

4.401/4.464 Environmental Technologies in Buildings

Christoph Reinhart

L16 Internal Gains + Load Calculations

Thermal Module

- Thermal Mass & Heat Flow
- Insulating Materials + Window Technologies
- Shading + Integrated Façade Design
- Ventilation
- Internal Gains & Load Calculations
- HVAC for Small Buildings
- HVAC for Large Buildings
- Simulation Game

Internal Gains

Internal Heat Gains

Internal heat gains correspond to heat that is generated in buildings as part of their programmatic use. Internal heat gains in buildings are typically divided into three groups:

- Heat from occupants
- Heat from electrical equipment and appliances
- Heat from electric lighting

Obviously, all three are (or should be) strongly correlated with building occupancy...

Internal Heat Gain from Occupants

- ❑ Same as individuals' thermal comfort sensation varies, building occupants generate varying amounts of heat and moisture. Key factors that determine how much sensible and latent energy a person releases are activity, age, and gender.
- ❑ Sensible heat gains from occupants raise the indoor temperature. Latent heat gains need to be considered if the indoor air is actively dehumidified.
- ❑ 'Occupancy load schedules' are determined through two factors: maximum occupancy heat gains and time of day schedules.

Maximum occupancy heat gains = activity-related heat gain/person x occupancy density

Internal Heat Gain from Occupants

Our Classroom

Together, we each generate around 100 W of sensible heat. Maximum occupant density is 45 divided over 12 m x 12 m. The resultant maximum occupancy heat gain is

$$100 \text{ W/person} \times 45 \text{ person}/144 \text{ m}^2 = 31 \text{ W/m}^2 = \mathbf{0.31 \text{ person/m}^2}$$

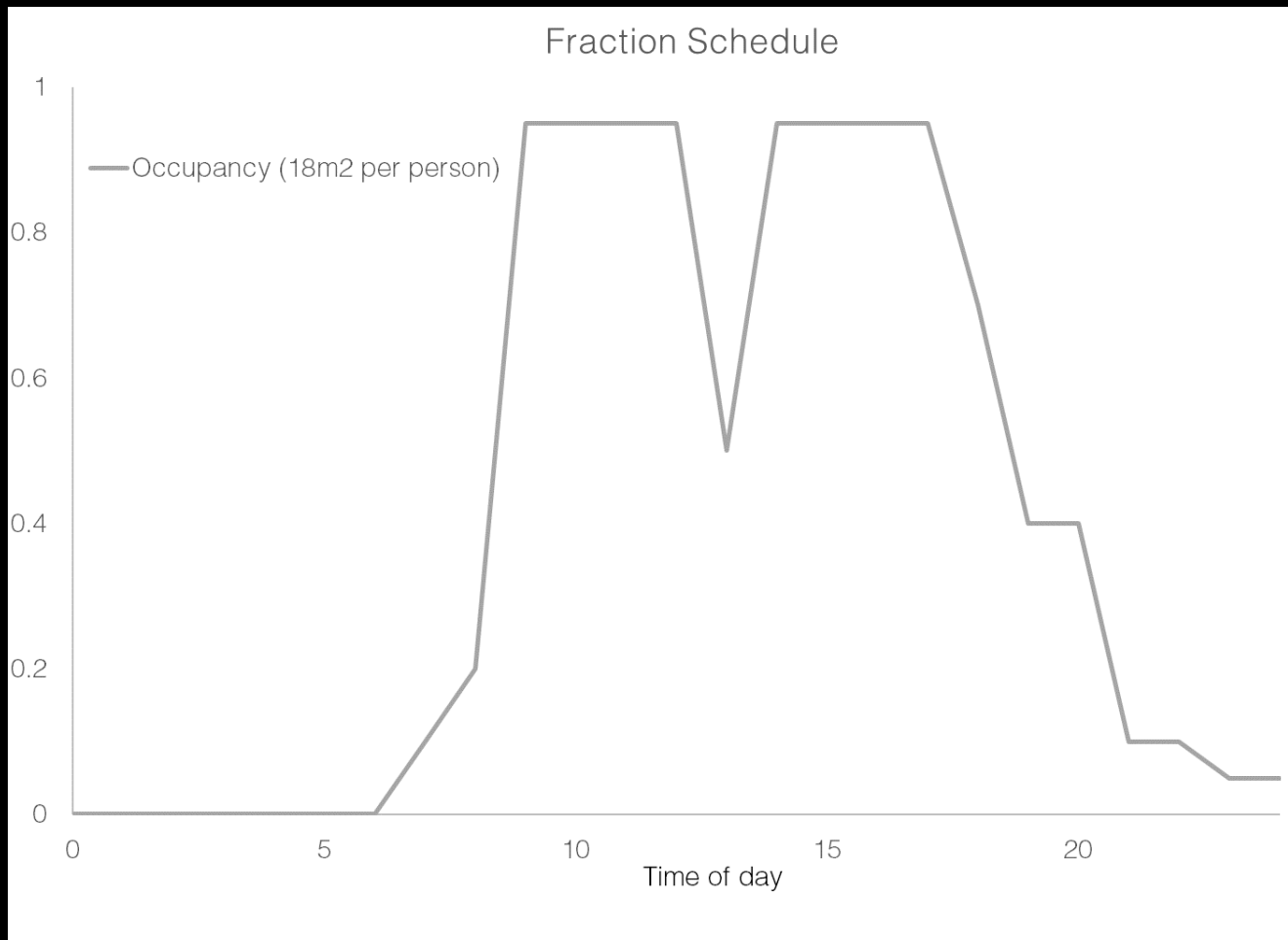
Example Cottage

Assume a 4-person household distributed over 125 m² and so

$$400 \text{ W}/125 \text{ m}^2 = 3.2 \text{ W/m}^2 \text{ or } \mathbf{0.0326 \text{ person/m}^2}$$

Schedules

The maximum occupancy heat gain corresponds to heat gains when everybody is at their work place. Since occupants temporarily leave their building, 'schedules' are used in energy simulation software in order to determine occupancy loads on different week days and for different times of the day.



Equipment and Appliances

Heat gain due to a variety of equipment, including computers, coffee machines, hot water pipes etc.
Sun Wind and Light (Chapter 4) provides lower and upper margins for different building types:

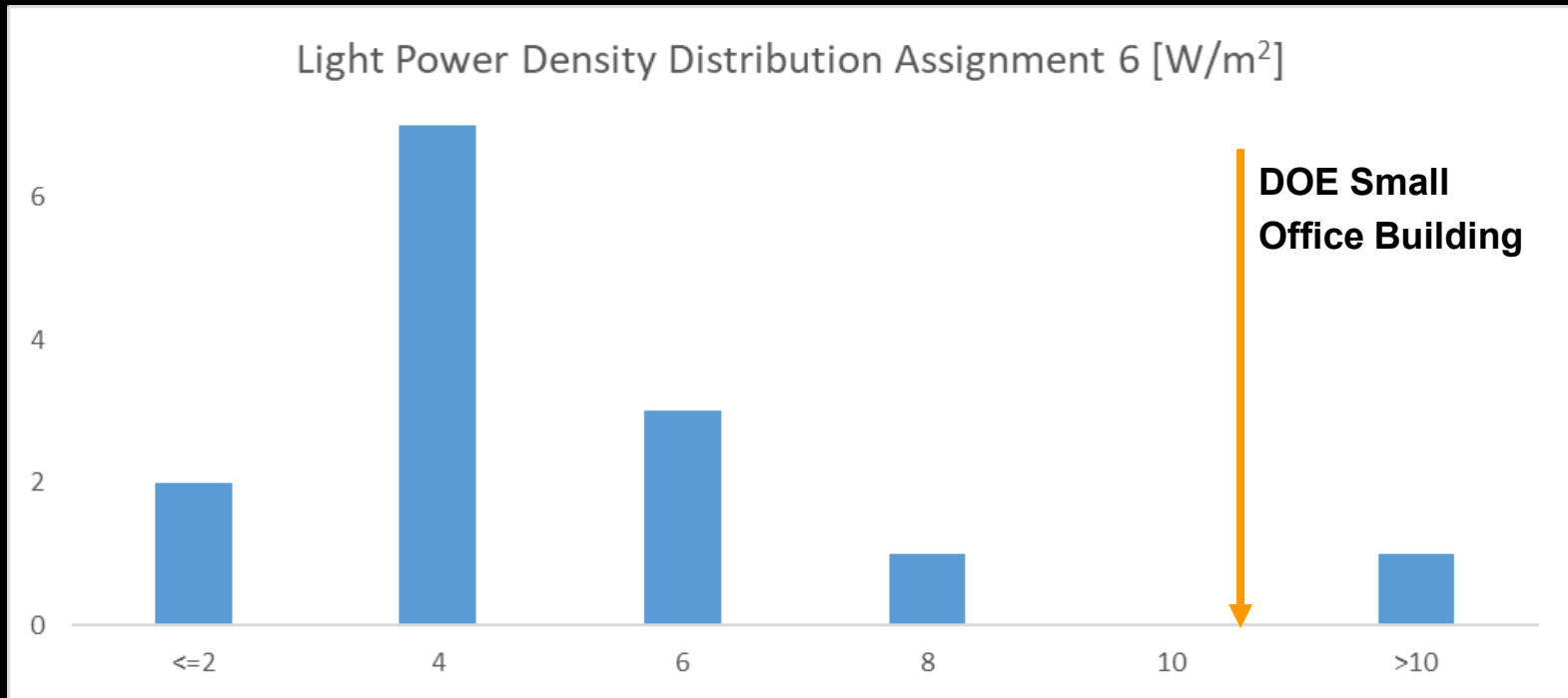
Offices : 8 to 17 W/m² (Studio load typically around 26 W/m²)

Education: 14 to 23 W/m²

Residential: 2 to 6 W/m²

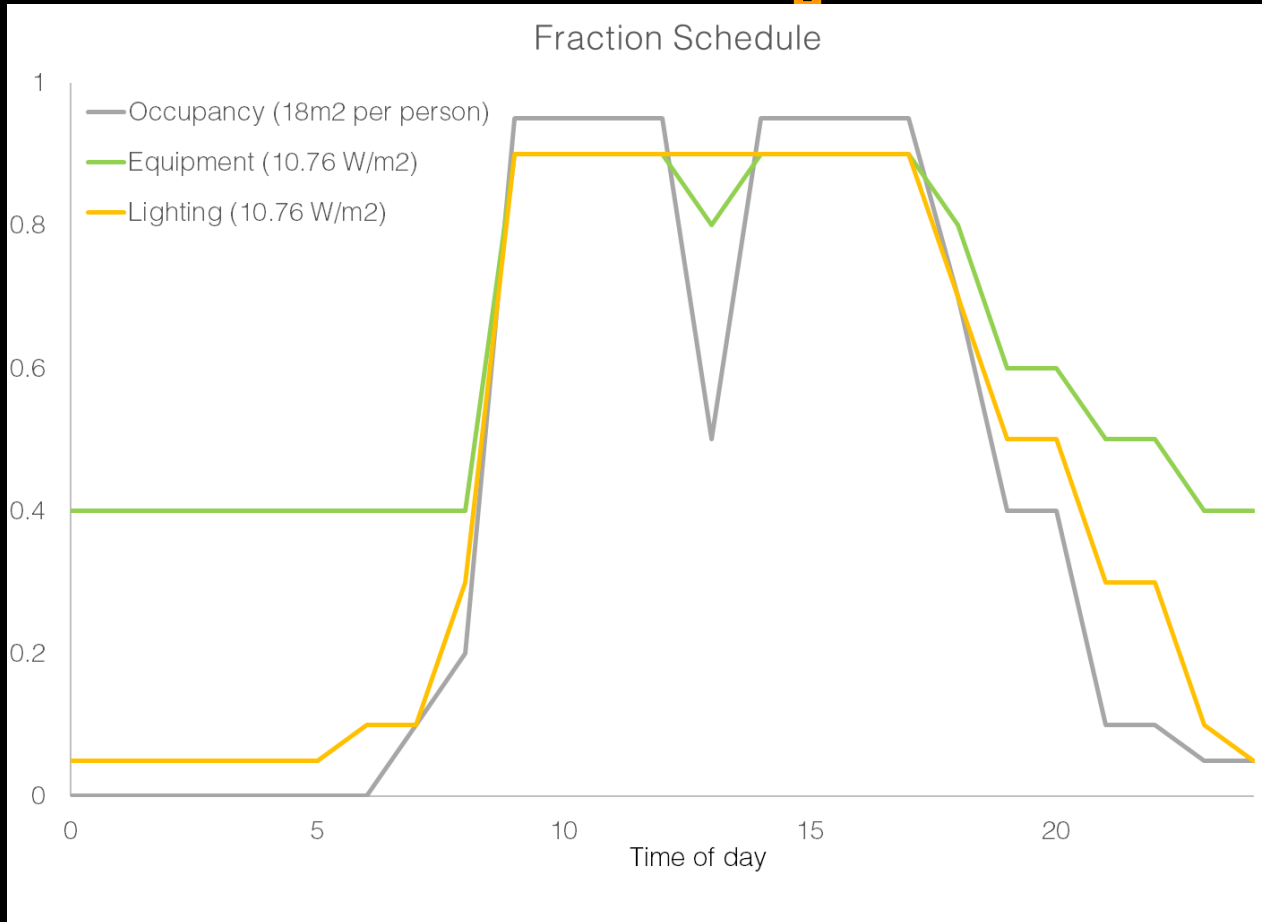
Electric Lighting

Can vary dramatically for different lighting requirements, types of lighting systems and for different types of controls. Values range between 1 and 25 W/m². LEDs are a game changer.



