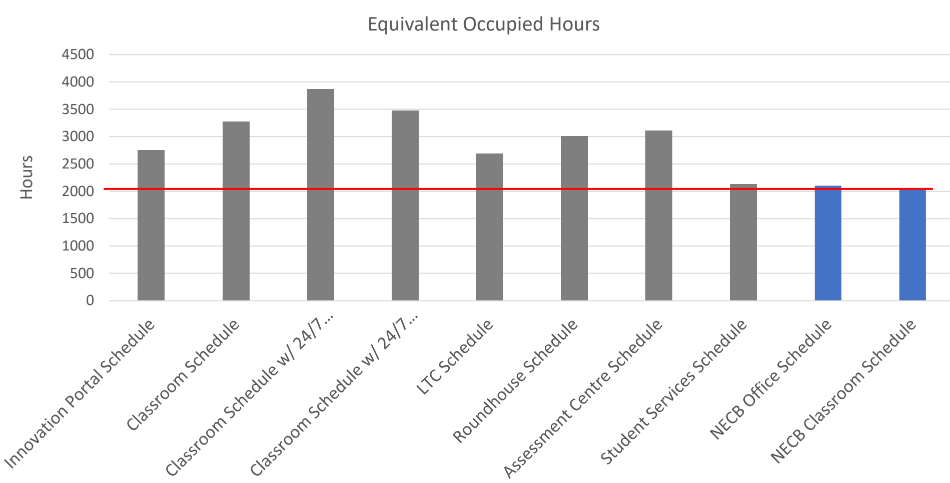
75kWh/month
Avg 104 W



Resulting Schedule from Process



Resulting Schedule from Process



The Challenge of Controls

- Models based on control sequences included in the design
  - Sometimes control sequences are unavailable and are assumed

"Controls shall allow heating system to operate in the most efficient manner" – name withheld

- In the field, control sequences may be amended to adapt to peculiarities of equipment and installation
  - Sometimes (often!) field controls are not working or are misbehaving

Case Study – Office B: Office & Workshop

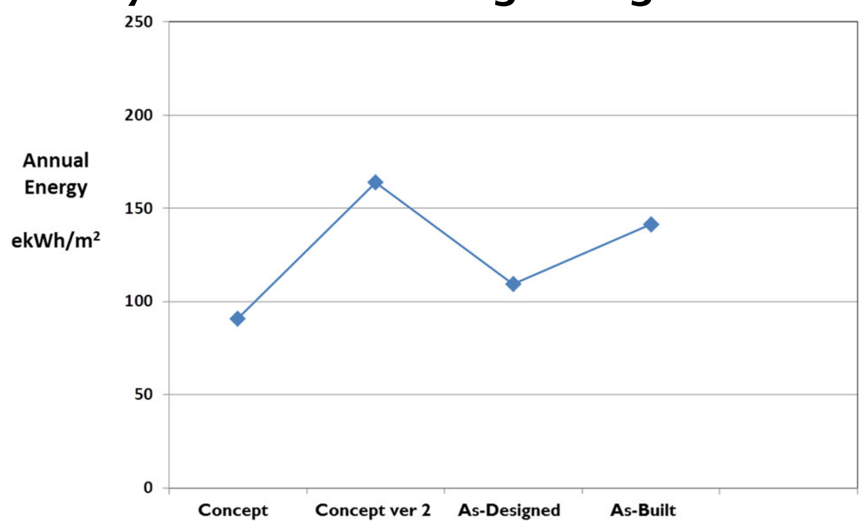
- 20,000 sq. ft., 1-storey office and workshop in Southern Ontario
- Ground source heat pump, high performance windows, etc.
- Metering included: potable & cistern water, NG main, electric main plus sub-panels on PV, lighting, HVAC pump and fan status, receptacles

