CAE 463/524
Building Enclosure Design
Spring 2015

Lecture 11: April 7, 2015
Thermal mass modeling
Finish energy simulation and enclosure design

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Scheduling

- Take home exam graded and returned today (most of them)

- HW #4 was assigned last week
  - eQUEST modeling of energy impacts of enclosures on a commercial building

- Updated schedule:

13	Apr 7	Finish energy simulation and enclosure design • Thermal mass • BEopt and EnergyPlus (residential bldg.)		HW4 (Energy modeling)
14	Apr 14	Codes and standards		HW5 (Energy modeling)
15	Apr 21	*Guest lecture*		
16	Apr 28	Course wrap-up and future of enclosure research		
Final	May 5	No final scheduled		Final project report due

Final project topic selection

Name	Project topic
Behrens, Maria C.	Advanced insulation (aerogel/VIPs)
Geoghegan, Thomas	Double skin facades
Irazabal, Carlos H.	Cool roofs
Jung, Yun Joon	Passive solar + thermal mass
Lis, Kimberly A.	Enclosure commissioning
Ng, Yin Ling	Window design
Theisen, Whitney A.	
Carrillo Garcia, Jose	BIPV
Dorn, Lawrence E.	Electrochromic glass
Erukulla, Dilip Kumar	Phase change materials
Liang, Jinzhe	Double skin facades
Mullin, Elizabeth M.	Straw bale construction (or earthen materials)
Tuz, Oleg	BioSkin evaporative panel?
Chandler, Julie A.	Electrical and non electrical smart glass
Chung, Allan	Double skin facades
Fortune, Roger G.	Brooklyn Trust building
Gadani, Dhaval S.	Green walls
Jarosz, Michelle M.	Structural steel bridging
Linn, Rebecca C.	Bio-bricks

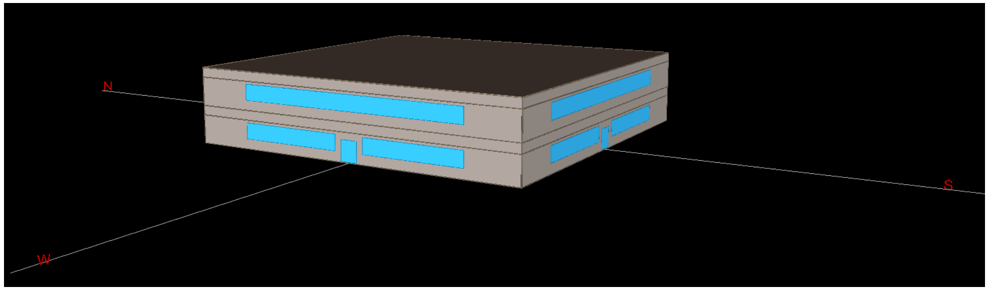
Last time

- Introduced energy simulation in building enclosure design
  - Introduced system of equations
  - Introduced eQUEST

- In HW4 you had to make changes to the enclosure and explore impacts on annual electricity, natural gas, and overall energy costs

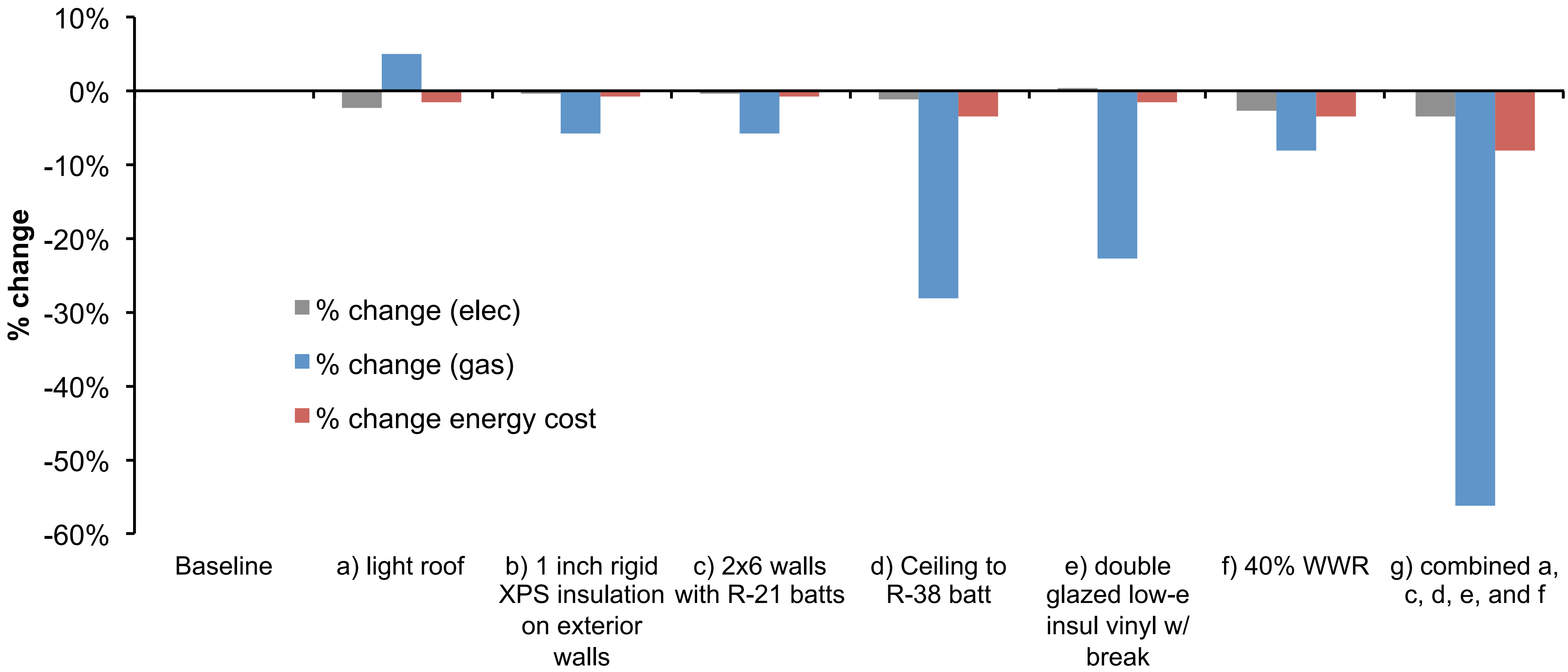
HW #4 eQUEST modeling

- eQUEST modeling of a commercial building
- 2 story office building in Chicago
  - 25,000 sq ft square
  - Baseline: dark uninsulated roof, metal frame with R-11 batts, concrete floors, 53% WWR with double pane clear windows ¼ thick ¼ air gap with no thermal breaks
  - Individual changes: light roof, 1 in R-7 rigid polyiso insulation on exterior walls, R-21 walls with R-4 rigid insulation, R-38 roof insulation with radiant barrier, improved windows to double low-e argon filled ½” gap with insulated spacers, and decreased WWR to 40%



HW #4 eQUEST modeling solutions

- Baseline results ~235,000 kWh electric and 454 MMBTU gas
  - About $31,000 in total energy costs annually



This time

- Thermal mass and thermal mass modeling
- Finish energy simulation in building enclosure design
  - BEopt for residential energy simulation
    - And as a utility for enclosure design
    - Assign HW 5

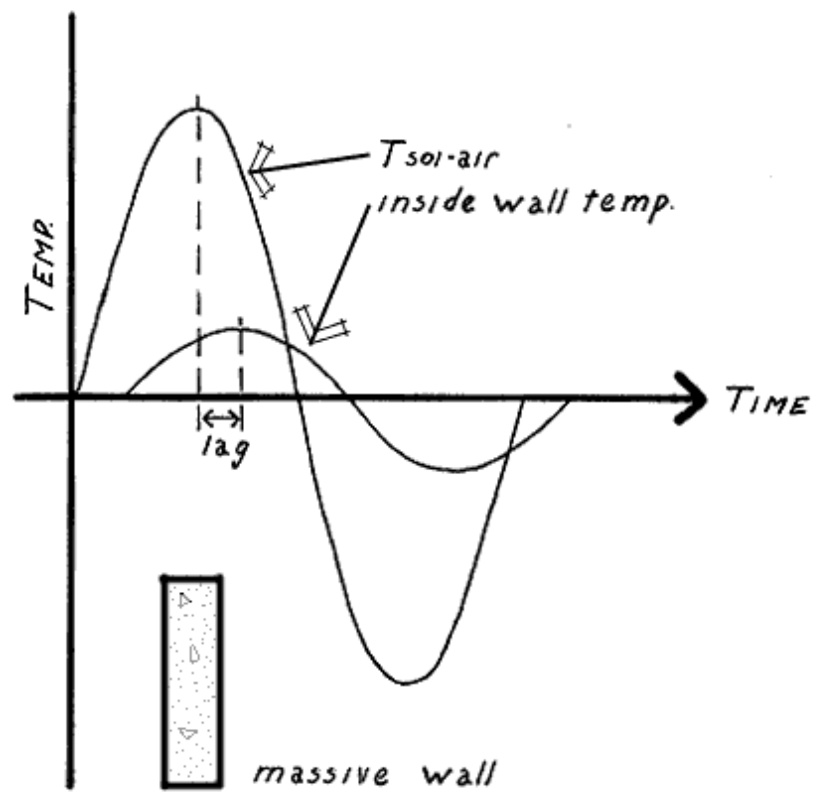
THERMAL MASS

Heat storage and release

Thermal mass

- Thermal mass refers to materials that have the capacity to store thermal energy for extended periods of time

- Thermal mass can absorb daytime heat gains
- Reduces peak cooling load
- Releases heat during the night (can reduce heat load or can extend cooling load)



Historical use of thermal mass

- Thermal mass is not a new idea
- The use of thermal mass in construction dates to the beginning of history
  - Stone caves are great examples of ancient thermal mass buildings
  - Mud-brick houses have been used for thousands of years by numerous civilizations in hot climates
    - Helps buffer harsh exterior conditions

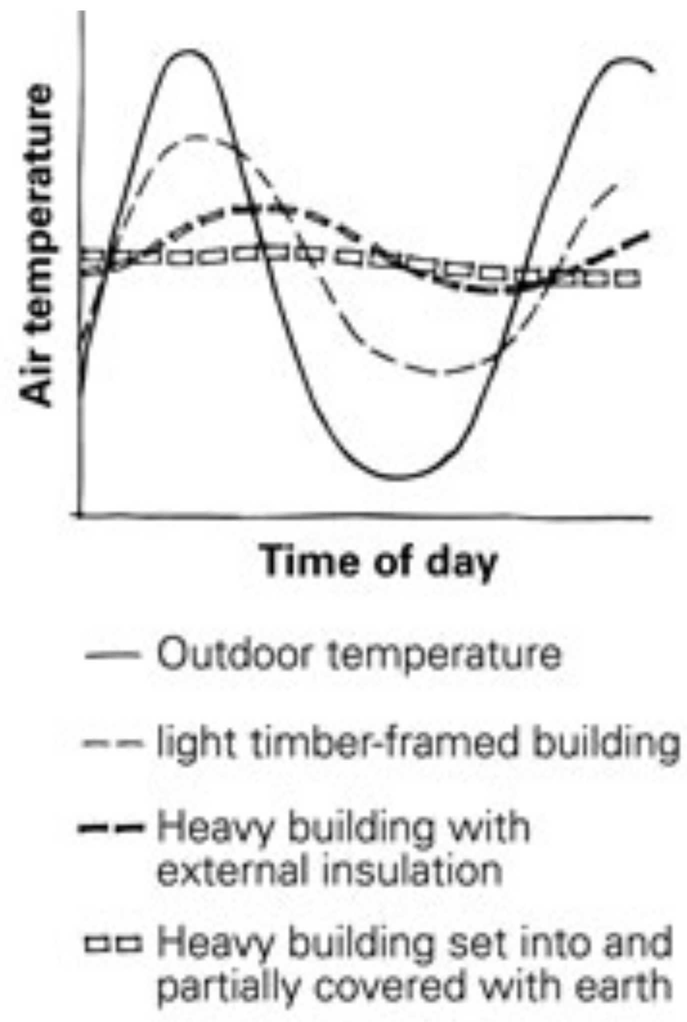
Types of thermal mass

- Traditionally, materials with high **thermal mass** have also had a high mass themselves:
  - Water, earth, stone, brick, cement, concrete, thick tiles
  - All these materials have high **densities** and high **specific heat capacities**