Discussion: Relevance of the installed electric lighting power density.

US DOE Small Office Building



Occupants: $0.0538 \text{ p/m}^2 * 100 \text{ W} = 5.38 \text{ W/m}^2$ Mean daily gain 2.3 W/m^2

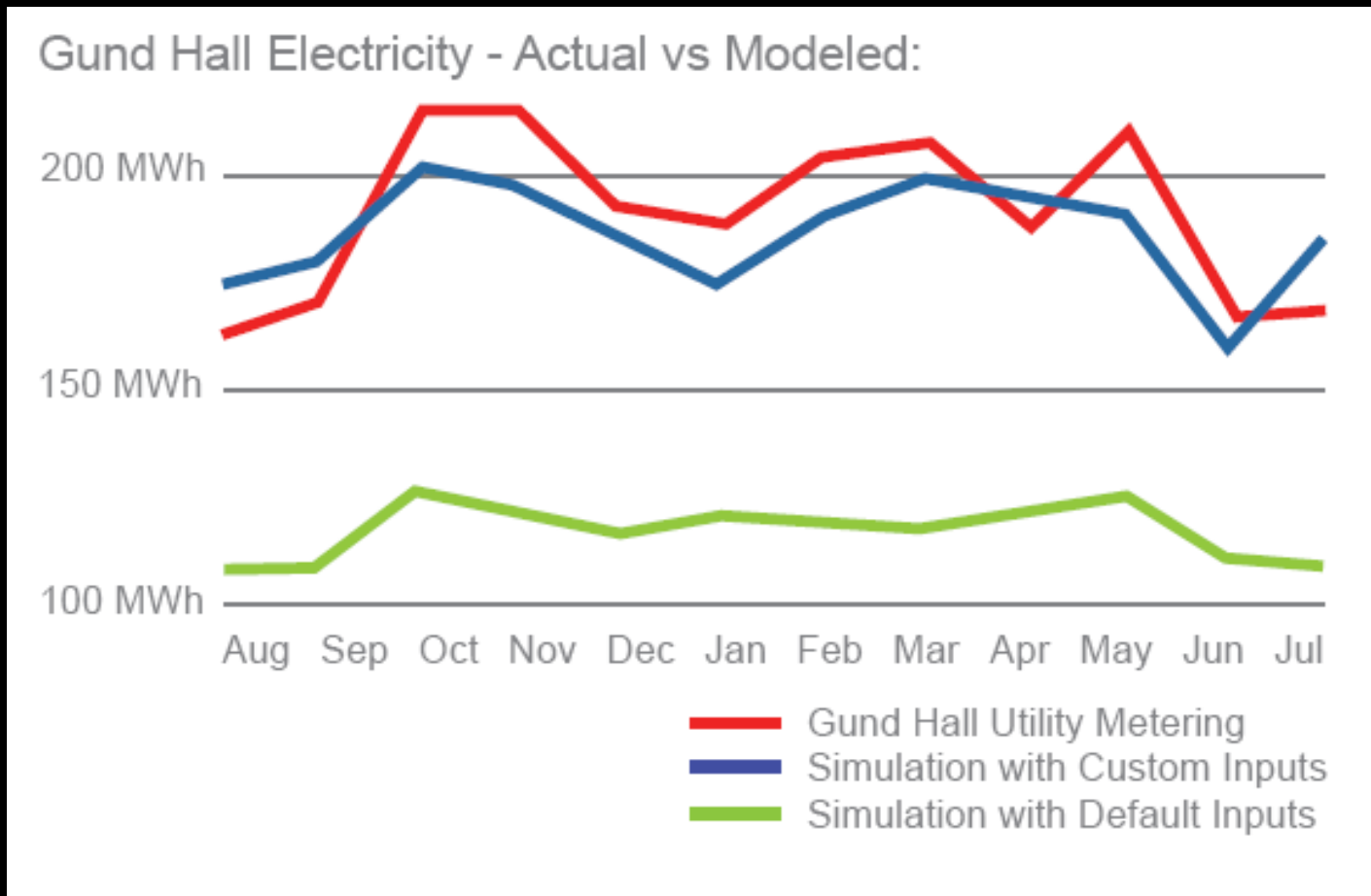
Equipment: Mean daily gain 6.7 W/m^2

Lighting: Mean daily gain 5.1 W/m^2

Total internal gains: Mean daily gain 14.1 W/m^2

The Value of Building Surveys

(Based on data from Wasilowski & Reinhart, 2009)



Gund Hall: 150 kWh/m²yr (includes circulation areas etc. as well as pumps, fans, server rooms, cafeteria etc.)

Building Surveys



Field Visits

GSD Tray Survey [Exit this survey](#)

1. Tray Occupancy

50%

* 1. Where is your desk located on the trays?

- Mezzanine
- 2/F Tray
- 3/F Tray
- 4/F Tray
- 5/F Tray
- Other (please specify)

* 2. On an average WEEKDAY (M-F), how many hours do you spend on the Trays for the given time slots?

| | 6am - 12pm | 12pm - 2pm | 2pm - 6pm | 6pm - 12am | 12am - 6am |
|--------------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| An Average Weekday (M-F) | <input type="text"/> | <input type="text"/> | <input type="text"/> | <input type="text"/> | <input type="text"/> |

* 3. On an average WEEKDAY (M-F), how many other people do you estimate are on YOUR Tray for the given time slots?

| | 6am - 12pm | 12pm - 2pm | 2pm - 6pm | 6pm - 12am | 12am - 6am |
|--------------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| An Average Weekday (M-F) | <input type="text"/> | <input type="text"/> | <input type="text"/> | <input type="text"/> | <input type="text"/> |

* 4. On an average WEEKEND DAY (Sa -Su), how many hours do you spend on the Trays for the given time slots?

| | 6am - 12pm | 12pm - 2pm | 2pm - 6pm | 6pm - 12am | 12am - 6am |
|--------------------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| An Average Weekend Day (Sa-Su) | <input type="text"/> | <input type="text"/> | <input type="text"/> | <input type="text"/> | <input type="text"/> |

* 5. On an average WEEKEND DAY (Sa -Su), how many other people do you estimate are on YOUR Tray for the given time slots?

| | 6am - 12pm | 12pm - 2pm | 2pm - 6pm | 6pm - 12am | 12am - 6am |
|--------------------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| An Average Weekend Day (Sa-Su) | <input type="text"/> | <input type="text"/> | <input type="text"/> | <input type="text"/> | <input type="text"/> |

[Next](#)

Online Surveys

Thermostat Settings

To what temperatures do you set your thermostat in Winter/Summer?

Thermostat Setting

- According to ASHRAE 90.2, in residential buildings, heating set points and setbacks are 20° C and 15.5° C, respectively.

Different Thermostat Models



Manual



Programmable



Self-learning/wireless

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Center photo courtesy of [joininnaclephotos](#) on Flickr. License: CC BY-NC.

Right photo courtesy of [Green Energy Futures](#) on Flickr. License: CC BY-NC-SA.

Common Misconceptions about Thermostats

- Thermostat is an on/off switch
- Thermostat is a dimmer switch
- Thermostat is an accelerator
- Turning down the thermostat has little or no effect on energy consumption

Default Thermostat Setpoints and Setbacks

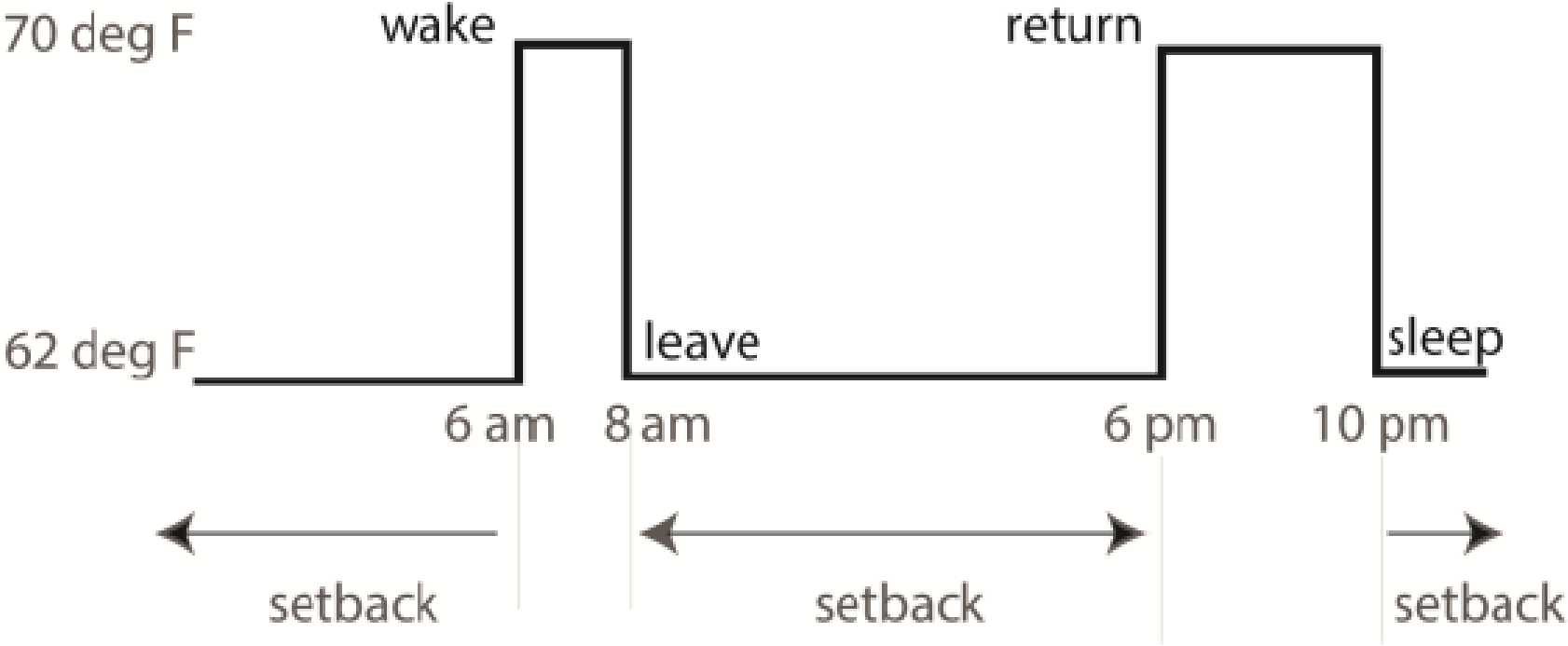


Figure 1 Default thermostat setpoint program.

Figure courtesy of Bryan Urban. Used with permission.