Case Study – Office B: Office & Workshop

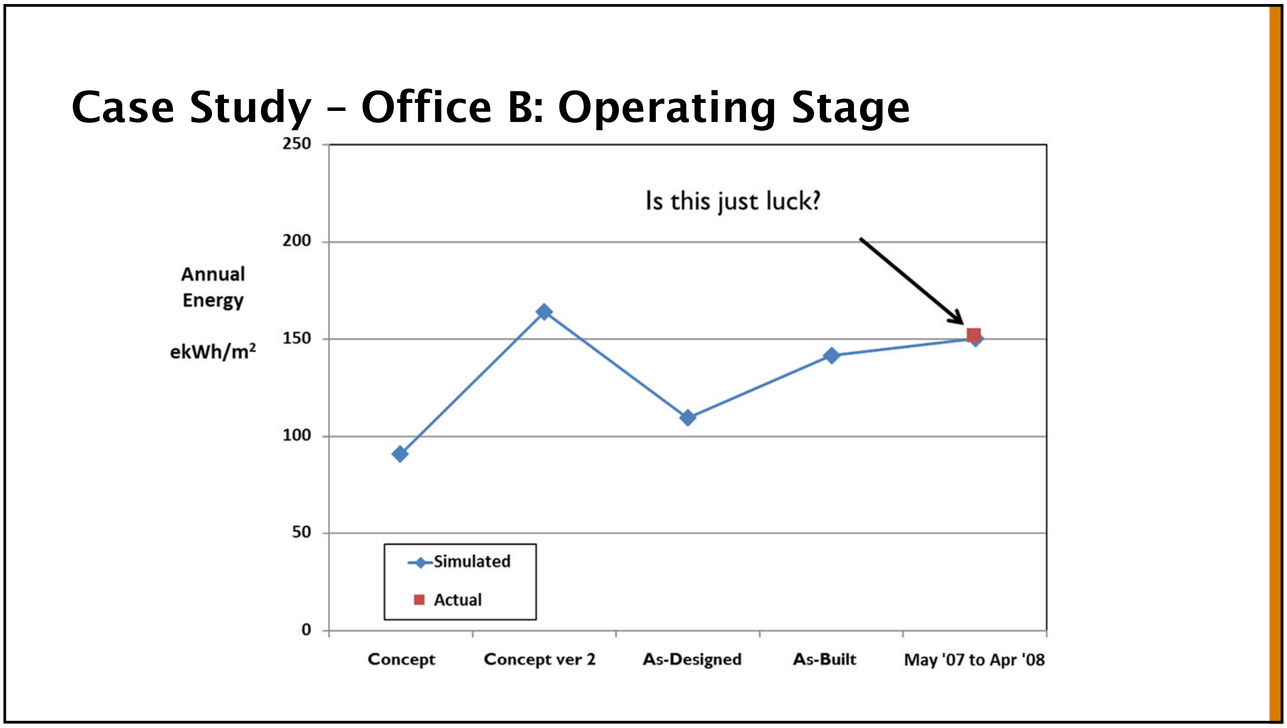
FUNCTIONAL TEST

- Storage room hot, office cool
  - Found crossed floor loops
  - Office thermostat controlling floor heat in storage room
  - Loops not labeled
- Heat pump constantly tripping
  - Supplier blamed system, but did not measure any parameters
  - Cx measurements showed water flows ok
  - Heat pump diagnostics finally found faulty TX valve and low-refrigerant charge
- Controls are probably the single most important item in ensuring successful system operation for comfort and energy savings
  - Controls contractor programmed system heating water temps lower than specified because they thought this worked better
  - Improperly programmed 24-hour moving average outdoor temp caused the system to flip-flop between heating and cooling