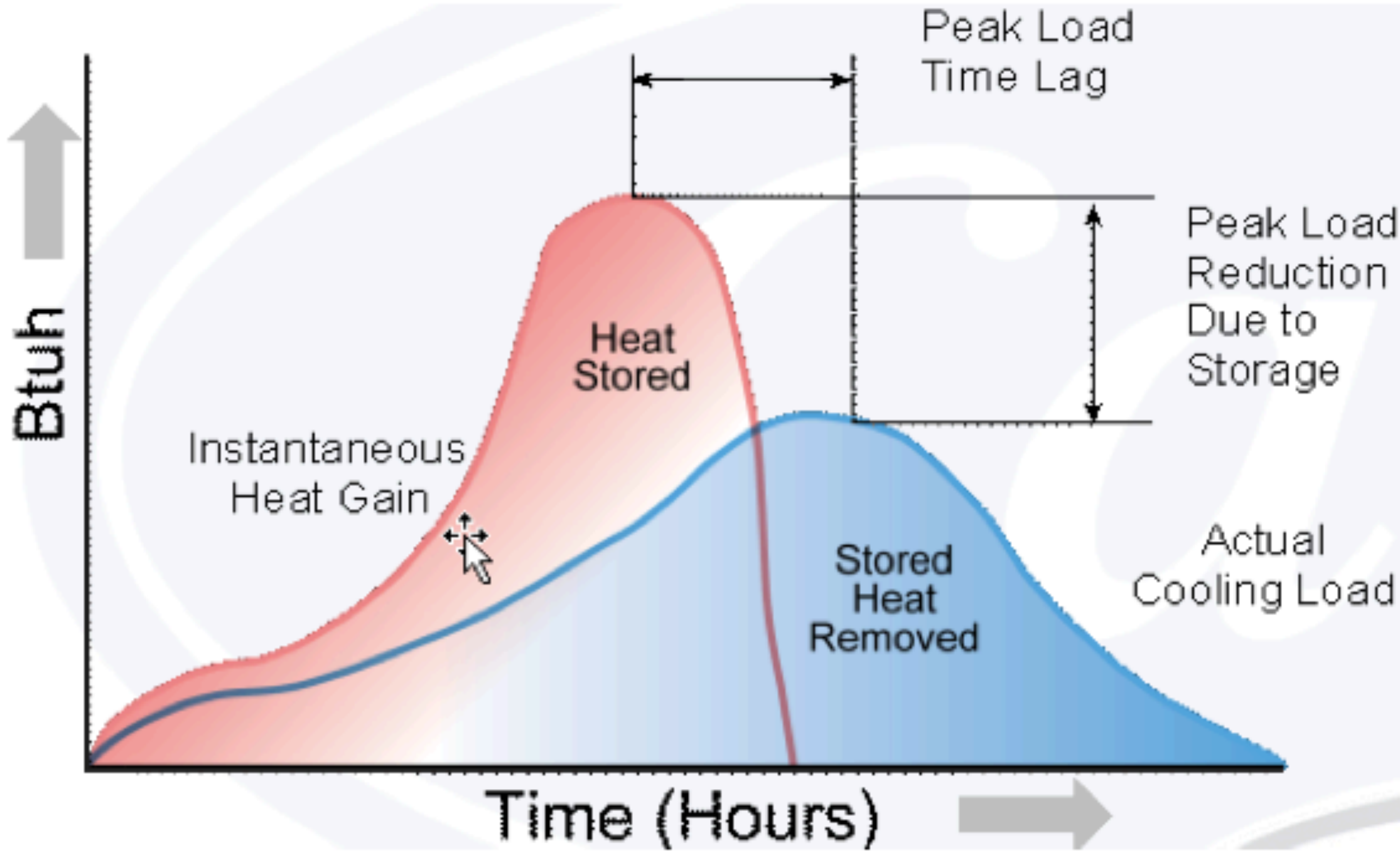
- More recently, phase change materials are being used:
  - Solid-liquid salts, paraffin wax, crystalline hydrocarbons
  - These are materials that melt at room temperature and can store/ release large amounts of latent heat with much lower mass than traditional materials

Thermal mass: Why do we care?

- All materials/constructions have some thermal mass
  - But constructions with a high thermal mass have large effects on the dynamic energy transfer in a building
  - Thermal mass can be both useful and detrimental to maintaining thermal comfort with changing heating and cooling loads
- A high thermal mass will be slow to heat up
  - But also slow to cool down
  - Can store large amounts of heat
- The result is that exterior temperatures can fluctuate greatly
  - But the interior temperature will fluctuate less



Cooling load calculations and thermal mass



What thermal mass is not

- Thermal mass is not the same as thermal insulation/thermal resistance
  - In fact, most materials with high thermal resistance have low thermal mass

- Some material in a construction needs to have a high heat capacity for the construction to have a high thermal mass

Heat Capacity, HC

- The **heat capacity** (HC) of a material is the product of the **density** of the material, the **specific** heat capacity, and the material **thickness**
  - HC = $\rho L C_p$ [J/m^{2}K]
  - HC is a measure of the ability of a material to store energy per unit area
  - L = length [m]
  - ρ = density [kg/m^3]
  - C_p = specific heat capacity [J/kgK]
  - You sometimes also see HC*A = ρLAC_p or ρVC_p [J/K]

- Heat capacity is important to thermal mass, but needs to be compared with **thermal conductivity** to get the whole story

Thermal Diffusivity, α

- Thermal diffusivity, α, is the measure of how fast heat can travel through an object
- α is proportional to conductivity but inversely proportional to density and specific heat:

$$\alpha = \frac{k}{\rho C_p} \quad [\mathrm{m^2/s}]$$

- The lower the α, the better the material is as a thermal mass (low conductivity relative to storage ability)
  - The time lag between peak internal and external temperature is related to the diffusivity of the walls
  - Steel has a high ρC_p but also a high k so it is not as good a thermal mass as concrete or masonry

Thermal properties

- All three material properties can be found in ASHRAE HOF chapter on thermal transmission data (Ch. 25 in 2005 HOF)
  - Thermal conductivity, density, and specific heat

Description	Density, kg/m³	Conductivity[b] (k), W/(m·K)	Conductance (C), W/(m²·K)	Resistance[c] (R) 1/k, (m·K)/W	Resistance[c] (R) For Thickness Listed (1/C), (m²·K)/W	Specific Heat, kJ/(kg·K)
Gypsum partition tile						
75 by 300 by 760 mm, solid	—	—	4.50	—	0.222	0.79
75 by 300 by 760 mm, 4 cells	—	—	4.20	—	0.238	—
100 by 300 by 760 mm, 3 cells	—	—	3.40	—	0.294	—
Concretes[o]						
Sand and gravel or stone aggregate concretes (concretes	2400	1.4-2.9	—	0.69-0.35	—	—
with more than 50% quartz or quartzite sand have	2240	1.3-2.6	—	0.77-0.39	—	0.8-1.0
conductivities in the higher end of the range)	2080	1.0-1.9	—	0.99-053	—	—
Limestone concretes	2240	1.60	—	0.62	—	—
	1920	1.14	—	0.88	—	—
	1600	0.79	—	1.26	—	—

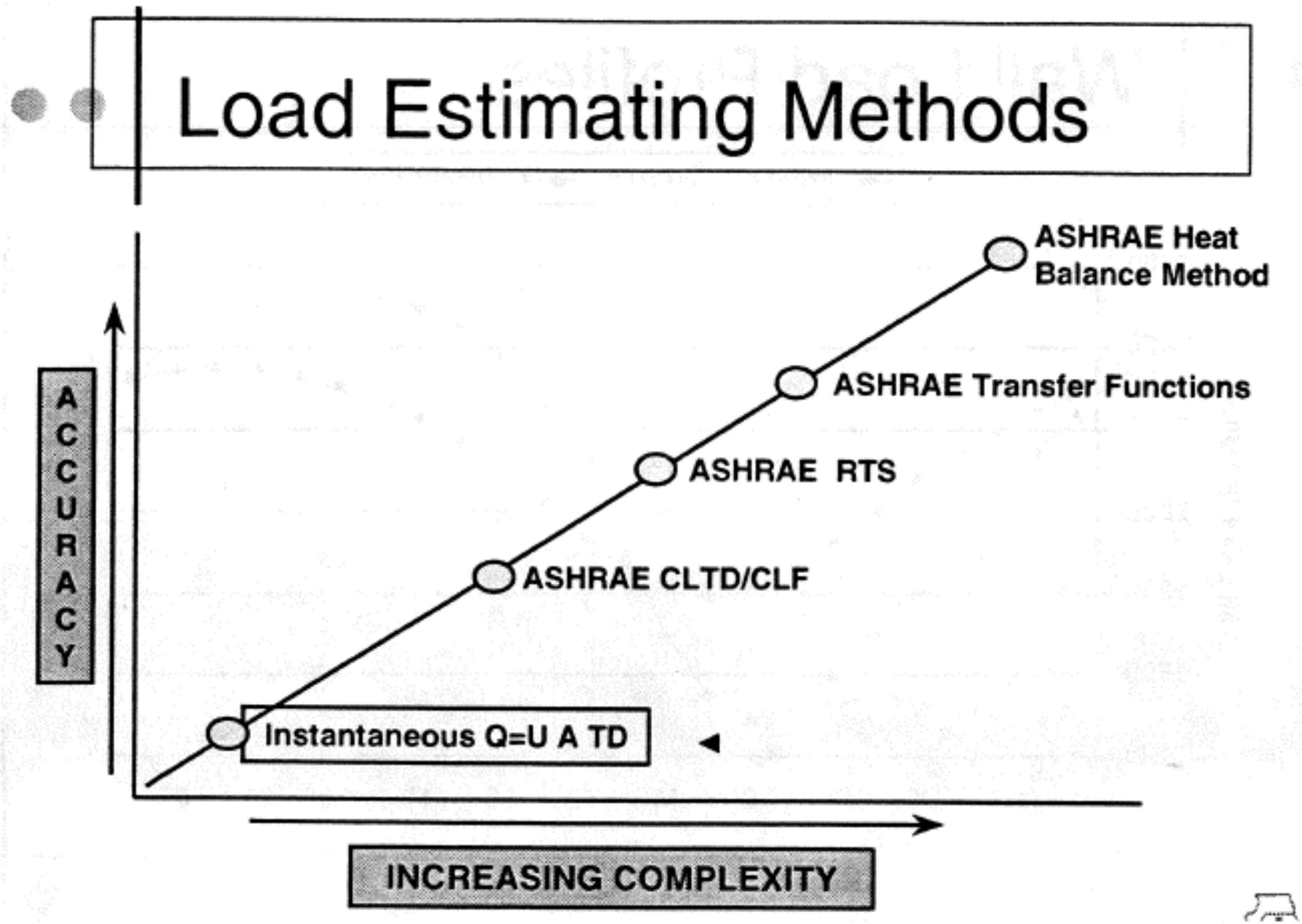
How do we model thermal mass

- Thermal mass can have a large impact on time-varying energy use and thus needs to be accounted for in energy simulation programs

- There are several ways to model thermal mass, with varying degrees of complexity and accuracy

- We briefly talked about some of these in CAE 331/513 Building Science (lectures on cooling load calculations)