Actual energy use depends on how occupants operate their thermostats

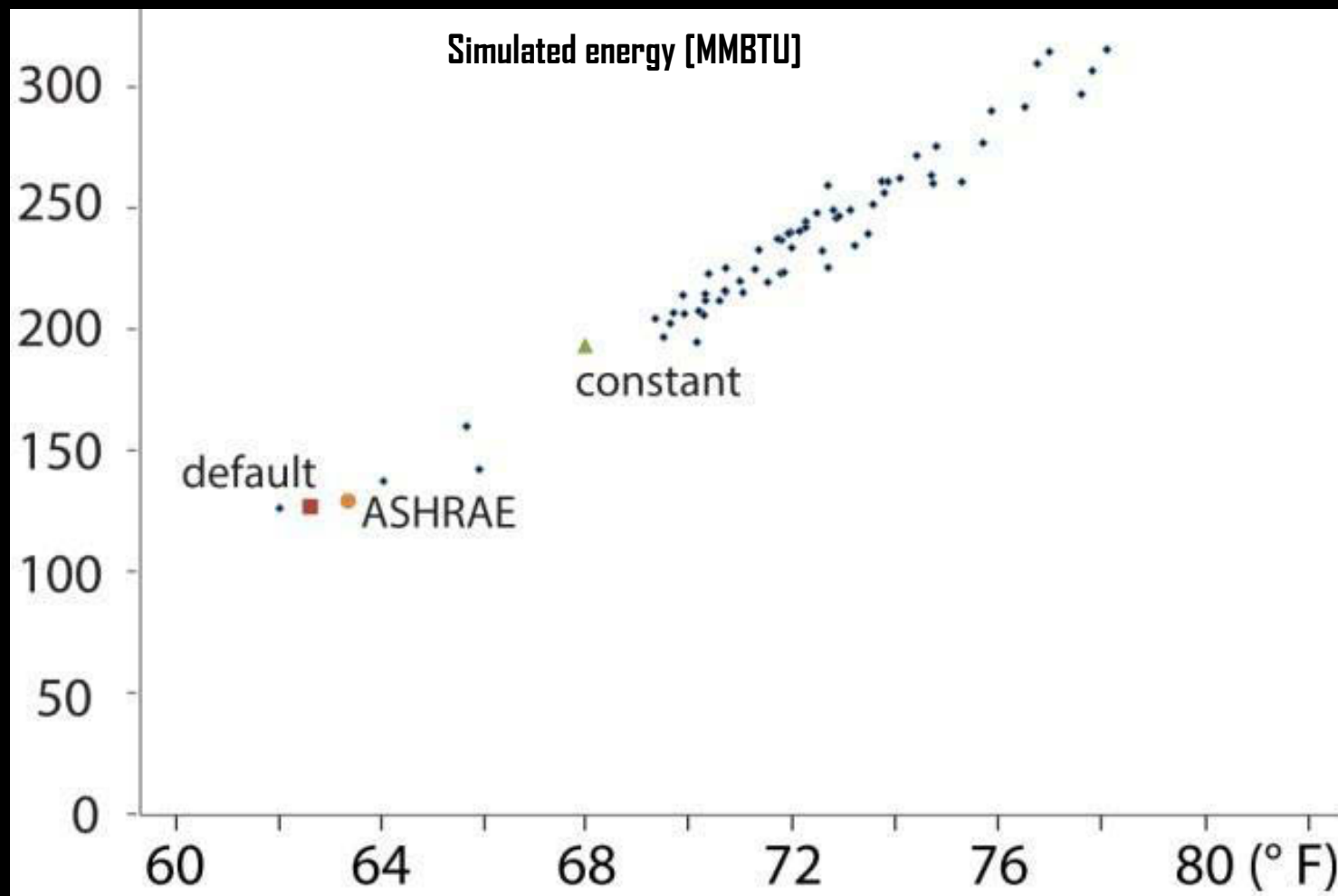
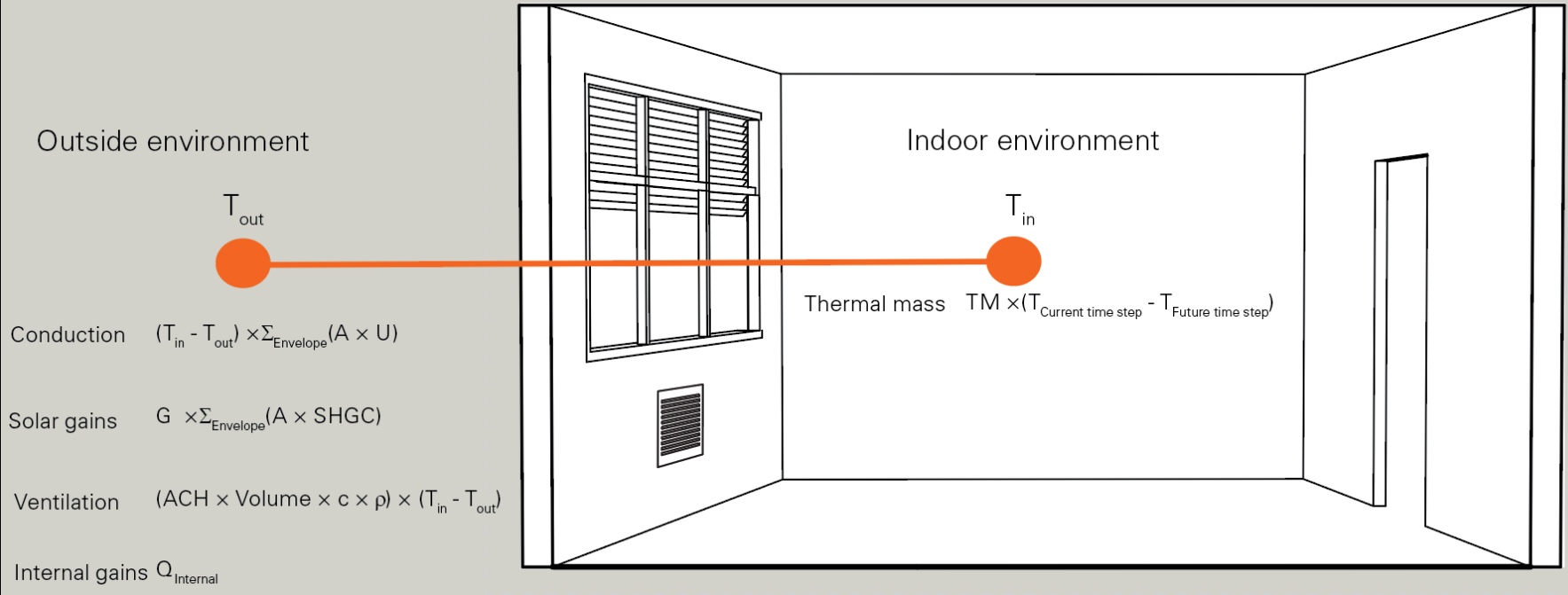


Figure courtesy of Bryan Urban. Used with permission.

How relevant are heating and cooling set points?

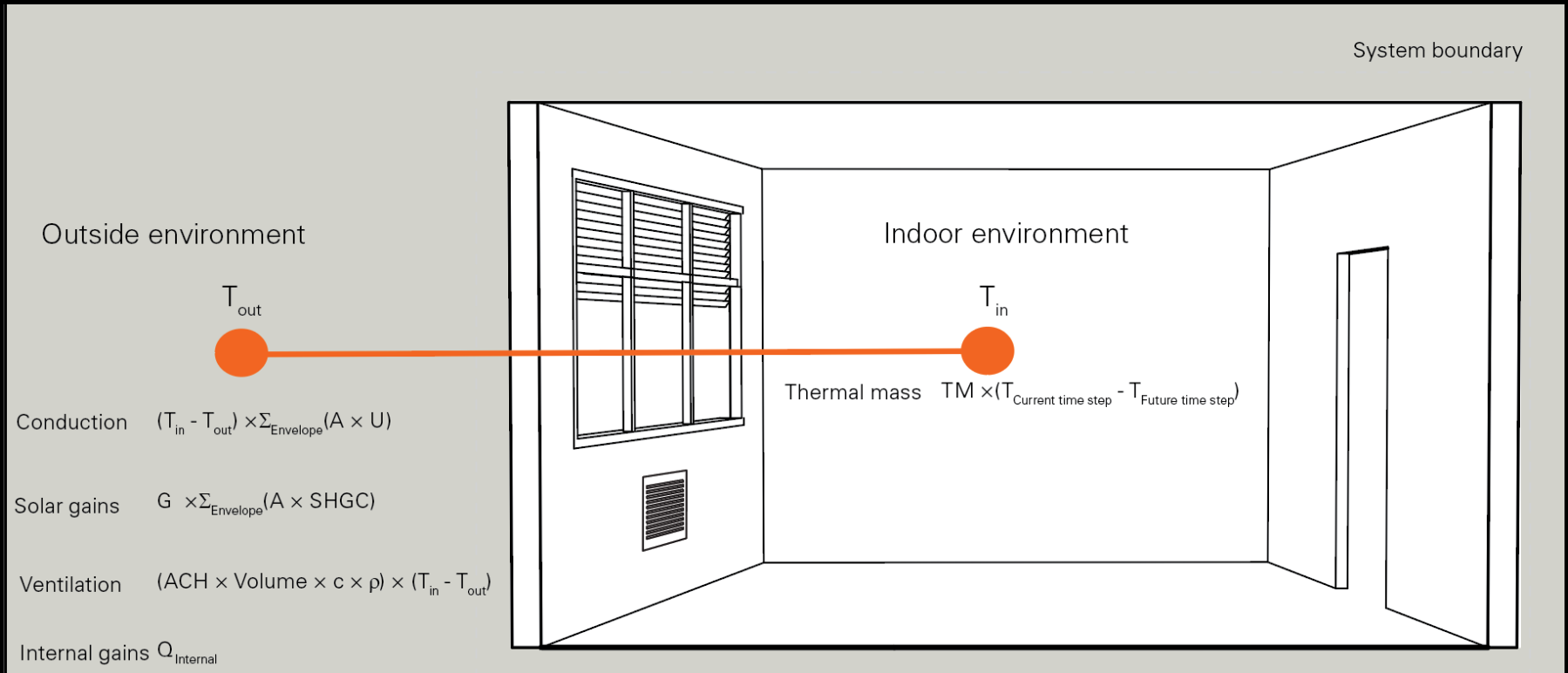
Heat Balance Equation

System boundary



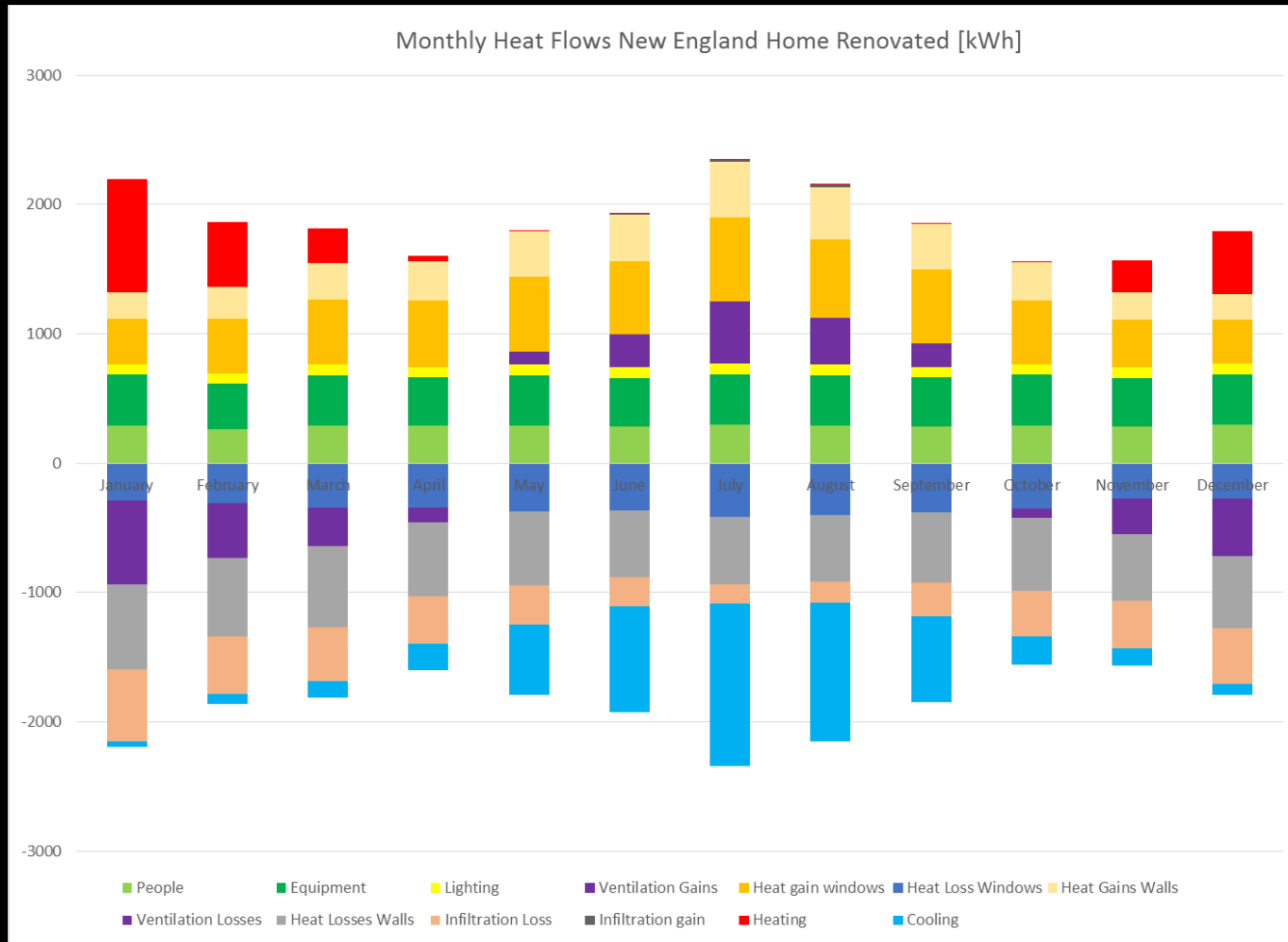
Internal gains are easy to model but hard to predict.