Case Study – Office B: Design Stage

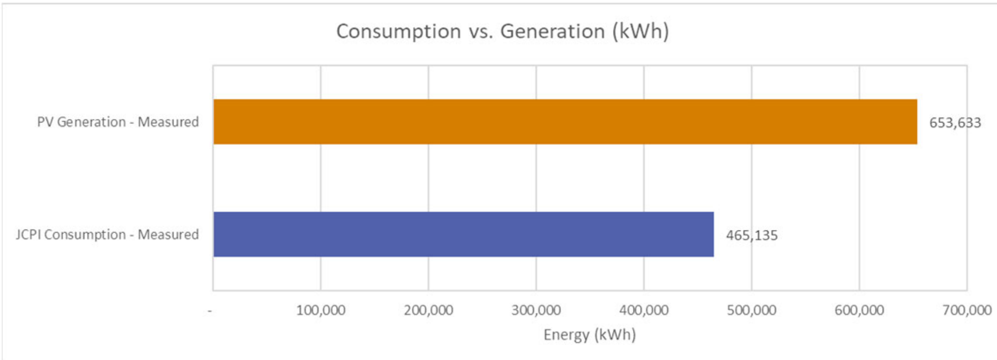


LEED Status: Platinum	LEED Energy Savings: 65% (10 pts)


Case Study – Office B: Operating Stage
Is this just luck?
Annual Energy
ekWh/m²
250
200
150
100
50
0
Simulated
Actual
Concept
Concept ver 2
As-Designed
As-Built
May '07 to Apr '08

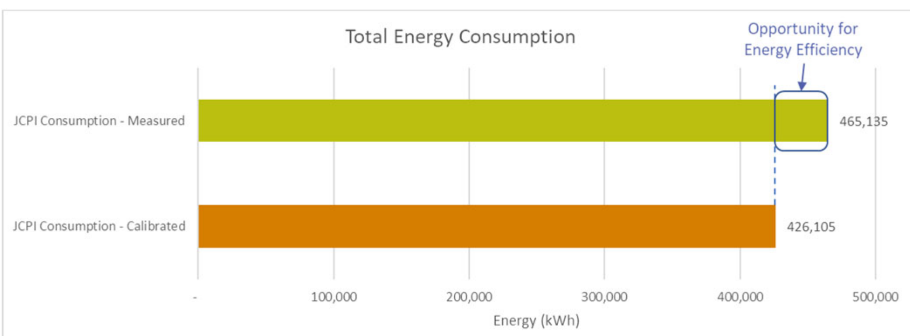

Mohawk JCPI

Net Zero Energy Building – Realized



RDH

Calibrated Energy Model

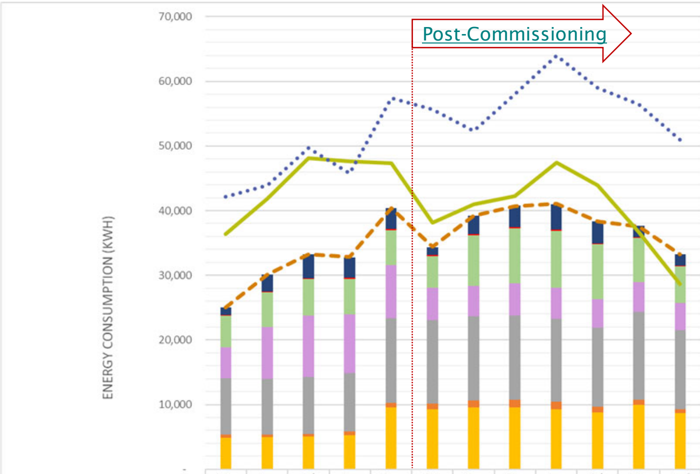


RDH

The Value of Commissioning

- Controls updates completed in late September 2019
- Lighting improvements to occupancy and daylighting controls still to be completed
- Summer receptacle loads are higher than expected, directing college to investigate