Cooling load calculation methods vary in how they treat thermal mass

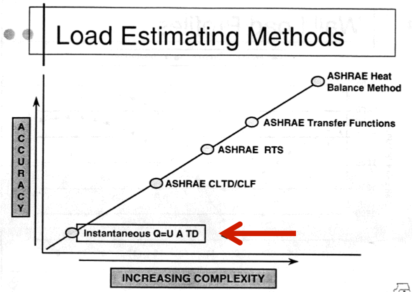


Instantaneous UA(dT) method

- The methods used for heat load calculations:

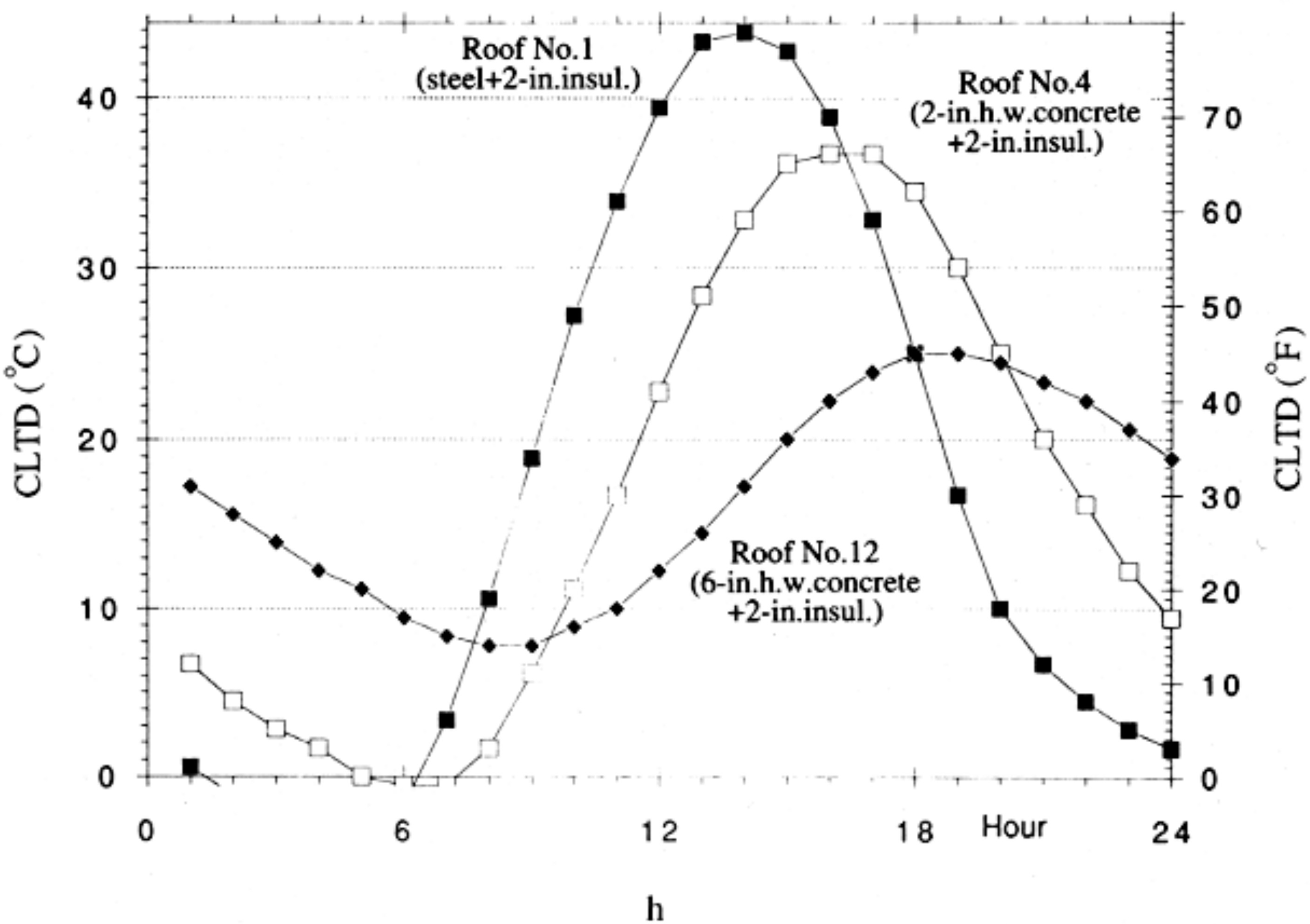
$$Q = UA\Delta T \qquad \text{or} \qquad Q = K_{total}\Delta T$$

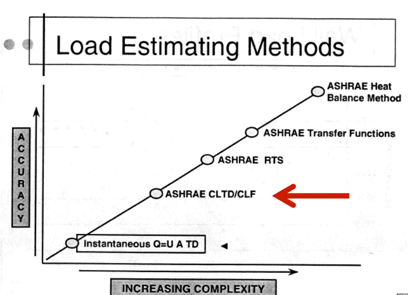
- Don't include any thermal mass
  - Simplest and least accurate



CLTD method

$$Q_{cooling,conduction} = UA(CLTD_t)$$





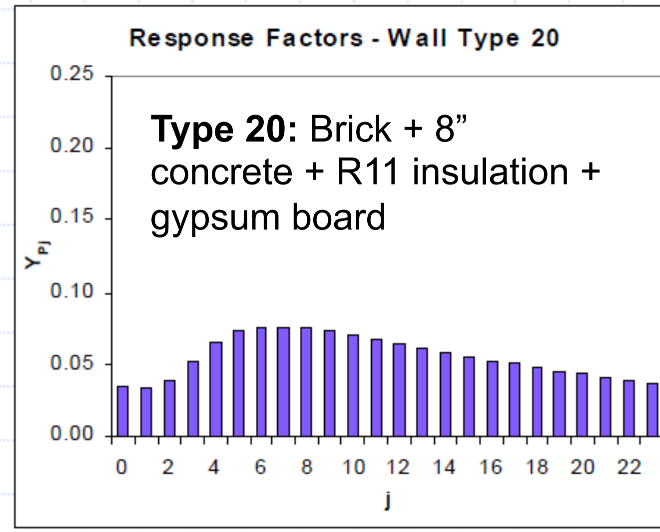
Radiant time series (RTS) method

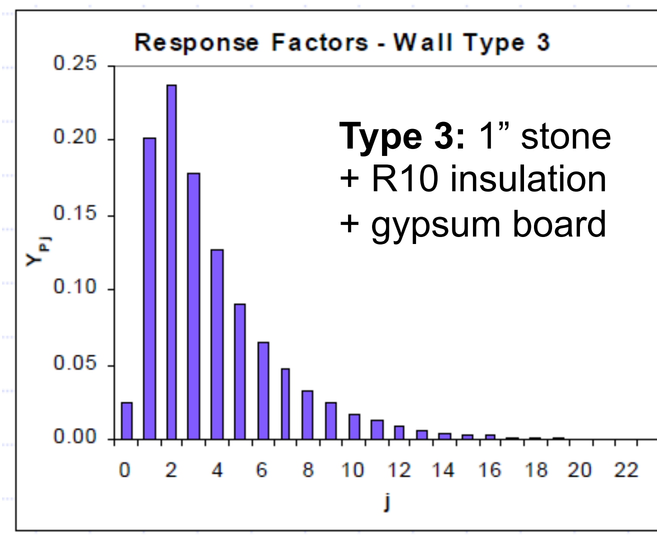
$$q(n) = C_0 U(T_e(n) - T_i(n)) + C_1 U(T_e(n\text{-}1) - T_i(n\text{-}1)) + \ldots + C_{23} U(T_e(n\text{-}23) - T_i(n\text{-}23))$$

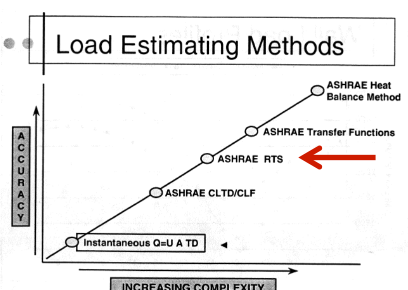
where $T_e = T_{sol\text{-}air}$

$Y_{pn} = C_n U$ is the periodic response factor (PRF) in [W/m²K]

$$q_{conduction,in,8am} = Y_{p0}\left(T_{e,8am} - T_{rc}\right) + Y_{p1}\left(T_{e,7am} - T_{rc}\right) + Y_{p2}\left(T_{e,6am} - T_{rc}\right) + Y_{p3}\left(T_{e,5am} - T_{rc}\right) + Y_{p4}\left(T_{e,4am} - T_{rc}\right) + Y_{p5}\left(T_{e,3am} - T_{rc}\right) + \cdots + Y_{p22}\left(T_{e,11am} - T_{rc}\right) + Y_{p23}\left(T_{e,10am} - T_{rc}\right) + Y_{p24}\left(T_{e,9am} - T_{rc}\right)$$



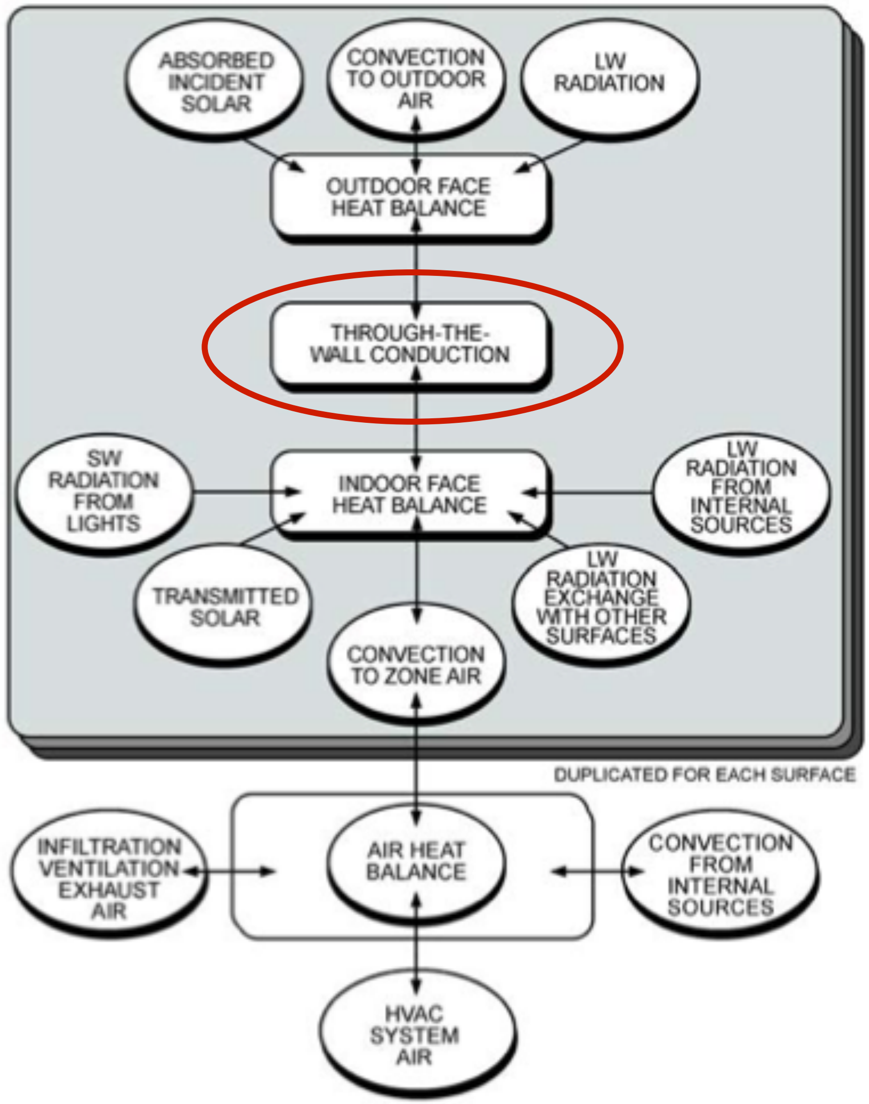


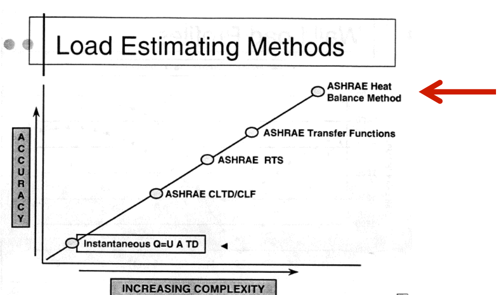


Heat balance method (HBM)