Final Heat Balance Equation



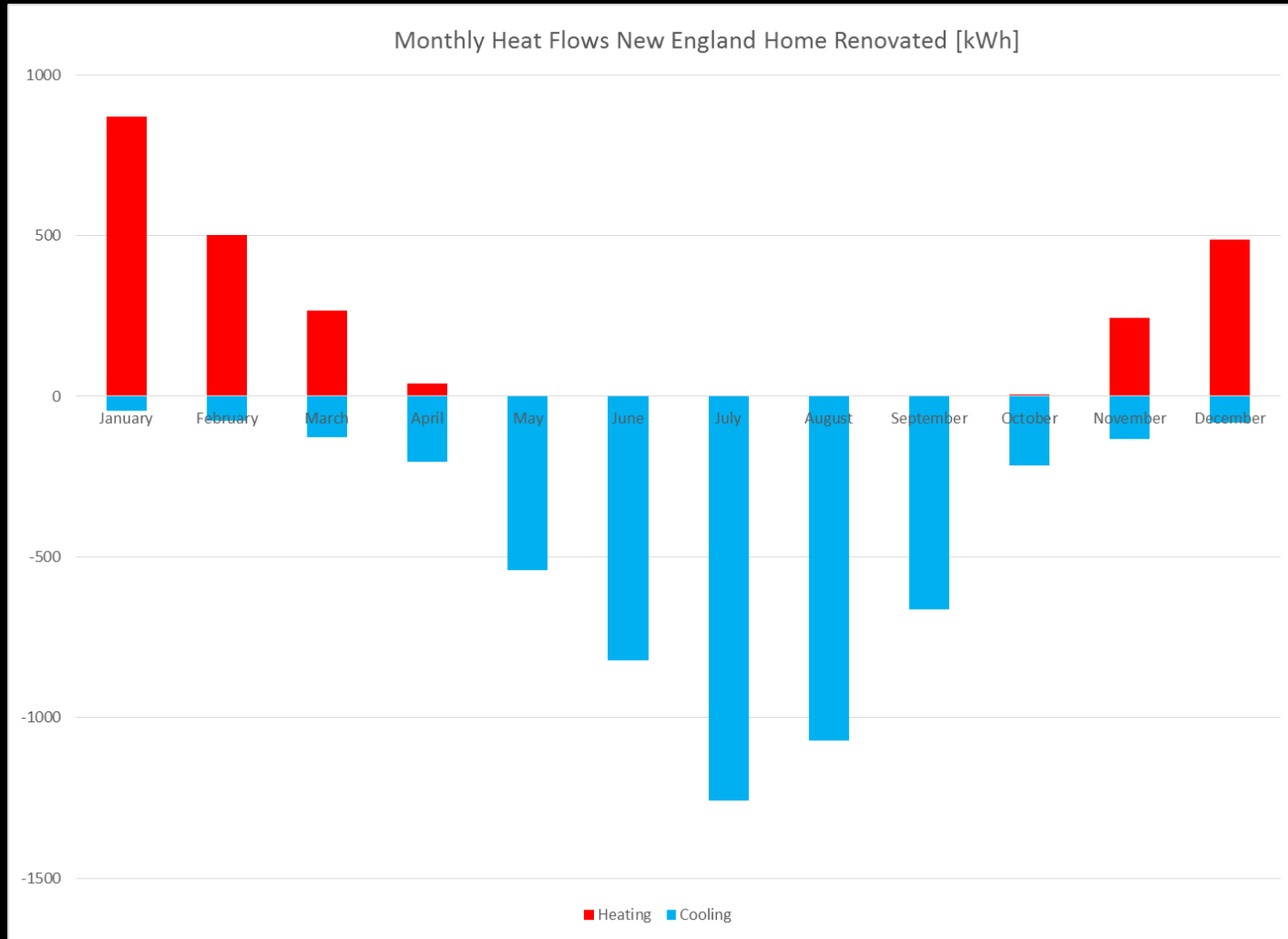
This is our final heat balance equation. Please note that a new term called "Load" has been added which needs to balance the heat flows during each hour to keep the temperature in the house from changing to outside of the set comfort range of 19° C to 27° C.

Monthly Heat Gains



Monthly heat flows are an effective way to show the relative size of ongoing and outgoing heat into a building. Heat flows are smallest during the transition period/shoulder months. Heating and cooling loads are required to balance the remaining heat flows.

Monthly Conditioning Loads



Note that there are temporary cooling loads in the building even during winter. Again, those loads could be met by simply opening the window. This effect will be covered in future lectures.

Load

- ❑ The ideal load is the amount of heat that has to be added or subtracted from a space for it to maintain the zone air temperature at a certain level.
- ❑ Load is measured in kWh or BTU.
- ❑ Normalizing the load to the conditioned area helps to compare different spaces. (EUI equivalent.)
- ❑ The **load** of a space **does not correspond to its energy use** which requires further conversion depending on the HVAC equipment used.

Load Calculations

Load Calculation Procedures

There are two types of methods to calculate annual heating and cooling loads.

- **Manual methods** are solving the heat balance equation for each hour independently (steady state) and can be implemented, for example in Excel.

$$(\Sigma UA + ACH \times \text{volume} \times c \times \rho) \cdot (T_{\text{inside}} - T_{\text{outside}}) + G \cdot A \cdot SHGC + Q'_{\text{internal gains}} = \text{Load}_{\text{heating/cooling}} + TM \cdot (T_{\text{inside}} - T_{\text{inside future}})$$

- **Numeric methods** also take transient thermal effect from thermal mass into account. Example simulation programs are EnergyPlus, TRNSYS, eQuest/DOE2 and ESP-r. In 4.401/4.464 we are using EnergyPlus through DIVA4/Archsim.

Balance Point Temperature

The balance point temperature is a building and climate dependent temperature at which internal gains and solar gains are equal to conduction, ventilation and infiltration losses. In other words, all heat gains and heat losses 'balance' each other and the building is in thermal equilibrium with its surrounding without the need for additional heating or cooling ($\text{Load}_{\text{heating/cooling}} = 0$; $T_{\text{inside}} = T_{\text{inside future}}$).

$$(\sum UA + ACH \times \text{volume} \times c \times \rho) \cdot (T_{\text{inside}} - T_{\text{outside}}) + G \cdot A \cdot SHGC + Q'_{\text{internal gains}} = \text{Load}_{\text{heating/cooling}} + TM \cdot (T_{\text{inside}} - T_{\text{inside future}})$$

$\text{Load} = 0$; $T_{\text{inside}} = T_{\text{inside future}}$

Balance Point Temperature

$$T_{\text{Balance point}} = T_{\text{inside comfort range}} - (G \cdot A \cdot \text{SHGC} + Q'_{\text{internal gains}}) / (\Sigma UA + \text{ACH} \times \text{volume} \times c \times \rho)$$

- ❑ To calculate the different heat flows usually averaged over 24 hours to cancel out thermal mass effects.
- ❑ The tighter and better insulated a building envelope is, the lower becomes the balance point temperature.
- ❑ High solar and internal gains lower the balance point.
- ❑ A low balance point is desirable during the heating season and may become a liability during the cooling season.

Example – DOE Small Office Building

$$T_{\text{Balance point}} = T_{\text{inside comfort range}} - (G \cdot A \cdot \text{SHGC} + Q'_{\text{internal gains}}) / (\Sigma UA + \text{ACH} \times \text{volume} \times c \times \rho)$$

$$\Sigma UA_{\text{Envelope}} = 11.6 \text{ kW/K}$$

$$\text{ACH} \times \text{volume} \times c \times \rho = 0.2 \text{ kW/K}$$

$$Q_{\text{internal gains}} = 14.1 \text{ W/m}^2 \times 511 \text{ m}^2 = 7.2 \text{ kW}$$

$$G \cdot A \cdot \text{SHGC} = 3.9 \text{ W/m}^2 \times 511 \text{ m}^2 = 2.0 \text{ kW}$$

$$T_{\text{Balance point}} = T_{\text{inside comfort range}} - 2\text{kW} + 7.2\text{kW} / (11.6\text{kW/K} + 0.2\text{kW/K})$$

$$= T_{\text{inside comfort range}} - 1.5\text{K}$$

Heating Degree Days (HDD)

- ❑ The number of heating degrees in a day is defined as the difference between a reference value of 65° F (18° C) and the average outside temperature for that day.
- ❑ Rule of thumb: If a site has
 - ❑ >5000 °F HDD (~2800 °C HDD): long cold winters
 - ❑ <2000 °F HDD (~1100 °C HDD): mild winters
- ❑ A fixed base temperature of 18° C allows us to compare different climates. However, 18° C is not representative for all buildings. For the New England Home the lower balance point level is 8° C.

Heating and Cooling Degree Hours Boston

Monthly Heating and Cooling Degree Hours

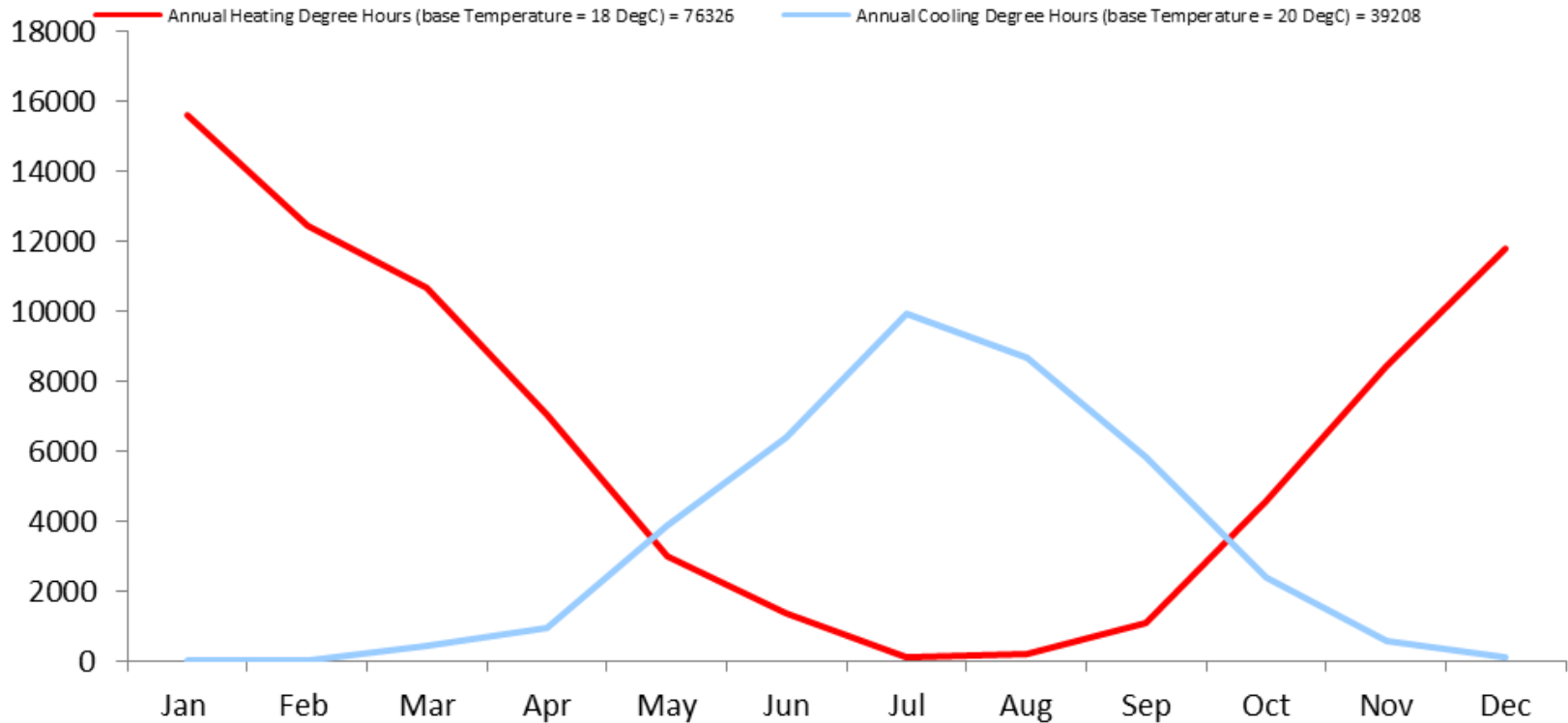


Figure generated using the Climate File Analyzer (Excel spreadsheet) http://web.mit.edu/sustainablelab/teaching_resources.html

For a base temperature of 18° C Boston has 76326 heating degree hours.