RDH



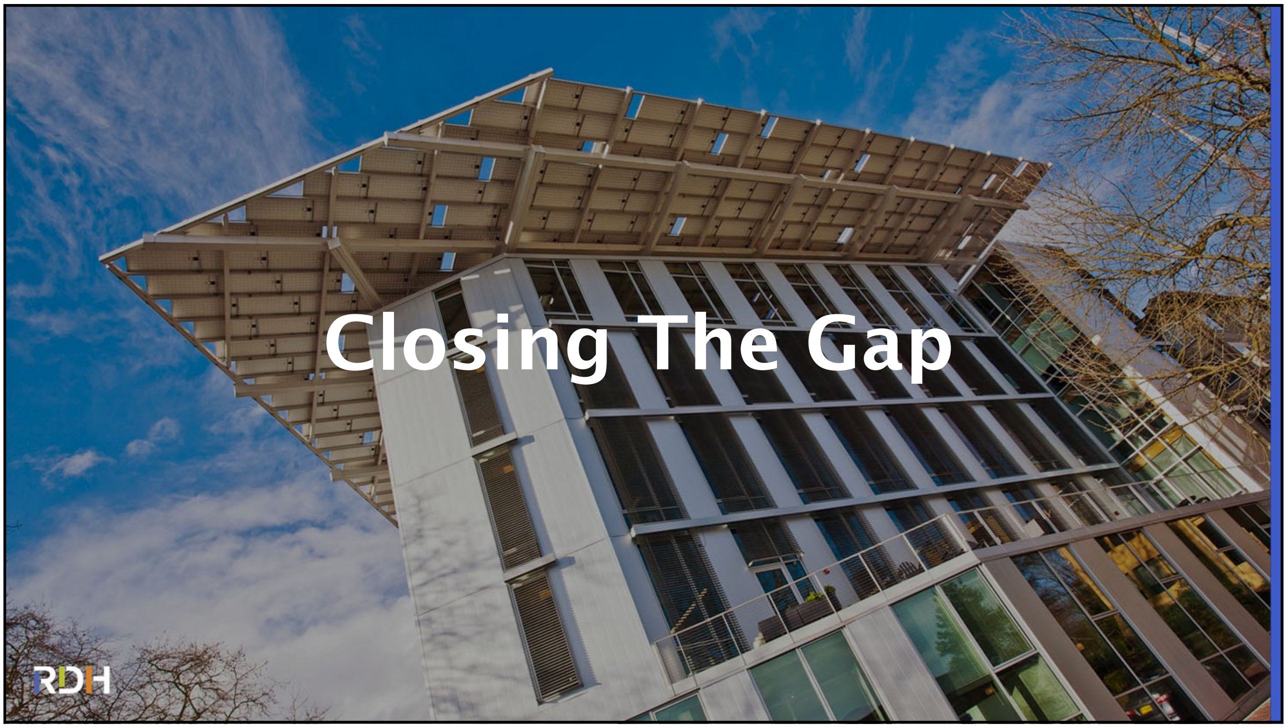
	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr*
Heating and Cooling	1,100	2,600	3,700	3,200	3,300	1,200	2,800	3,300	3,900	3,400	1,700	1,700
DHW	170	170	170	170	170	170	170	160	160	160	170	160
Pumps	4,900	5,300	5,600	5,500	5,400	4,900	7,800	8,600	8,800	8,500	6,800	5,600
Fans	4,800	8,100	9,500	9,100	8,200	5,000	4,700	4,900	4,800	4,400	4,600	4,300
Interior Equipment (IV)	8,700	8,600	8,800	9,000	13,100	12,900	13,100	13,100	12,900	12,200	13,600	12,200
Exterior Lighting (IV)	430	340	390	520	670	870	1,000	1,100	1,100	880	760	560
Interior Lighting (IV)	4,900	5,000	5,100	5,300	9,600	9,300	9,600	9,600	9,300	8,800	10,000	8,700
Total Calibrated	25,000	30,100	33,200	32,900	40,400	34,400	39,200	40,700	41,100	38,300	37,600	33,200
Total Measured	36,400	41,900	48,100	47,600	47,300	38,100	41,000	42,300	47,400	43,900	36,700	28,600
Total As-Built (prior to calibr.)	42,200	43,900	49,700	45,800	57,400	55,700	52,300	58,000	64,000	59,000	56,400	51,000

*IV = Independent Variable; *Includes April 24-30, 2019, April 1-23, 2020*

What Matters, What Doesn't?