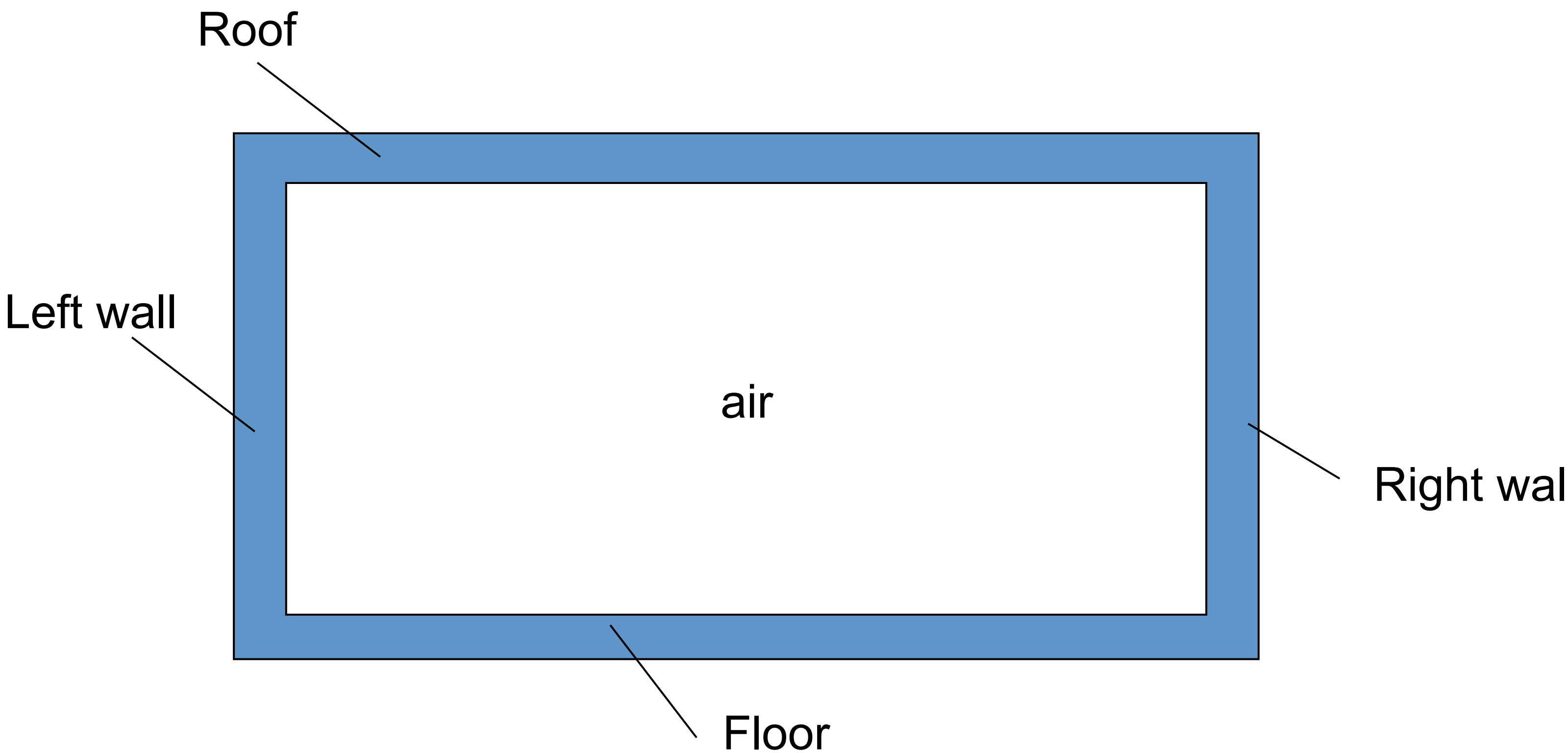
Same as our energy balance method introduced last time

- Most complex and most accurate method
- Within this method, there are various ways of treating thermal mass





Simplest 'box' model



Elements are connected by:

1) Convection – air node
2) Radiation – surface nodes

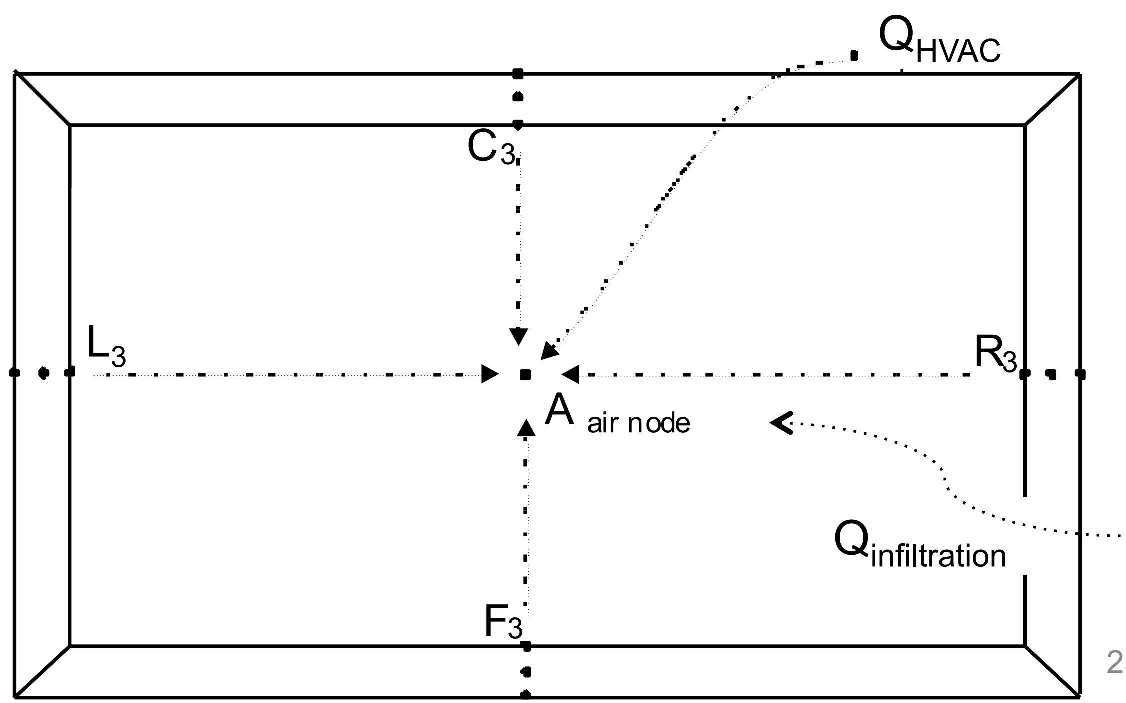
Slide courtesy Atila Novoselac, University of Texas at Austin

Unsteady energy balance for air node

- To get the impact on indoor air temperature (and close the system of equations)
  - Write an energy balance on the indoor air node
  - Air impacted directly only by convection (bulk and surface)

$$(V_{room}\rho_{air}c_{p,air})\frac{dT_{air,in}}{dt} = \sum_{i=1}^{n} h_i A_i \left(T_{i,surf} - T_{air,in}\right) + \dot{m}c_p\left(T_{out} - T_{air,in}\right) + Q_{HVAC}$$

In plain English:
The change in indoor air temperature is equal to the sum of convection from each interior surface plus outdoor air delivery (by infiltration or dedicated outdoor air supply), plus the bulk convective heat transfer delivered by the HVAC system



Bringing all modes (and nodes) together

- For an example room like this, you would setup a system of equations where the temperature at each node (either a surface or within a material) is unknown
  - 12 material nodes + 1 indoor air node

Heat Xfer @ external surfaces:
Radiation and convection

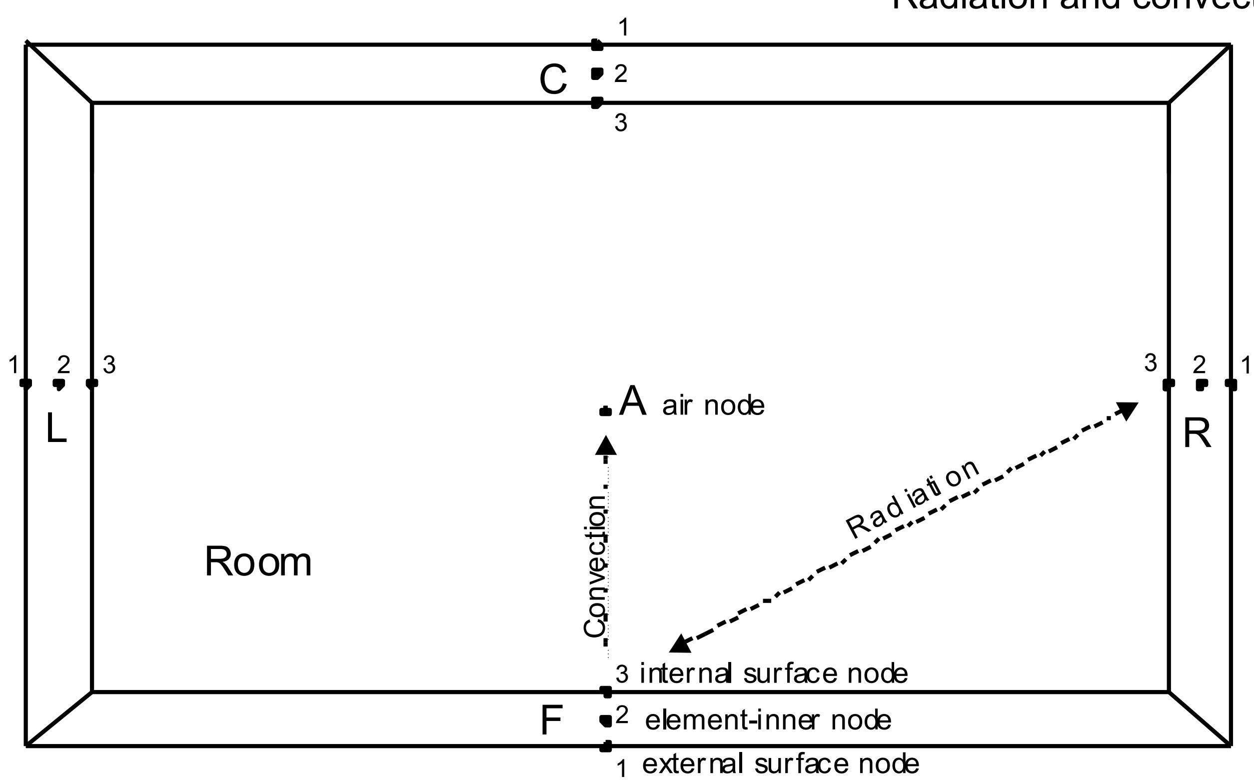
At surface nodes:

$$\sum q = 0$$

At nodes inside materials:

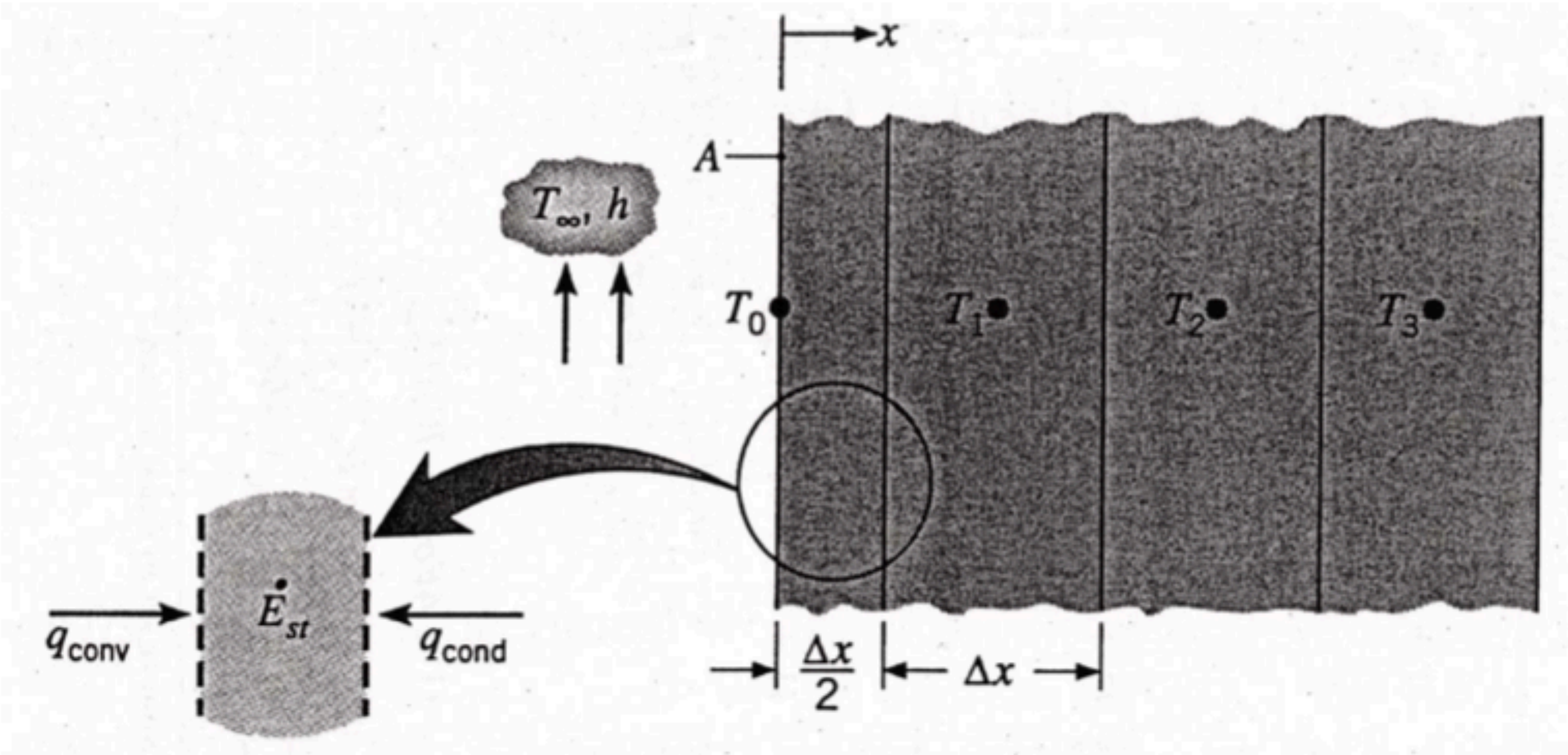
$$mc_p \frac{dT}{dt} = \sum q_{at\ boundaries}$$

Based on density and heat capacity of material



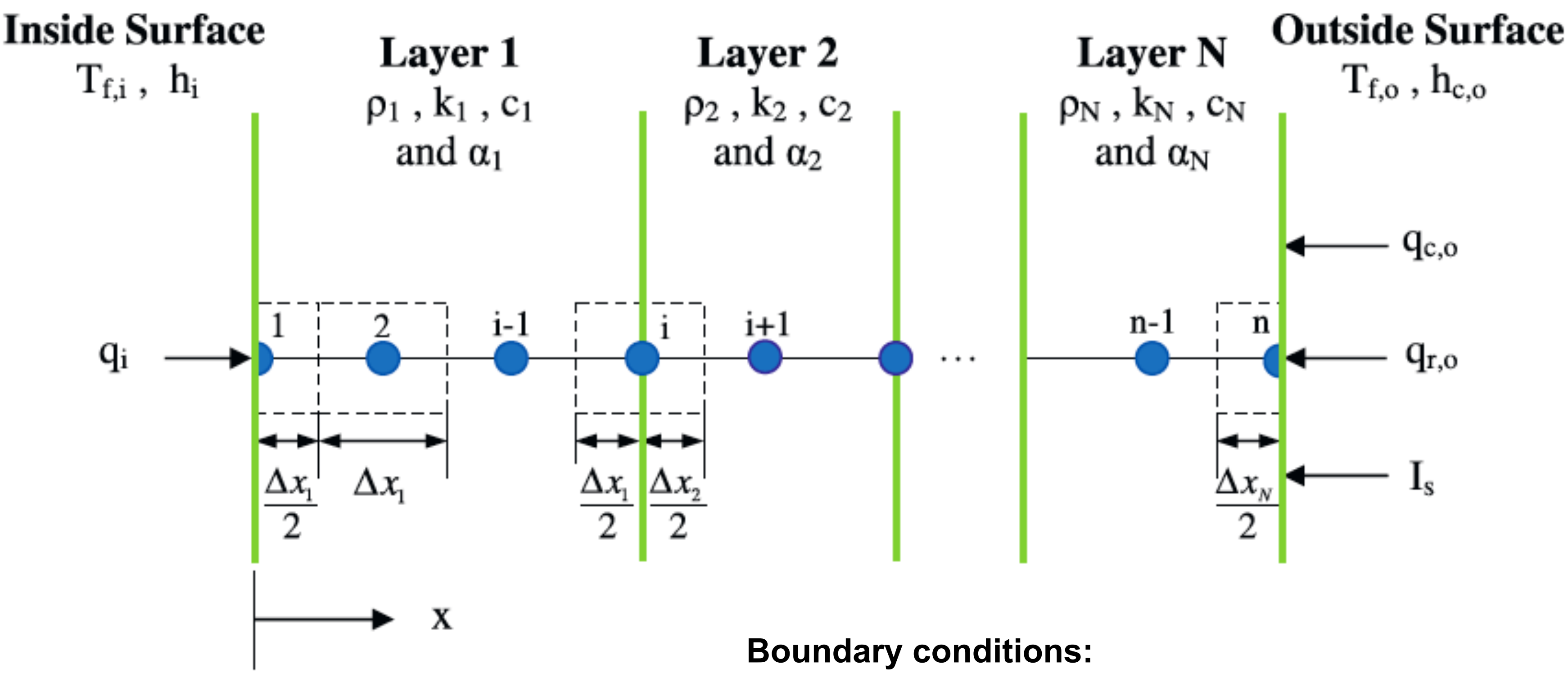
Modeling thermal mass: Transient (unsteady) conduction

- Divide material assembly into multiple nodes



Modeling thermal mass: Unsteady conduction

- Conduction and thermal mass together can be modeled using discrete nodes in 1-dimension:



Governing equation:

$$\frac{\partial^2 T_j}{\partial x^2} = \frac{1}{\alpha_j}\frac{\partial T_j}{\partial t}$$

$$\alpha = \frac{k}{\rho C_p} \quad [\text{m}^2/\text{s}]$$

t = time [s]

Boundary conditions:

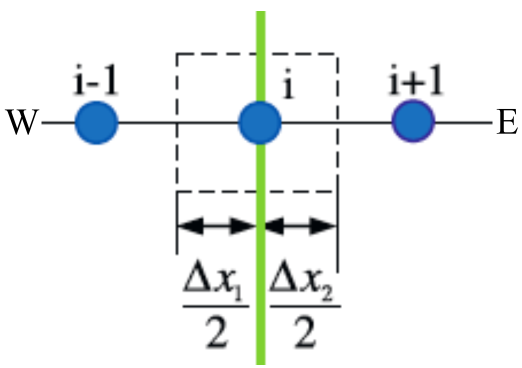
$$-k_1 \frac{\partial T}{\partial x}\bigg|_{x=0} = h_i(T_{f,i} - T_{x=0}) \qquad T_j(x,0) = T_0$$

$$-k_N \frac{\partial T}{\partial x}\bigg|_{x=L} = h_{c,o}(T_{x=L} - T_{f,o}) - \alpha I_s - q_{r,o}$$

Modeling thermal mass: Unsteady conduction

- Conduction finite difference solution (**implicit**)

$$C_p \rho \Delta x \frac{T_i^{j+1} - T_i^{j}}{\Delta t} = \frac{1}{2}\left[\left(k_W \frac{\left(T_{i+1}^{j+1} - T_i^{j+1}\right)}{\Delta x} + k_E \frac{\left(T_{i-1}^{j+1} - T_i^{j+1}\right)}{\Delta x}\right) + \left(k_W \frac{\left(T_{i+1}^{j} - T_i^{j}\right)}{\Delta x} + k_E \frac{\left(T_{i-1}^{j} - T_i^{j}\right)}{\Delta x}\right)\right] \quad (36)$$



Where:
T = node temperature
Subscripts:
i = node being modeled
i+1 = adjacent node to interior of construction
i-1 = adjacent node to exterior of construction
j+1 = new time step
j = previous time step
Δt = calculation time step
Δx = finite difference layer thickness (always less than construction layer thickness)
C_p = specific heat of material
k_W = thermal conductivity for interface between i node and i+1 node
k_E = thermal conductivity for interface between i node and i-1 node
ρ = density of material

Selecting grid size:

$$\left(Fo = \alpha \Delta t / \Delta x^2\right) < 0.5$$

Implicit = temperatures are evaluated at time j+1 as a function of temperatures at time j

Modeling thermal mass: Unsteady conduction

- Conduction and thermal mass together can also be modeled more simply using a **lumped capacitance** approach in 1-dimension:

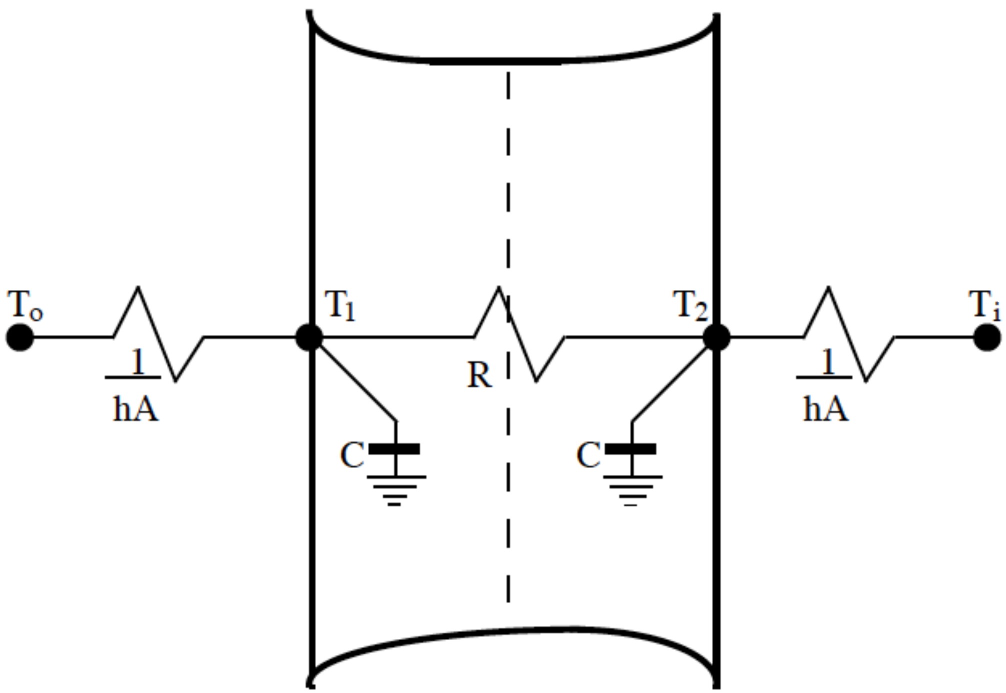


Figure 9. Two Node State Space Example.

$$C\frac{dT_1}{dt} = hA\left(T_o - T_1\right) + \frac{T_2 - T_1}{R}$$

$$C\frac{dT_2}{dt} = hA\left(T_i - T_2\right) + \frac{T_1 - T_2}{R}$$

where:

$$R = \frac{\ell}{kA},$$

$$C = \frac{\rho c_p \ell A}{2}$$

Lumped capacitance model

- Wall example: Exterior surface balance at T_1 changes

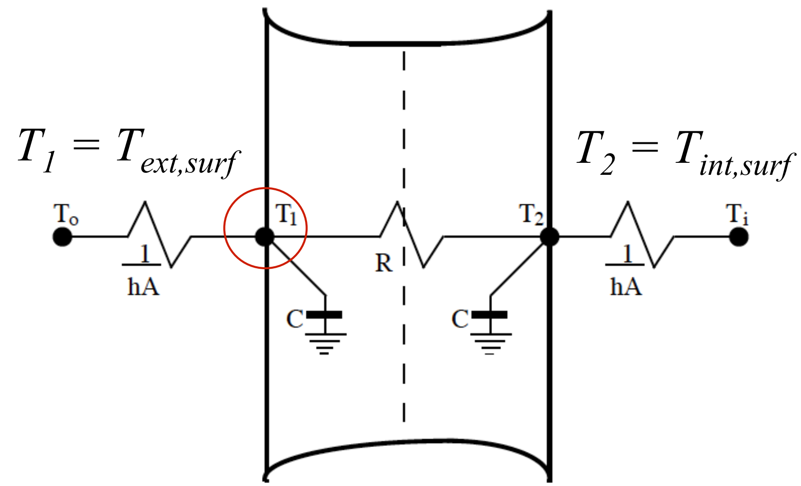


Figure 9. Two Node State Space Example.