Heating Load Calculation

The heating degree days with respect to the balance point of a building indicate how much energy is needed to keep the buildings at the balance point over the course of a year.

$$\text{Heating load} = \text{HDD}_{\text{Balance point}} \times (\Sigma UA + Q_{\text{infiltration}})$$

$$\begin{aligned}\text{Heating load}_{\text{Feb}} &= 76326 \text{ Kh} \times (11.6 \text{ kW/K} + 0.2 \text{ kW/K}) \\ &= 900,647 \text{ kWh}\end{aligned}$$

Assuming a heating efficiency of 90% and a gas price of \$0.035/kWh, the annual heating costs are:

$$\text{Heating costs}_b = \$0.035/\text{kWh} \times 900,647 \text{ kWh} / 0.9 \sim \$35,000$$

Cooling Degree Days (CDD)

- ❑ The number of cooling degrees in a day is defined as the difference between a reference value of 65° F (20° C) and the average outside temperature for that day.
- ❑ Rule of thumb: If a site has
 - ❑ >1500 °F CDD (~800 °C CDD): long hot summers
 - ❑ < 500 °F CDD (~ 300 °C CDD): mild summers

Energy Modeling

What is a building thermal simulation?

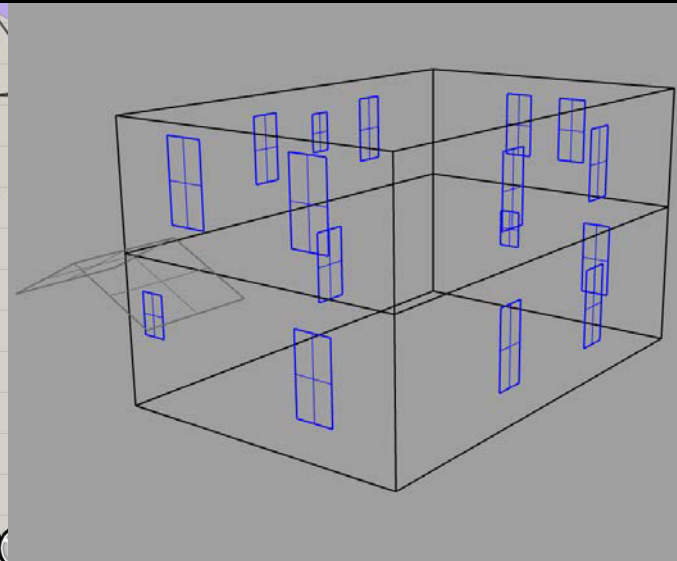
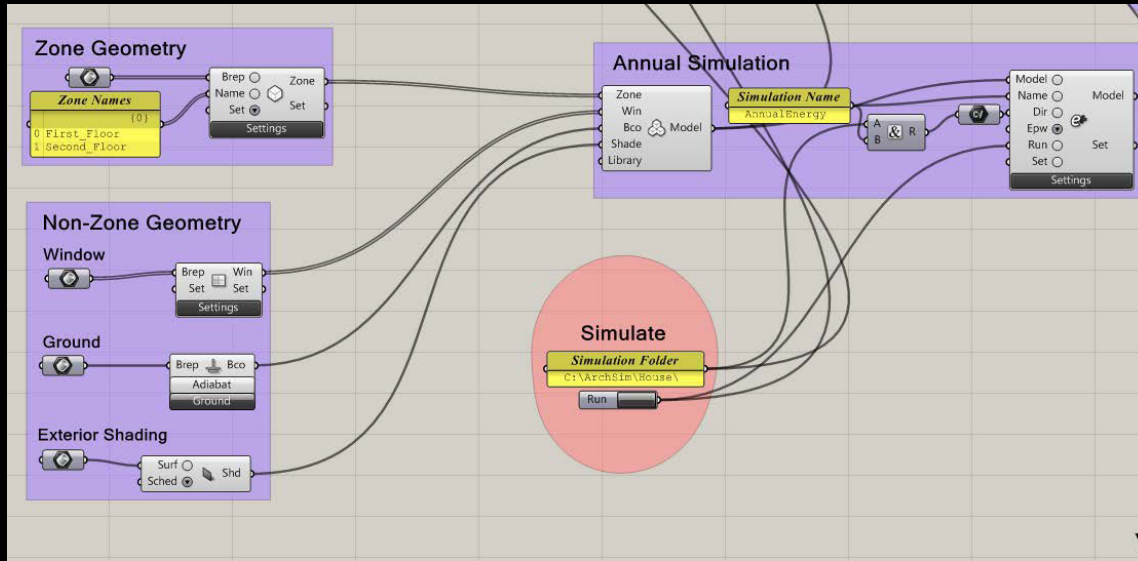
- Approximate definition: a computer model of the energy processes within a building that are intended to provide a thermally comfortable environment for the occupants (or contents) of a building.

What are the goals of a building thermal simulation?

- Load Calculations: Generally used for determining sizing of equipment such as fans, chillers, boilers, etc.
- Energy Analysis: Helps evaluate the energy cost of the building over longer periods of time.

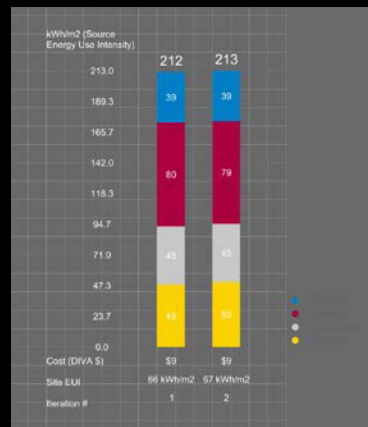
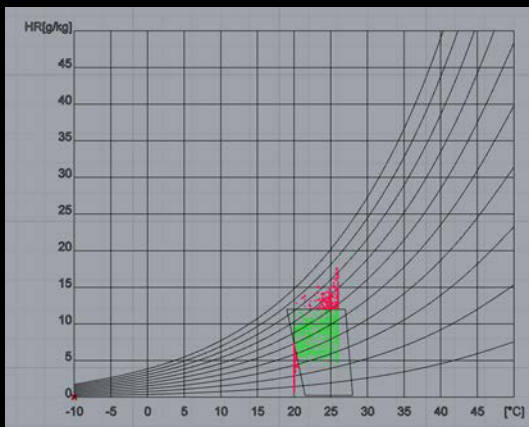
What does one need for a BPS?

Elements needed for BPS are a **building model**, a **simulation program (GUI & engine)** and a **suitable metric** that is able to measure the performance in question.



GUI/Engine

Model



Simulation Engine vs. GUI

Most building energy simulation programs come with a graphical user interface (GUI) as well as the actual simulation engine. The former is used to prepare simulation input files for the latter and to display simulation results once a simulation is complete.

While the choice of GUI determines the ease of use of a simulation program, it is ultimately the engine that determines how reliable simulation results are.

A great GUI with a weak engine cannot yield reliable results!

History of Energy Modeling Tools

- ❑ BLAST at US-DOD, DOE2 at US-DOE, TRNSYS at University of Wisconsin and ESP at Strathclyde University
- ❑ 2001: DOE2 and BLAST merged into **EnergyPlus** (E+)
- ❑ Today:
 - several interfaces for DOE2: eQuest, Green Building Studio
 - several interfaces for EnergyPlus: DesignBuilder, Open Studio
 - several commercial interfaces for TRNSYS
 - IDA-ICE is gaining increased recognition in Europe
 - IES/VE uses proprietary APACHE engine
 - Spawn of EnergyPlus: Modelica, equation based simulation environments

Reasons for using E+: ASHRAE 140

Purpose of the standard:

- ❑ Analyzing and diagnosing building energy simulation software using software-to-software and software-to-analytical-solution comparisons.
- ❑ Checking a program against a previous version of itself after internal code modifications such as an algorithmic change.

Uncle Sam thinks so, too.

Tax Deduction Information

Under IRS rules, taxpayers' building energy use performance must be calculated using software that has been tested according to ANSI/ASHRAE Standard 140 to qualify for tax deductions.

EnergyPlus continued...

- EnergyPlus is freely available for download. The program comes with ample documentations but without a GUI. EnergyPlus's capabilities are constantly being further expanded so that more recent modules might not be accessible through any GUI. As a result advanced users often start editing their models manually using a text editor. **Once any manual changes have been made to a model one usually cannot go back to the GUI.**
- Expert users can get access to the source code allowing for third-party validation which adds to the software's credibility and long term reliability.

Example EnergyPlus Interfaces

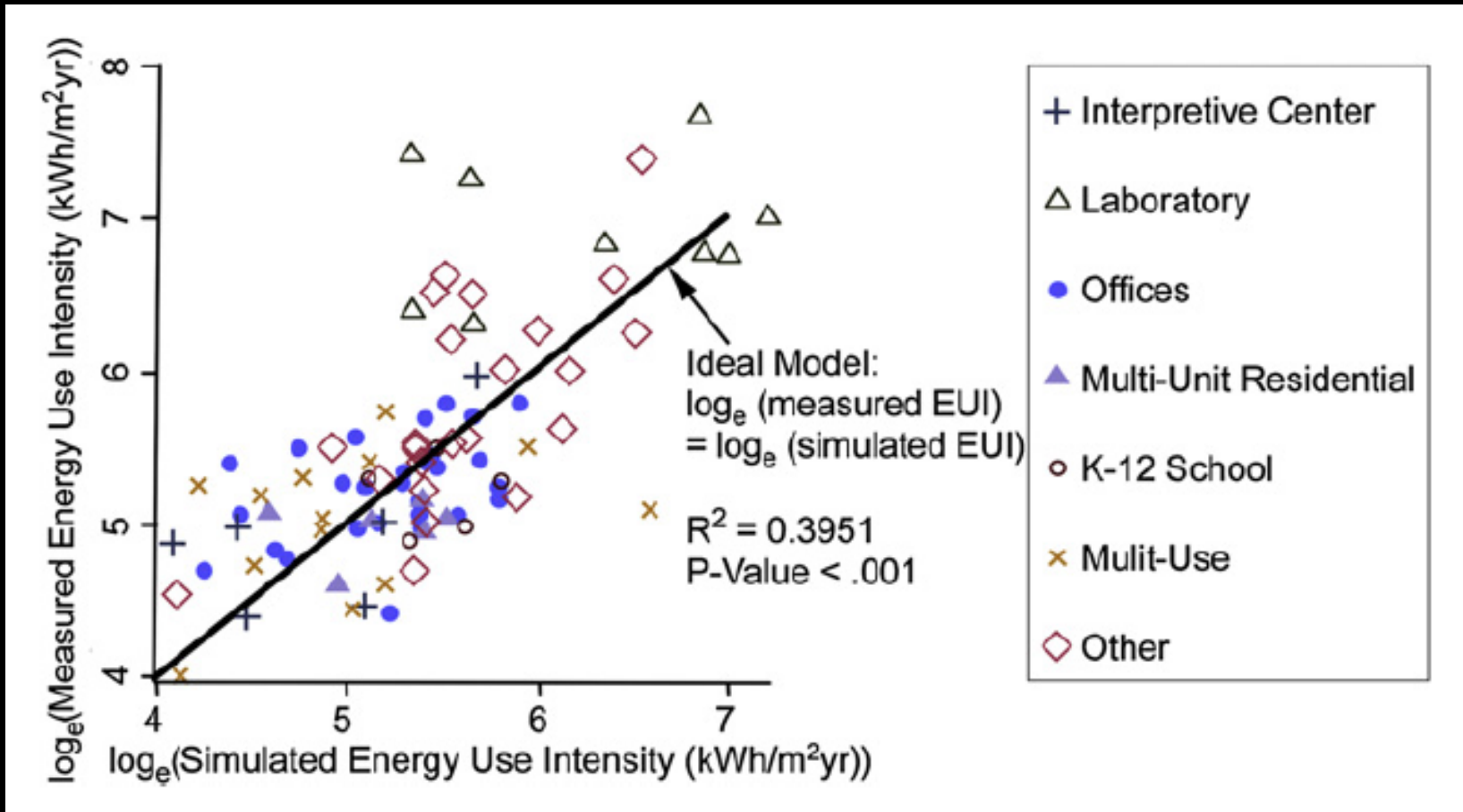
- ❑ New generation of design tools.
- ❑ Remaining question: How can designers effectively use them?