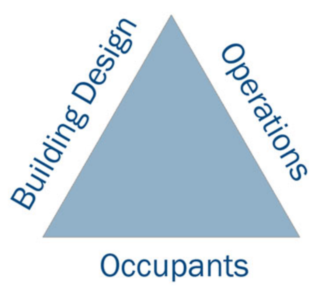
- People are challenging to predict
  - Hours of operation
  - Plug loads
- Commissioning is essential
- If these are considered, then the energy model can identify operational deficiencies

RDH



Triumvirate of Building Performance

To Maximize Performance, All Operational Aspects Must Work Together



→ Designers are necessarily aware of performance

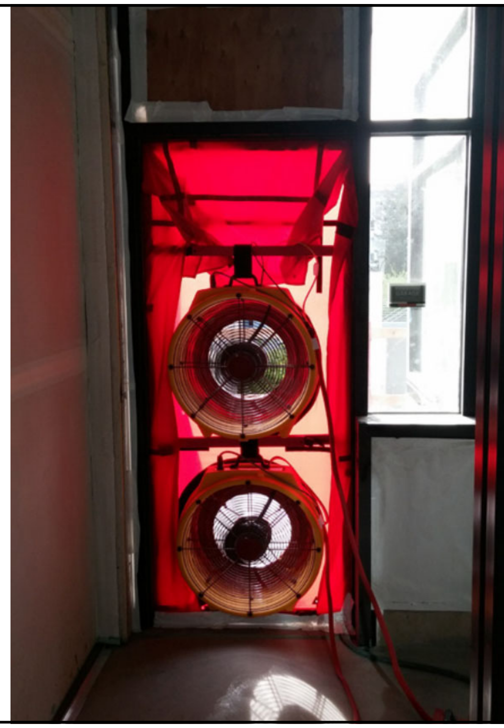
→ Operators and maintenance are necessarily aware of performance

→ Occupants are not necessarily aware of performance

Closing The Gap

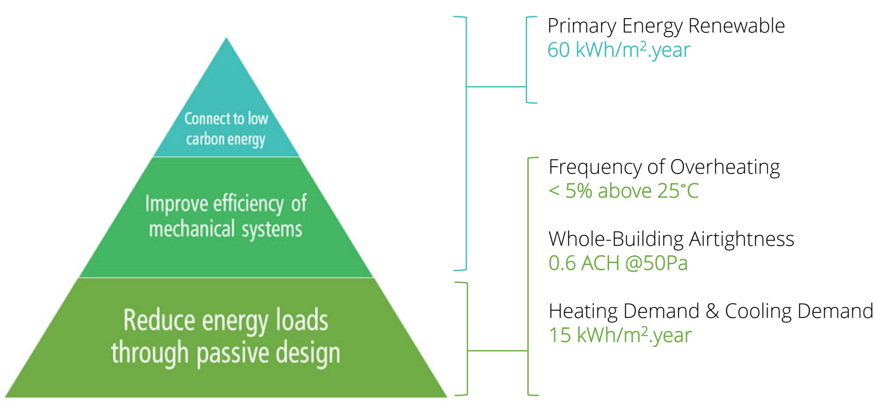
- Absolute performance targets
- Design process
- Focus on the building enclosure
- Measurement and verification
- Operations – commissioning, post-occupancy evaluation, monitoring
- Reviews & 3rd party verification
- Training and education

RDH



Absolute Performance Targets

- Measure what you want to manage



RDH

Final Thoughts

- We're making progress!
- Set performance targets in design
- Update & sensitivity analysis
- Do measurement and verification – learn for the next project, design, model, etc.

RDH

Discussion + Questions

Learn more at
rdh.com

RDH Building Science

@RDHBuildings

RDH