From:

$$q_{sw,solar} + q_{lw,surface-sky} + q_{lw,surface-ground} + q_{convection} - q_{conduction} = 0$$

To:

$$q_{sw,solar} + q_{lw,surface-sky} + q_{lw,surface-ground} + q_{convection} - q_{conduction} = \rho C_p \frac{L}{2}\frac{dT}{dt}$$

Lumped capacitance model

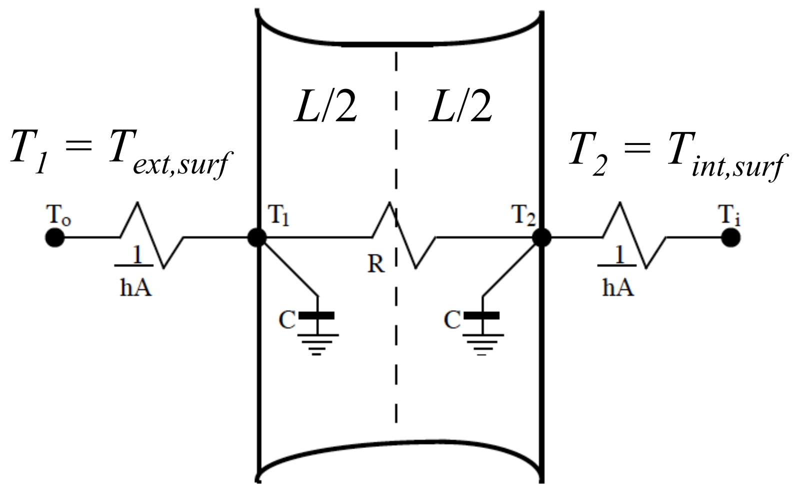


Figure 9. Two Node State Space Example.

Steady state surface energy balance…

$$\alpha I_{solar} + \varepsilon_1 \sigma F_{sky}(T_{sky}^4 - T_1^4) + \varepsilon_1 \sigma F_{ground}(T_{ground}^4 - T_1^4) + h_{conv}(T_{air} - T_1) - U(T_1 - T_2) = 0$$

…becomes a time-varying surface energy balance:

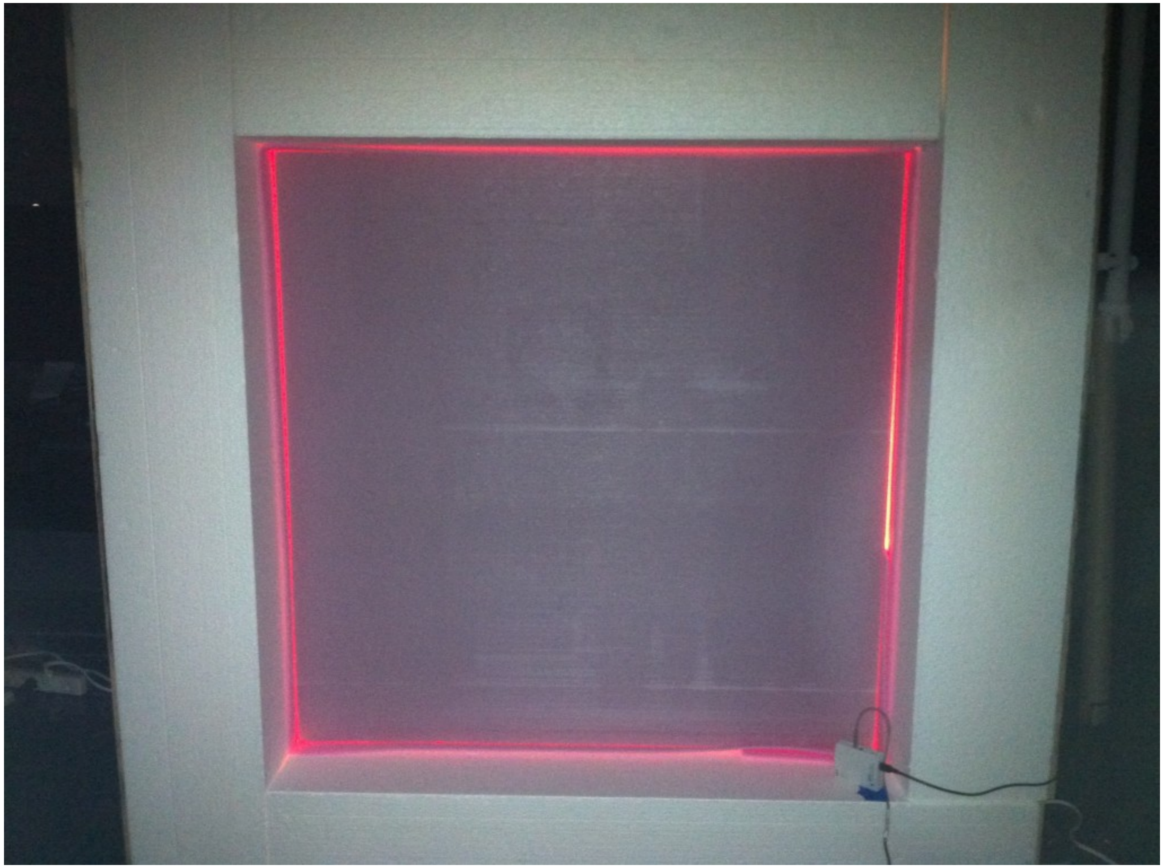
$$\alpha I_{solar} + \varepsilon_1 \sigma F_{sky}(T_{sky}^4 - T_1^4) + \varepsilon_1 \sigma F_{ground}(T_{ground}^4 - T_1^4) + h_{conv}(T_{air} - T_1) - U(T_1 - T_2) = \frac{\rho C_p}{\Delta t} \frac{L}{2} (T_1^n - T_1^{n-1})$$

Dynamic thermal mass: Example in a Hot Box

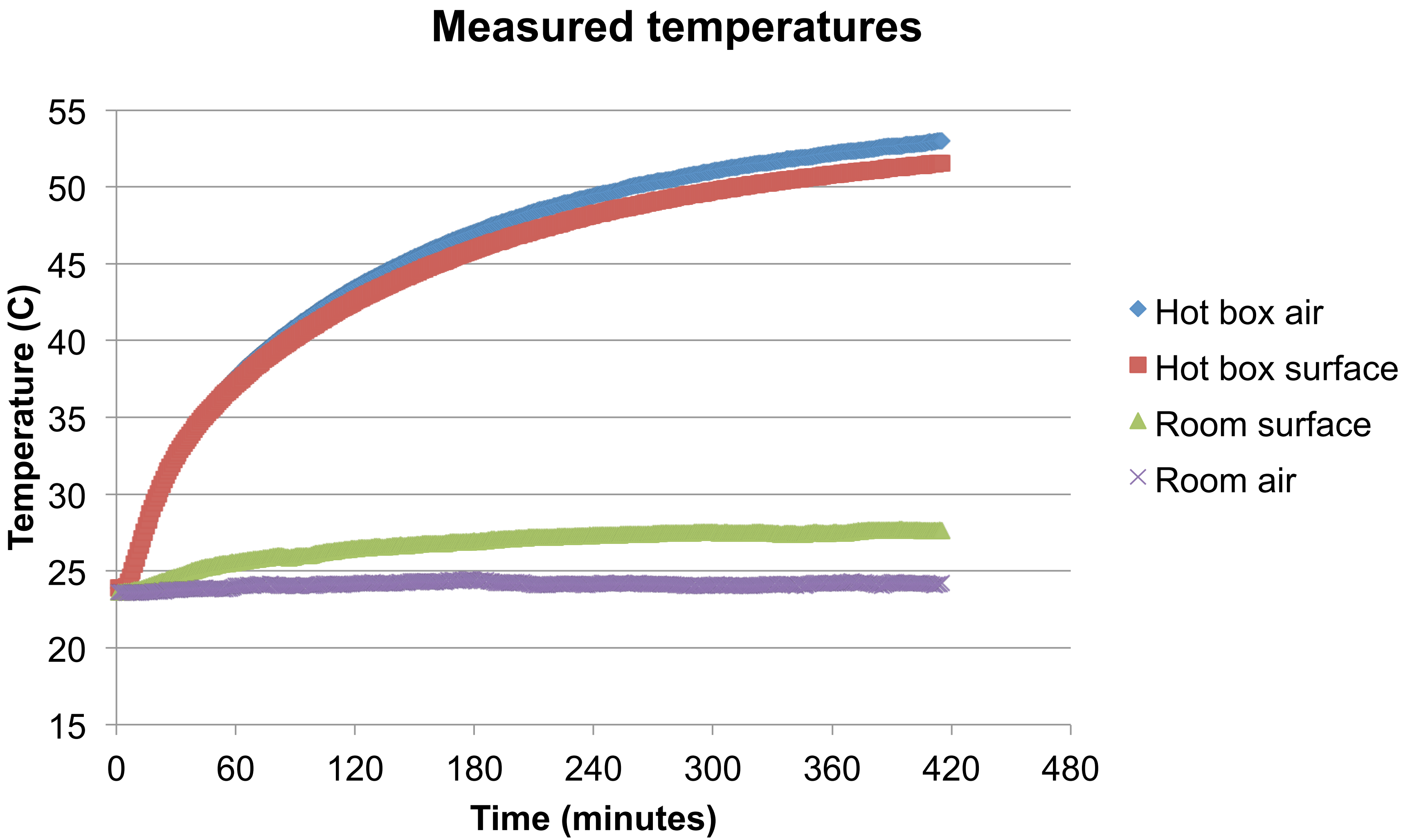
- Three 25 W bulbs inside a 1 m^3 insulated box with 8 inches of EPS insulation on all sides
- Known R-5 insulation installed as the sample