- [Diva for Rhino](#)
- [DesignBuilder](#)
- [Ladybug & Honeybee](#)
- [Urban Modeling Interface](#)

How accurate are design phase building energy models?

Comparison of measured and simulated energy use for 97 LEED Buildings

Courtesy of Elsevier, Inc., <https://www.sciencedirect.com>. Used with permission.



Model uncertainty from weather, infiltration rate, usage schedule and occupant behavior.

Paper

H W Samuelson, A Lantz and C F Reinhart, "Non-technical barriers to energy model sharing and reuse," *Building and Environment*, 54, pp. 71-76, 2012.

“Design” Model vs. “Calibrated” Model

- ❑ During the design process of a building exact numbers for the big uglies are necessarily not available. Energy models generated at that point are called **design models**.
- ❑ A design model can later be calibrated to the actual building based on measurements and surveys, at which point it becomes a **calibrated model**.

The 'Four Uglies'

The "Four Uglies" are the big unknowns in energy modeling: occupancy, plug-loads, weather, and infiltration. In 2011 the Boston chapter of the International Building Performance Simulation Association (IBPSA) organized three events related to the big uglies.

But models can be calibrated:

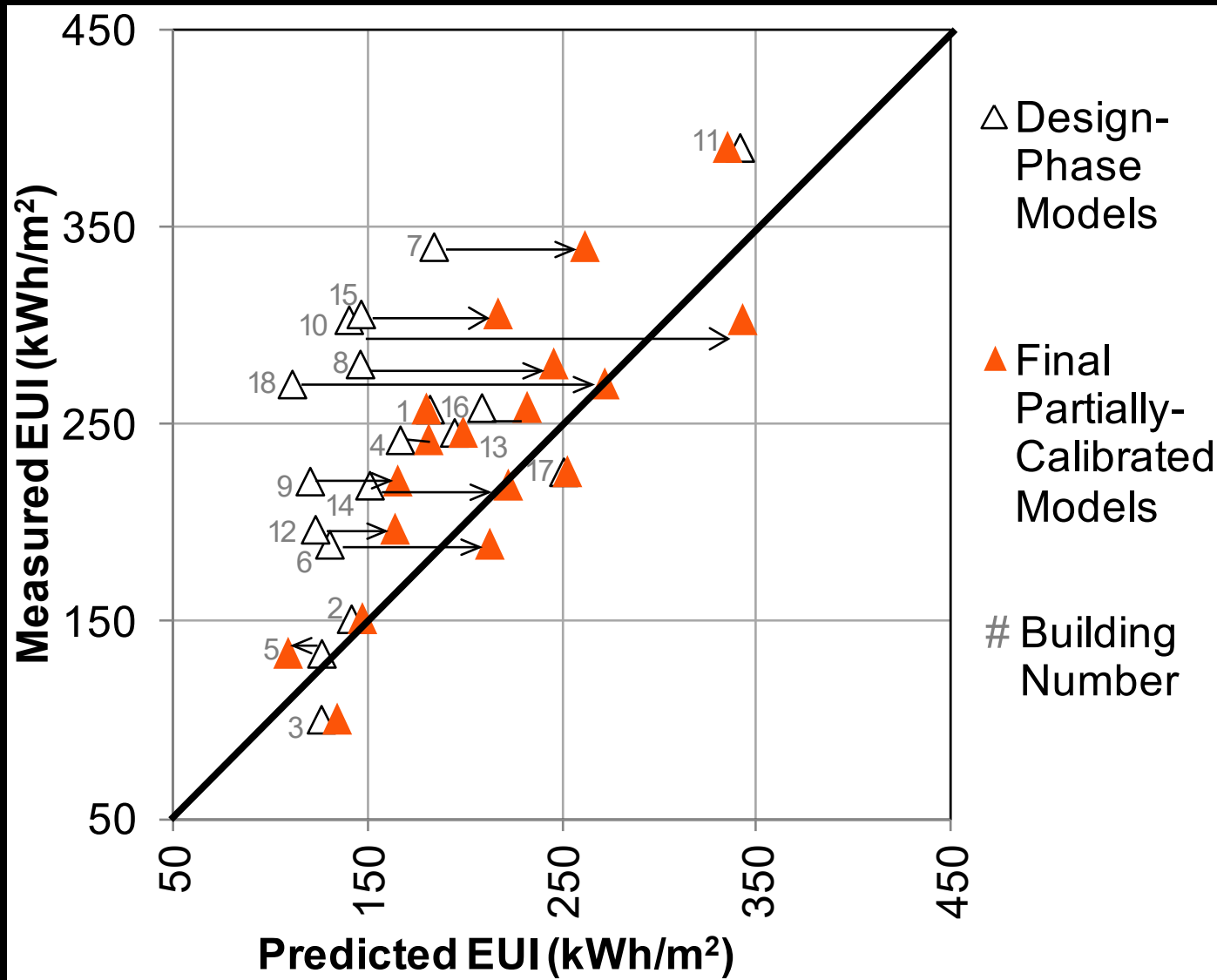


Figure courtesy of H W Samuelson, A Ghorayshib & C F Reinhart. Used with permission.

Paper: H W Samuelson, A Ghorayshib & C F Reinhart, 2015, "Analysis of a Simplified Building Energy Model Calibration Procedure for 18 Real-World Case Studies," *Journal of Building Performance Simulation*, published online January 2015.

So the tools work, but...

...you have to make sure that

- ❑ the tool that you use has been **validated**, that
- ❑ **you know how to use** it properly, and that
- ❑ you are using **meaningful performance metrics**.

*Should designers learn how to conduct a
energy model?*

"The energy model and focus on energy performance is not meant to supplant the importance of design. Rather, a building energy model is a tool that can be utilized throughout the design process to test various design options and optimize the performance of all building typologies."

-AIA, "An Architect's Guide to Integrating Energy Modeling in the Design Process"

"...to position architects as collaborative leaders at higher thresholds of building performance.."

Jeff Potter, 2012 AIA president

URL: <http://content.aia.org/sites/default/files/2016-04/Energy-Modeling-Design-Process-Guide.pdf>

Simulation Game

Is Solar Design a Straitjacket for Architecture?



Image courtesy of Tiffany Otis. Used with permission.

Paper: T Otis, "Is Solar Design a Straitjacket for Architecture?" Conference Proceedings of the 27th International conference on Passive and Low Energy Architecture (PLEA), Louvain-la-Neuve, Belgium, July 2011.

- ❑ Posed a design problem to two student groups only one of which (Group B) was trained to use the site specific solar design tools.
- ❑ The models were evaluated based on their adherence to solar criteria and geometrical diversity.
- ❑ Group B models showed a lower proportion of solar design deficiencies while demonstrating more geometrical creativity, suggesting that the use of more precise solar design tools actually helps to broaden the range of architectural form.

Hypothesis for the Simulation Game

Being able to read thermal simulation results and to adapt one's design accordingly has become an essential skill for graduating and practicing architects.

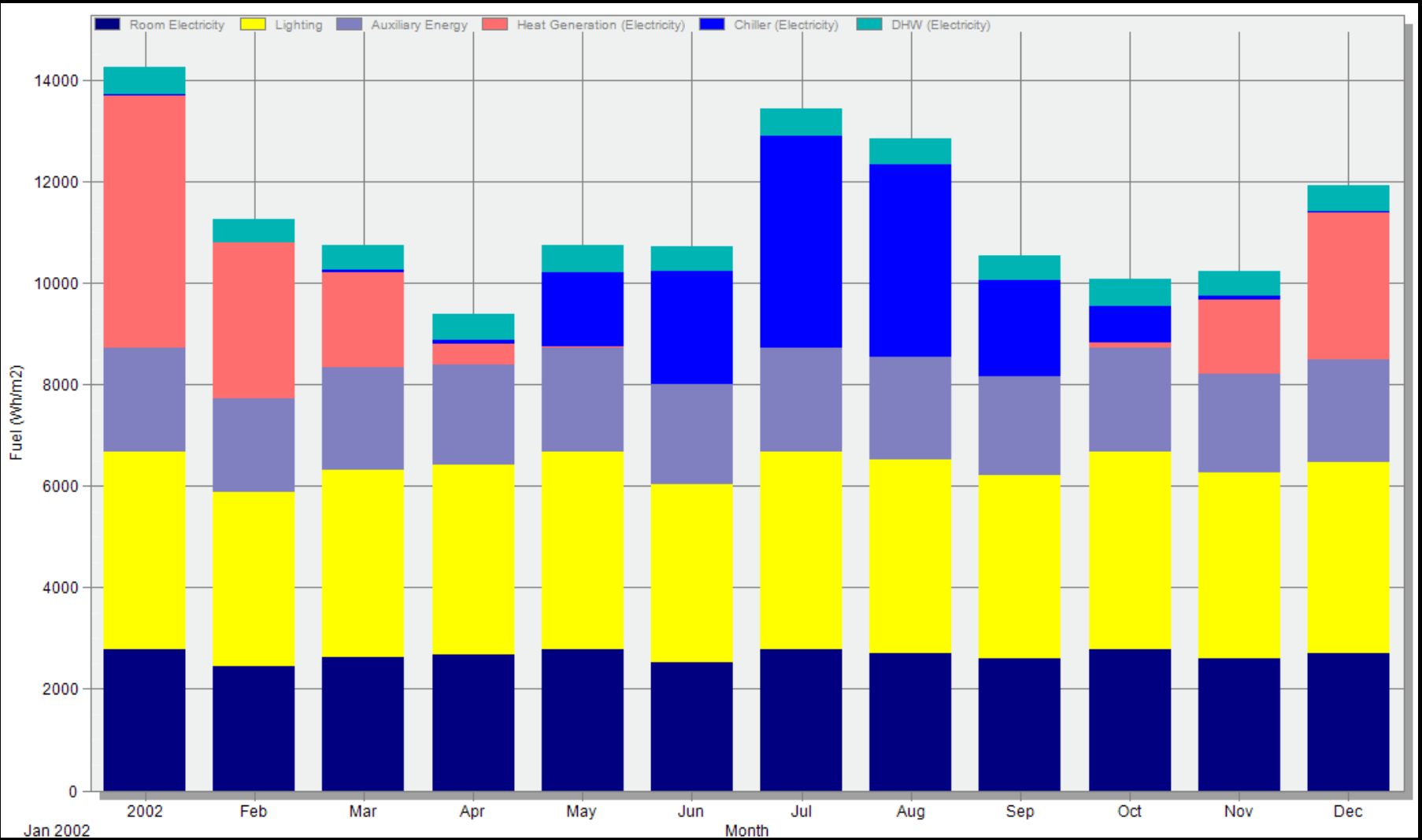
Why?

The alternatives for architects are to effectively ignore simulation output or to have the modeler take over key design aspects of the building. (Both alternatives are undesirable for architects.)

Note:

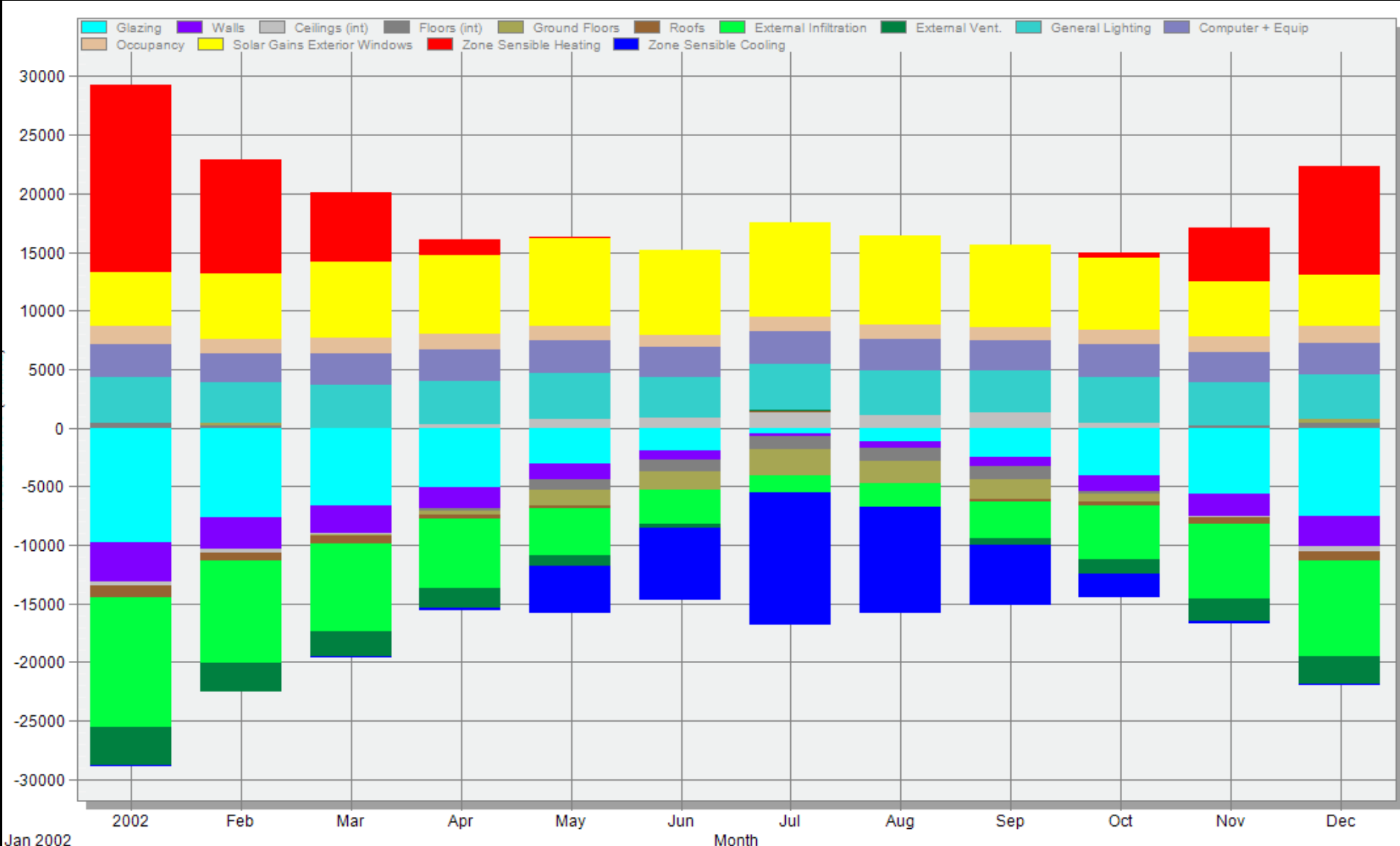
Engineers, this does not mean that the architects know how to do the simulations themselves.

Design analysis – Monthly system loads



❑ How could you improve your design?

Design analysis – Monthly heat balances



How could you improve your design?

2011, The Original Game ...

Paper: C F Reinhart, T Dogan, D Ibarra, and H W Samuelson, "Learning by playing - Teaching energy simulation as a game," *Journal of Building Performance Simulation*, October 2011.

Simulation Order Form

FINAL

SIMULATION ORDER FORM

Team Number: 2
 Variant Number/Name: 5
 Email Address: _____

1. Massing Circle one:

1 2 3 4 5 6 7 8 9 10 11

2. Orientation Circle One:

0 45 90 135 180 225 270 315

3. Purchasing Upgrades Circle your choice in each category below:

| ROOF INSULATION | | | | |
|-------------------------------------|---------------|-----------------------|---------------|----------|
| Description | | | | Cost |
| <input checked="" type="checkbox"/> | Base Building | Continuous Insulation | R-Factor: R20 | 0 |
| <input type="checkbox"/> | | Continuous Insulation | R-Factor: R30 | \$ |
| <input type="checkbox"/> | | Continuous Insulation | R-Factor: R40 | \$\$ |
| <input type="checkbox"/> | | Continuous Insulation | R-Factor: R60 | \$\$\$\$ |

| EXTERIOR WALL INSULATION | | | | |
|-------------------------------------|---------------|-----------------------|-----------------|------|
| Description | | | | Cost |
| <input type="checkbox"/> | Base Building | Continuous Insulation | R-Factor: R11.4 | 0 |
| <input type="checkbox"/> | | Continuous Insulation | R-Factor: R19.5 | \$ |
| <input checked="" type="checkbox"/> | | Continuous Insulation | R-Factor: R28.5 | \$\$ |

| WINDOW-TO-WALL-RATIO (WWR) | | | | |
|-------------------------------------|---------------|--|-----|------------|
| Description | | | | Cost |
| <input checked="" type="checkbox"/> | | Storefront or punched opening construction | 20% | -\$ |
| <input type="checkbox"/> | Base Building | Storefront or punched opening construction | 40% | 0 |
| <input type="checkbox"/> | | Storefront or punched opening construction | 60% | \$\$ |
| <input type="checkbox"/> | | Curtainwall construction | 80% | \$\$\$\$\$ |

| WINDOW GLASS TYPE | | | | |
|---|------------------------|-------------|-------------|--------|
| Description | | | | Cost |
| Code Compliant Double-Pane Argon-Filled | U-Factor = 3.12 (0.55) | SHGC= 0.577 | VLT = 0.700 | 0 |
| Double-Pane Low-e2 Coating | U-Factor = 2.00 | SHGC= 0.626 | VLT = 0.747 | \$\$\$ |

| | | | | |
|---|-------------------------|-------------|-------------|----------|
| (hard coat) Air-Filled | (0.35) | | | |
| Double-Pane Low-e3 (spectrally selective) Coating on Surface-3 Argon-Filled | U-Factor = 2.50 (0.235) | SHGC= 0.378 | VLT = 0.648 | \$\$\$\$ |
| Double-Pane Low-e3 (spectrally selective) Coating on Surface-2 Argon-Filled | U-Factor = 2.50 (0.235) | SHGC= 0.273 | VLT = 0.648 | \$\$\$\$ |

| EXTERIOR SHADING* | | | |
|-------------------------------------|---------------|---|--------------------|
| Description | | | Cost |
| <input checked="" type="checkbox"/> | Base Building | None | 0 |
| <input type="checkbox"/> | | 0.5m (1.64 ft) deep horizontal overhang | All facades \$ |
| <input type="checkbox"/> | | 1m (3.3 ft) deep horizontal overhang | All facades \$\$\$ |

*Note: Simulations including exterior shading will take longer to complete. Estimate: 5-7 rather than 2-4 minutes. For modeling simplicity, all facades are shaded.

| LIGHTING POWER DENSITY | | | | |
|-------------------------------------|---------------|--|----------------------------------|------|
| Description | | | | Cost |
| <input type="checkbox"/> | Base Building | 12 W/m ² during business hours | 5% LPD during non-business hours | 0 |
| <input checked="" type="checkbox"/> | | 9.0 W/m ² during business hours | 5% LPD during non-business hours | \$ |

| DAYLIGHT SENSORS* | | | |
|-------------------------------------|---------------|---|------|
| Description | | | Cost |
| <input type="checkbox"/> | Base Building | None | 0 |
| <input checked="" type="checkbox"/> | | Perimeter zones (0 - 4.5m from exterior wall) dim linearly down to complete shut-off (0% power) (target work plane illuminance 300 lux) | \$ |

*Note: Simulations including daylight sensors will take longer to complete. Estimate: 5-7 rather than 2-4 minutes.

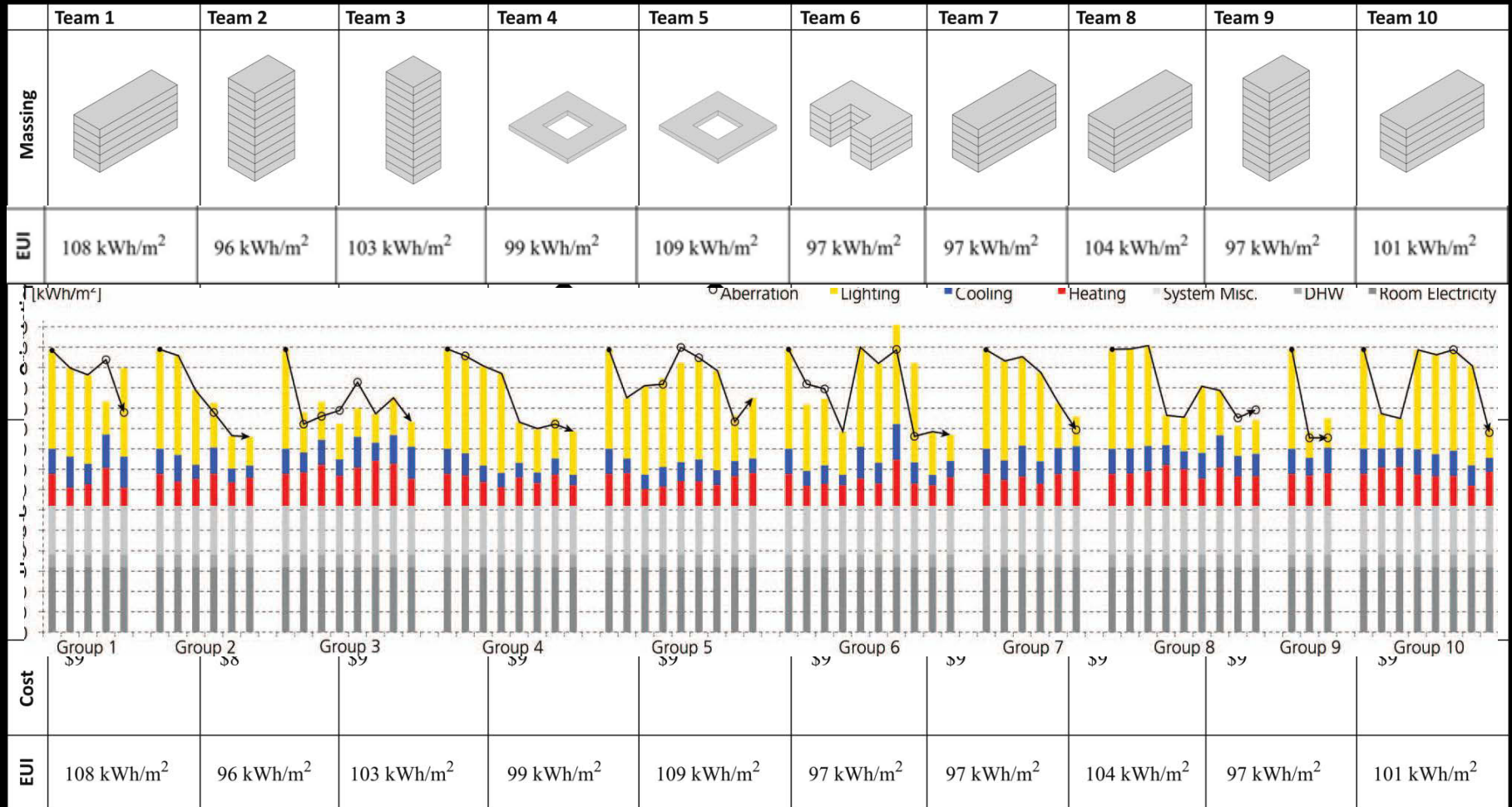
| OCCUPANT SENSORS | | | |
|-------------------------------------|---------------|--|------|
| Description | | | Cost |
| <input type="checkbox"/> | Base Building | None | 0 |
| <input checked="" type="checkbox"/> | | Reduces Lighting Power Density by 10% during all occupied hours. | \$ |

4. Total Cost: \$ 8
 5. Total EUI (to be completed by modeler): 95.67 kWh/m²

Provided by Modeler

Final Designs

This image is from C F Reinhart, T Dogan, D Ibarra, and H W Samuelson, "Learning by playing - Teaching energy simulation as a game," *Journal of Building Performance Simulation*, October 2011. <https://doi.org/10.1080/19401493.2011.619668>. This journal is available online at <https://www.tandfonline.com/doi/abs/10.1080/19401493.2011.619668>.



Final designs differed significantly, revealing that a performance-based design does not necessarily lead to converging architectural solutions.

"Today building science was definitely not boring."

Where do we want to be?