Dynamic thermal mass: Example in a Hot Box

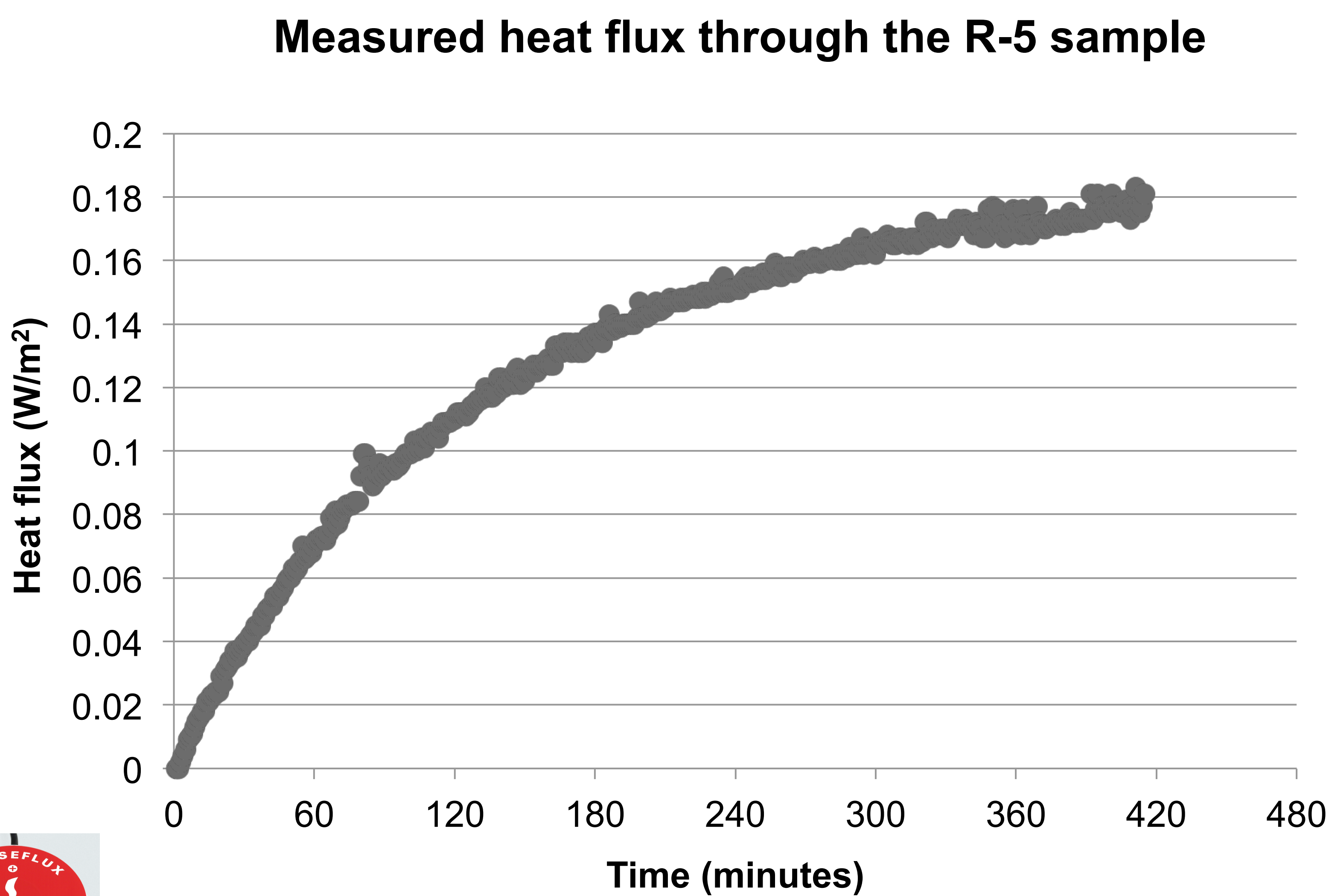
- Three 25 W bulbs inside a 1 m^3 insulated box with 8 inches of EPS insulation on all sides
- Known R-5 insulation installed as the sample



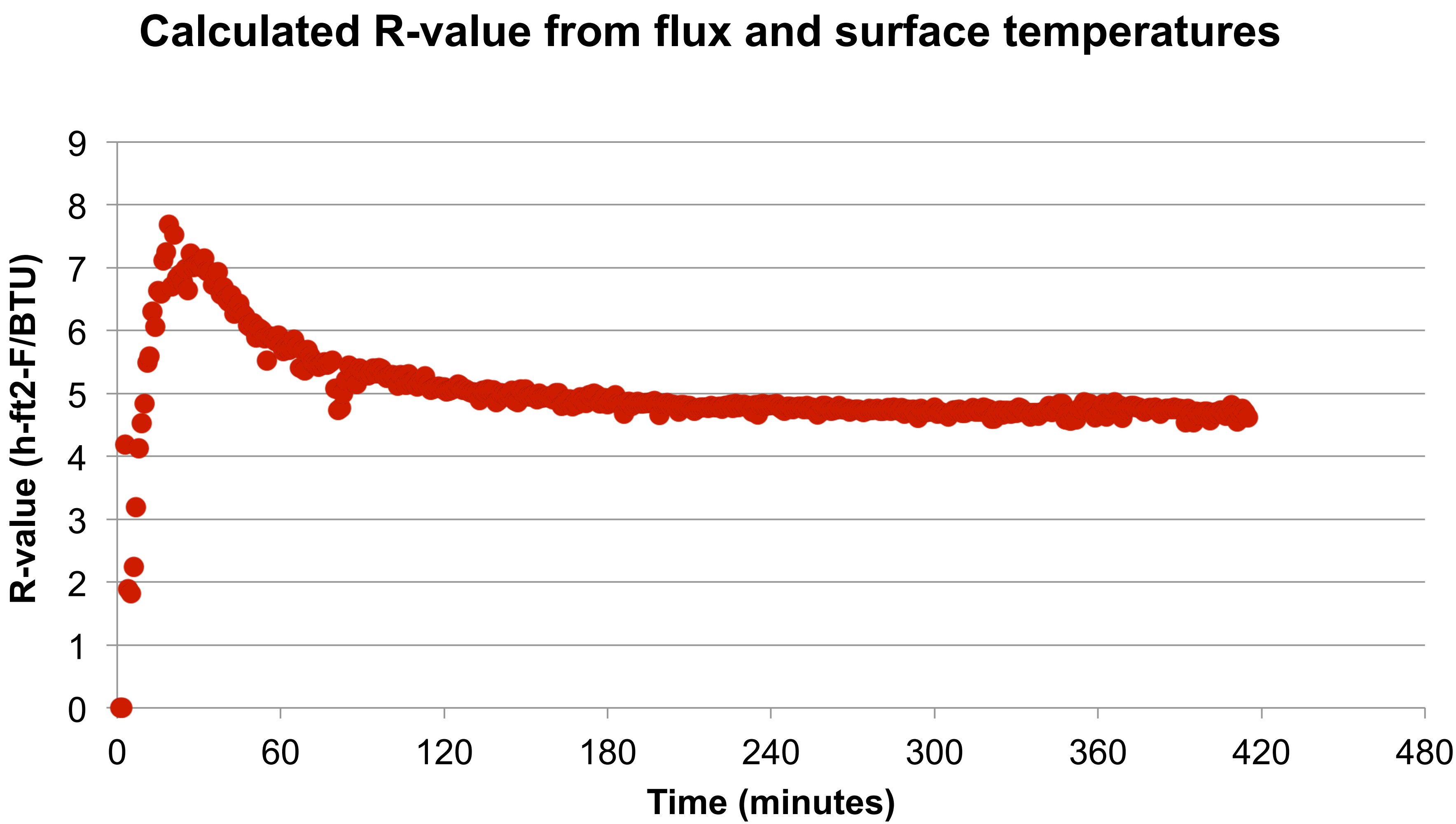
Dynamic thermal mass: Example in a Hot Box