From evaluating performance to suggesting new forms

Energy Game 2014

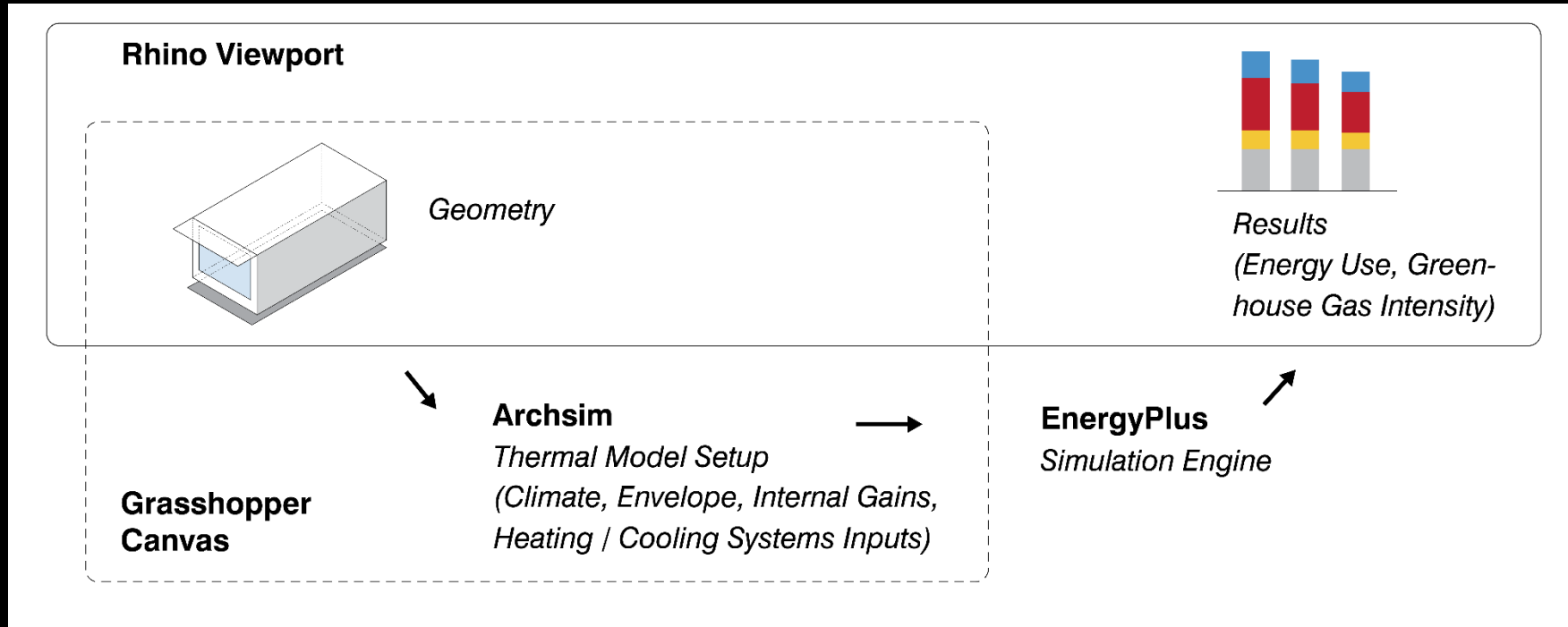


Figure courtesy of C. F. Reinhart, J., T. Dogan and E. Saratsis. Used with permission.

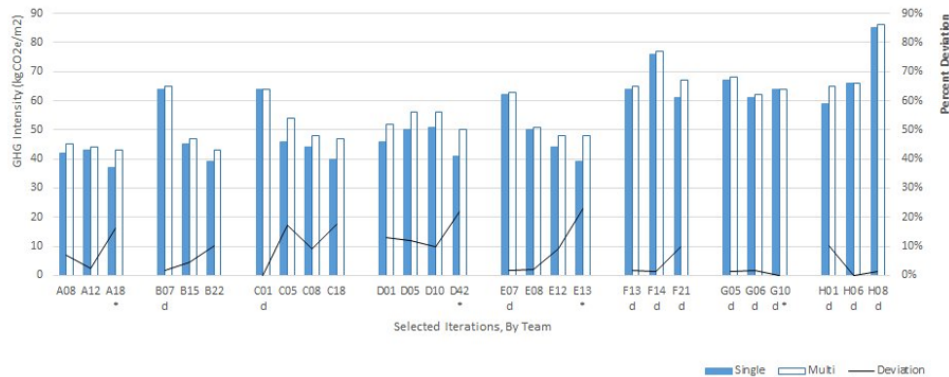
- You will be running the simulations yourselves in Rhino/Grasshopper/ArchSim.
- Full build-in cost analysis.

Energy Game 2014

Figure courtesy of C. F. Reinhart, J., T. Dogan and E. Saratsis. Used with permission.

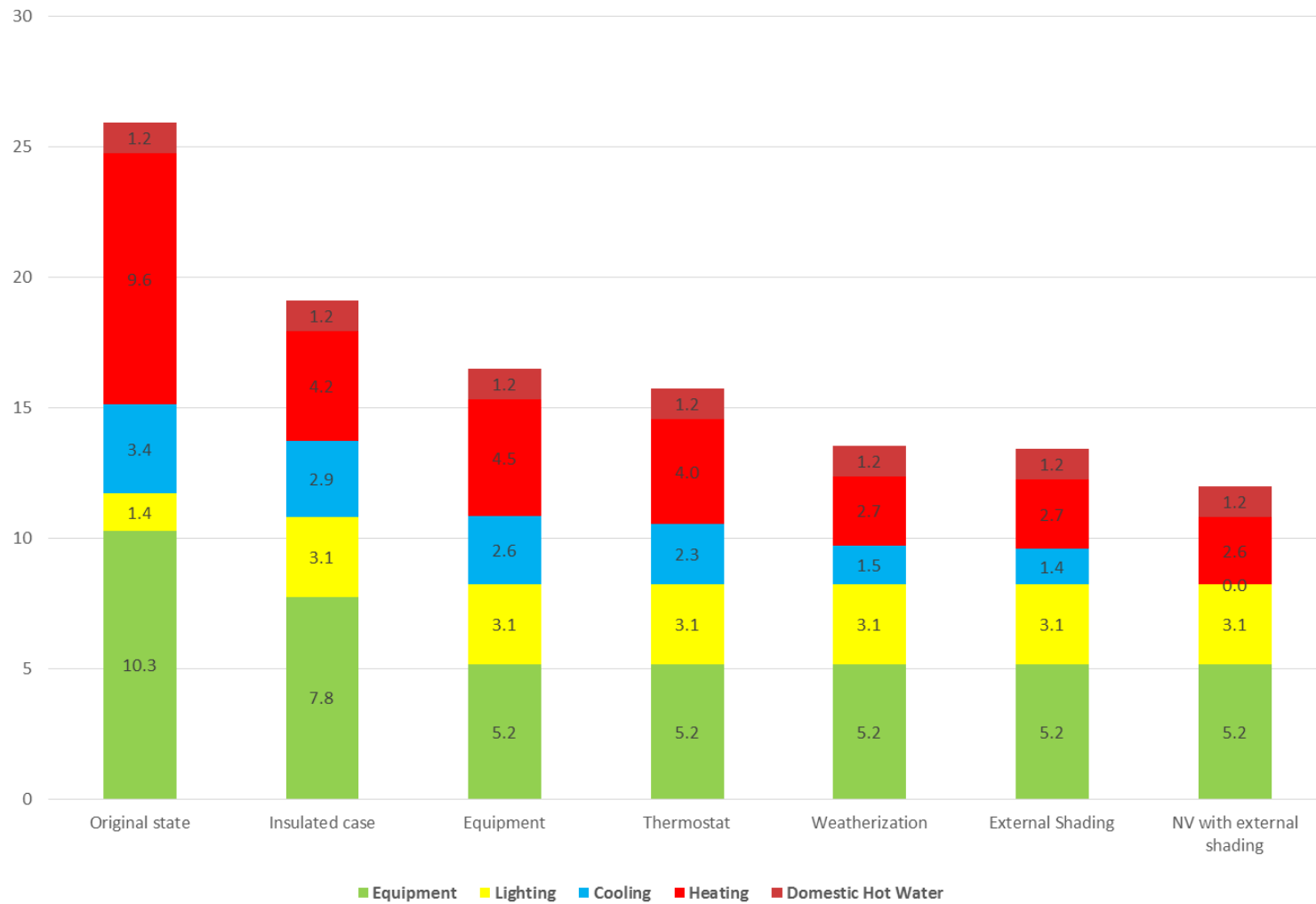
Table 3 Final design submissions for Exercise 7 (Simulation Game)

| | Team A | Team B | Team C | Team D | Team E | Team F | Team G | Team H |
|--------------------|--|--|--|--|--|--|--|---|
| Massing | | | | | | | | |
| Orientation | | | | | | | | |
| Upgrades | Roof R20 Wall R13 WWR=20% Lowε2 Ar low SHGC Occupancy Dimming Low LPD GSHP | Roof R20 Wall R28.5 WWR=20% Lowε2 Ar low SHGC Occupancy Dimming Low LPD GSHP | Roof R30 Wall R13 WWR=40% Lowε2 Ar low SHGC Occupancy Dimming Low LPD GSHP | Roof R30 Wall R28.5 WWR=40% Ar 2m Shading Occupancy Dimming Low LPD GSHP | Roof R20 Wall R13 WWR=20% Lowε2 Ar 1.5m Shading Dimming Low LPD GSHP | Roof R40 Wall R13 WWR=20% Lowε2 Ar .5m Shading | Roof R30 Wall R28.5 WWR=20% Lowε2 Ar low SHGC 1.5m Shading | Roof R30 Wall R28.5 WWR=20% -Lowε2 Ar low SHGC 1.5m Shading |
| Cost | \$46 | \$60 | \$45 | \$48 | \$44 | \$35 | \$43 | \$9 |
| GHG | 37 kgCO ₂ e/m ² | 39 kgCO ₂ e/m ² | 40 kgCO ₂ e/m ² | 41 kgCO ₂ e/m ² | 39 kgCO ₂ e/m ² | 59 kgCO ₂ e/m ² | 64 kgCO ₂ e/m ² | 59 kgCO ₂ e/m ² |

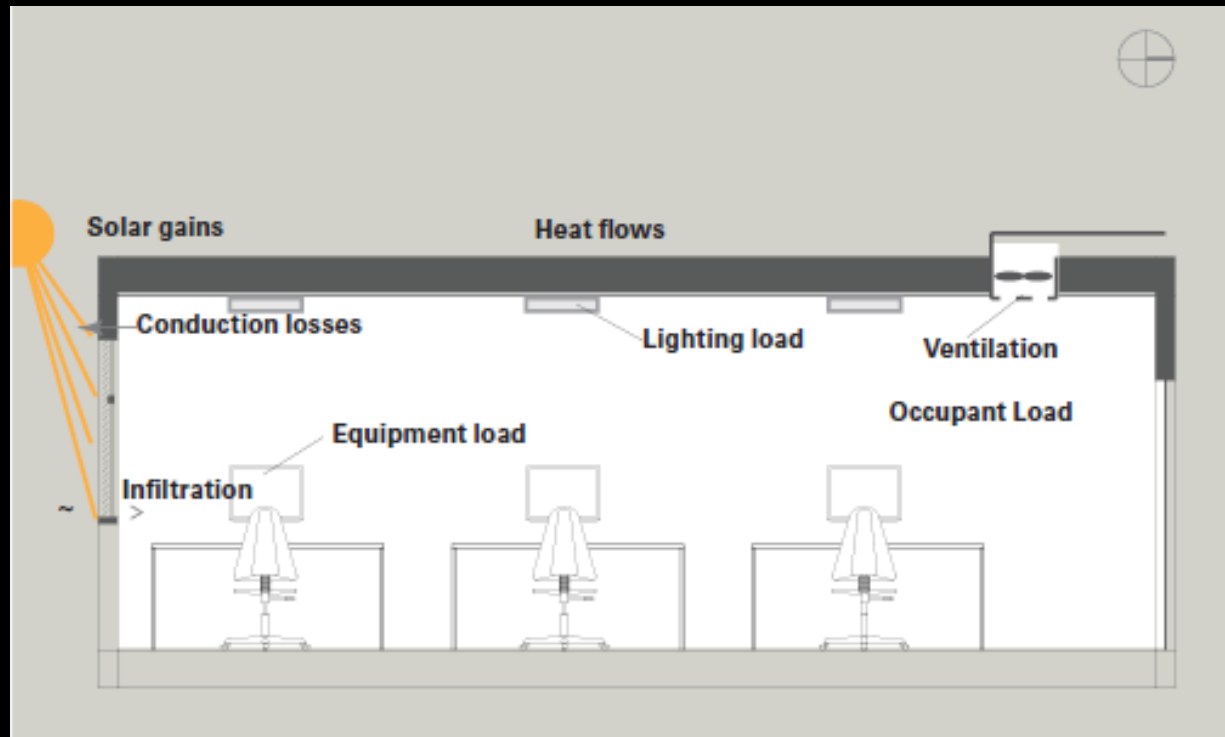


Dynamic Shading in DIVA4/Archsim

Annual Energy Use For New England Home[\$/m²yr]



Balance Point for an Office



| | Balance point range [°C] | |
|---------|--------------------------|------|
| | December | June |
| Boston | 8–14 | 8–14 |
| Phoenix | 7–13 | 8–14 |
| Seattle | 9–15 | 8–14 |

Fig 7.6 Balance point ranges for the reference office in different climates

Questions?

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4.401/4.464 Environmental Technologies in Buildings Fall 2018

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