Dynamic thermal mass: Example in a Hot Box

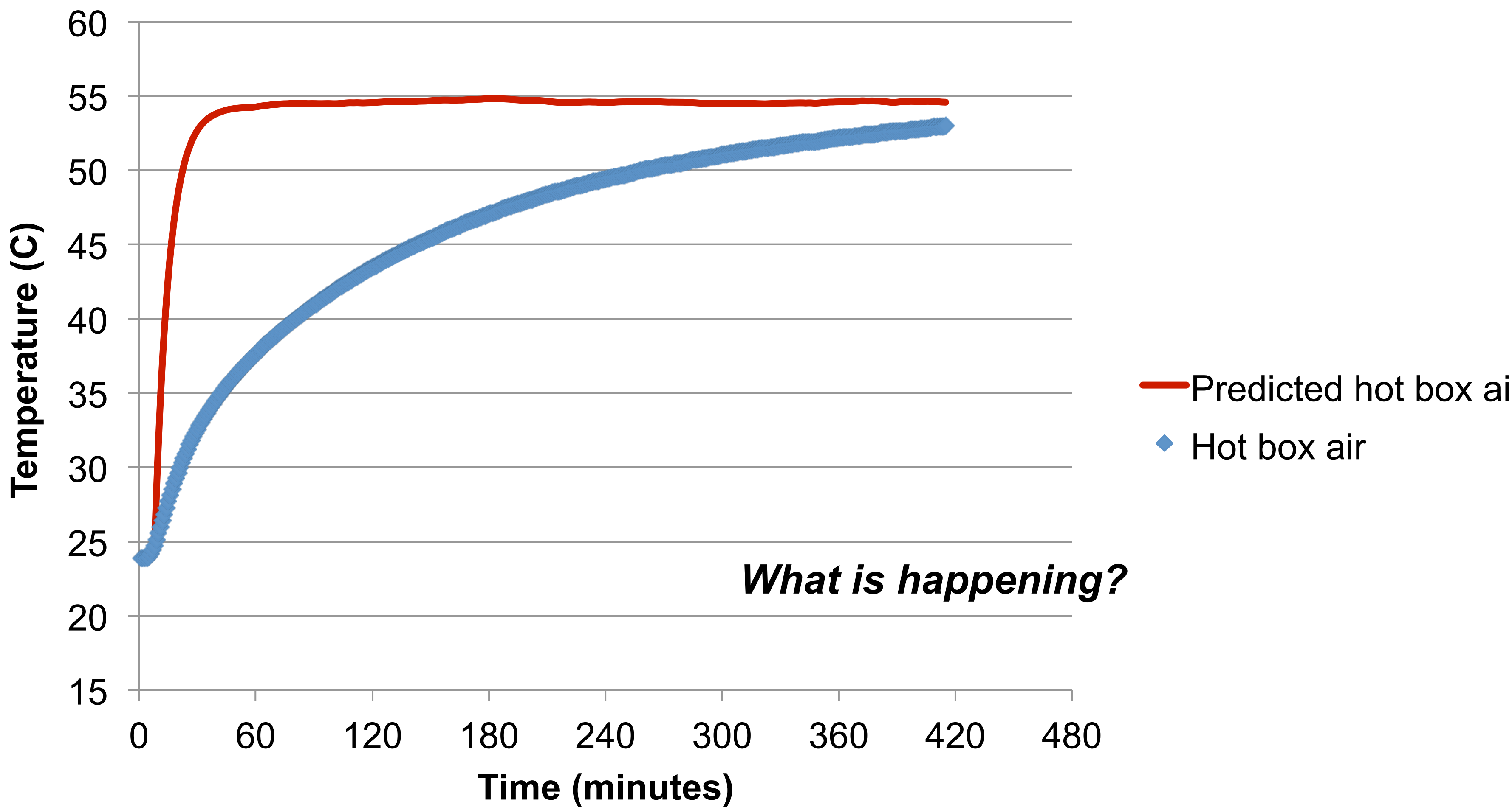


Dynamic thermal mass: Example in a Hot Box



Dynamic thermal mass: Example in a Hot Box

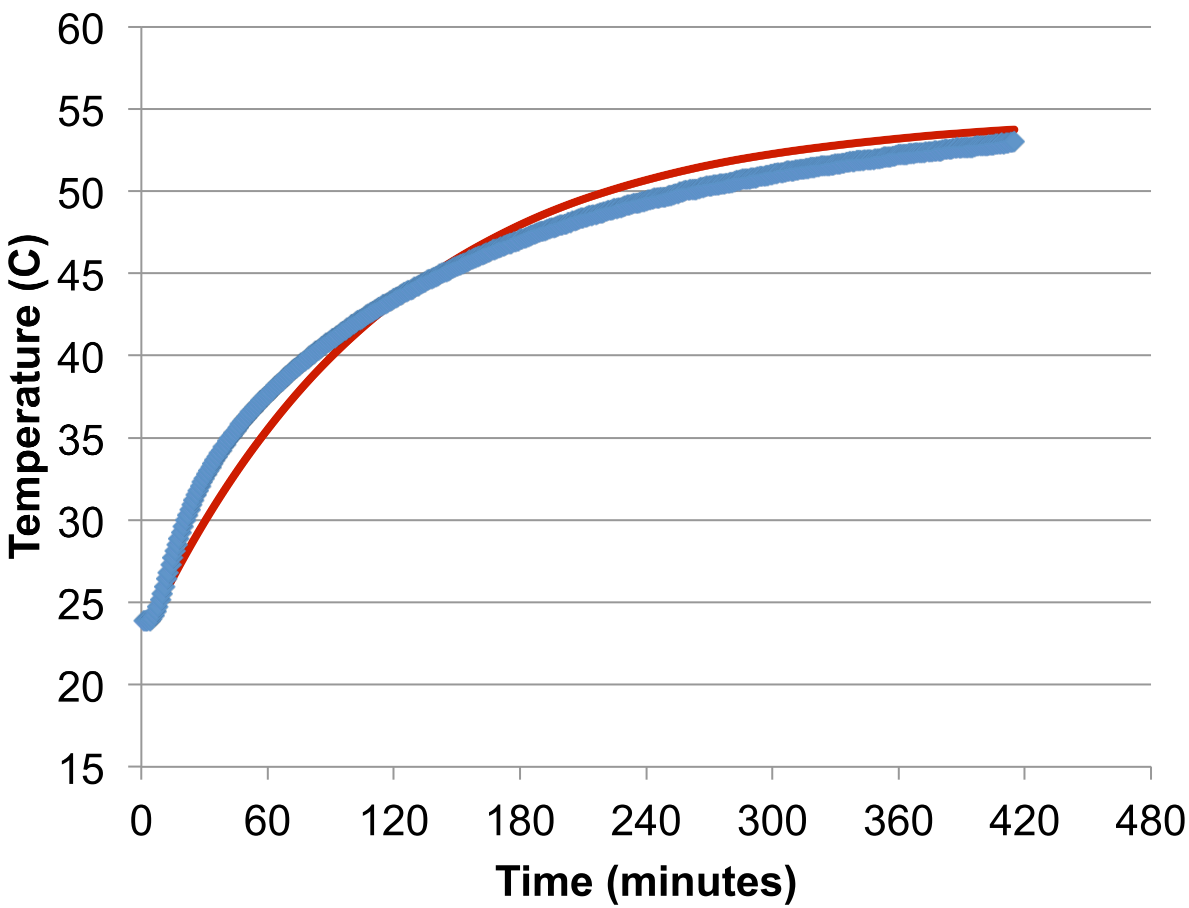
Predicted hot box air temperatures (ignoring heat capacity of insulation)



$$(V_{box}\rho_{air}c_{p,air})\frac{dT_{air,in}}{dt} = \sum_{i=1}^{n} h_i A_i \left(T_{i,surf} - T_{air,in}\right) + \dot{m}c_p\left(T_{out} - T_{air,in}\right)$$

Dynamic thermal mass: Example in a Hot Box

Predicted hot box air temperatures (adding heat capacity of insulation)



Assuming:
Density = 13 kg/m^3
C_p = 1200 J/kgK
V = 1 m^3

Accounting for heat capacity allows for more accurate estimation of when the peak occurs (about 8 hours later)

Adding this term: $$\frac{\left(V\rho C_p\right)_{insulation}}{\Delta t}(T_1^n - T_1^{n-1})$$

Simpler metrics: Time lags and decrement factors

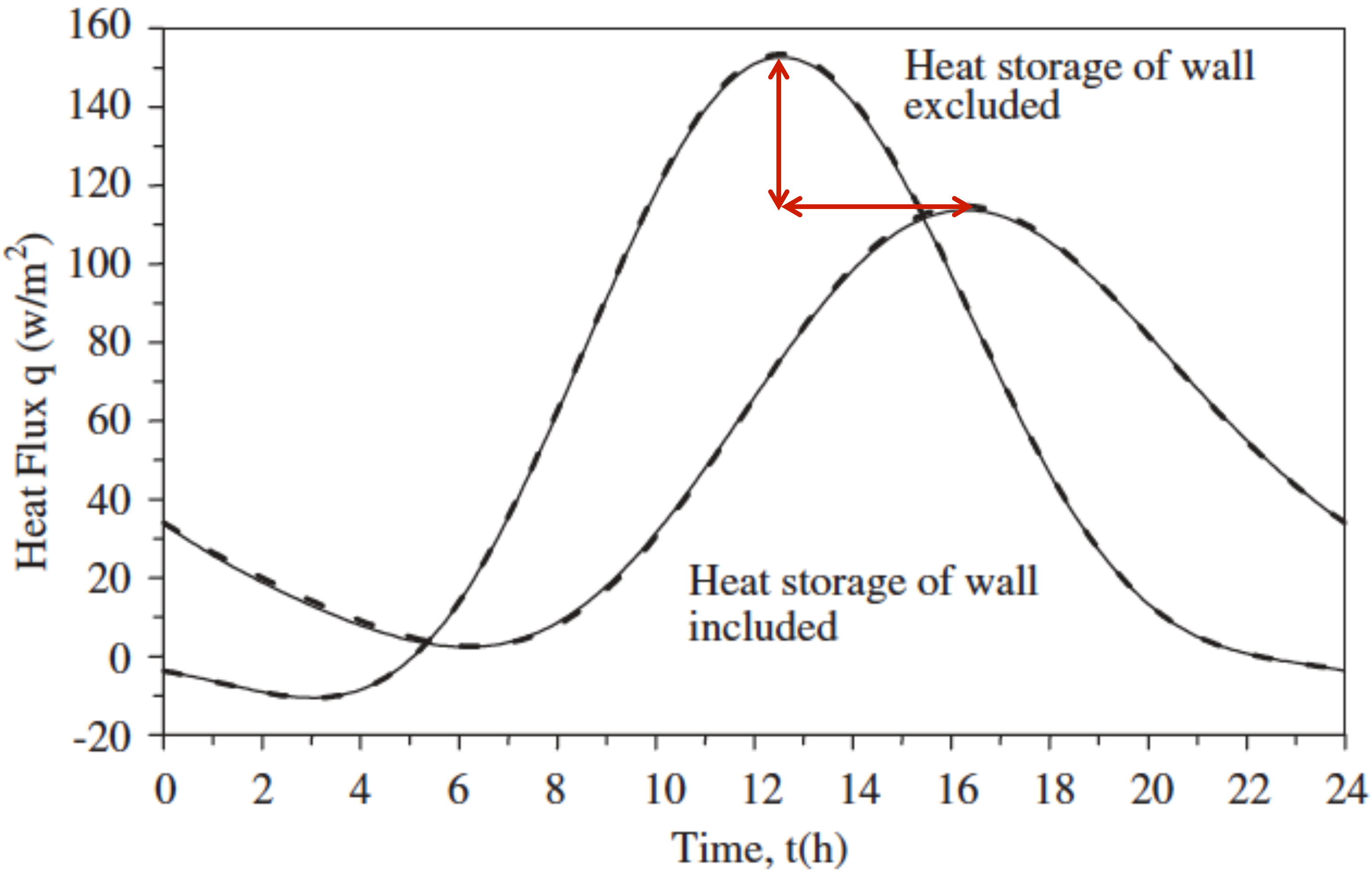
- These models (and measurements) can also be used to describe time lags and decrement factors

- Time lag describes:
  – For a given peak exterior surface temperature at a certain time for a material *without* thermal mass
  – How much later (in time) does the peak interior surface temperature actually occur because of thermal lag effects?

- Decrement factor describes:
  – How much lower is the peak temperature swing (amplitude) with an enclosure with high thermal mass relative to no thermal mass
    - e.g., How squished is the peak temperature profile?

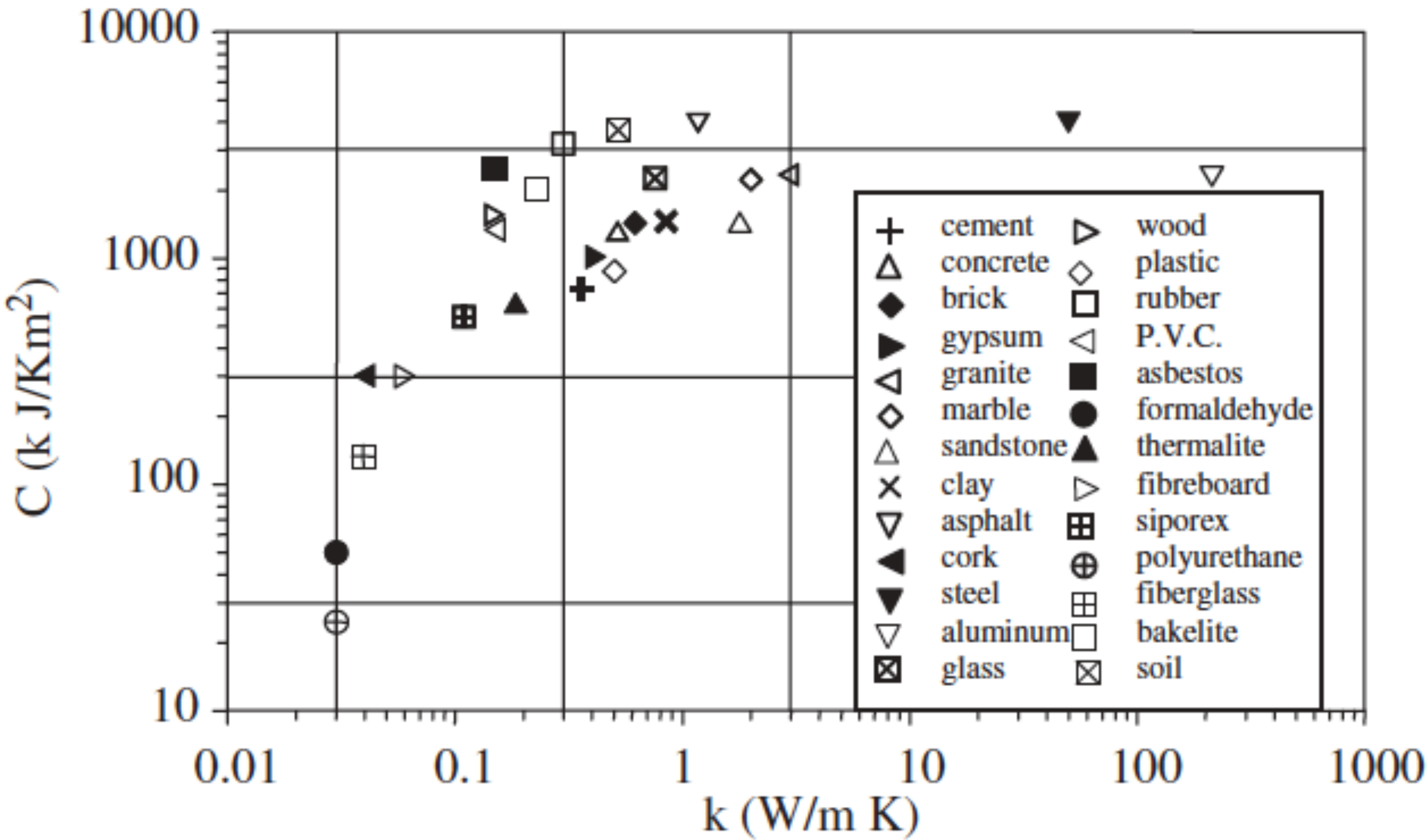
Thermal mass impacts

Decrement factors (ϕ) and time lags (f)



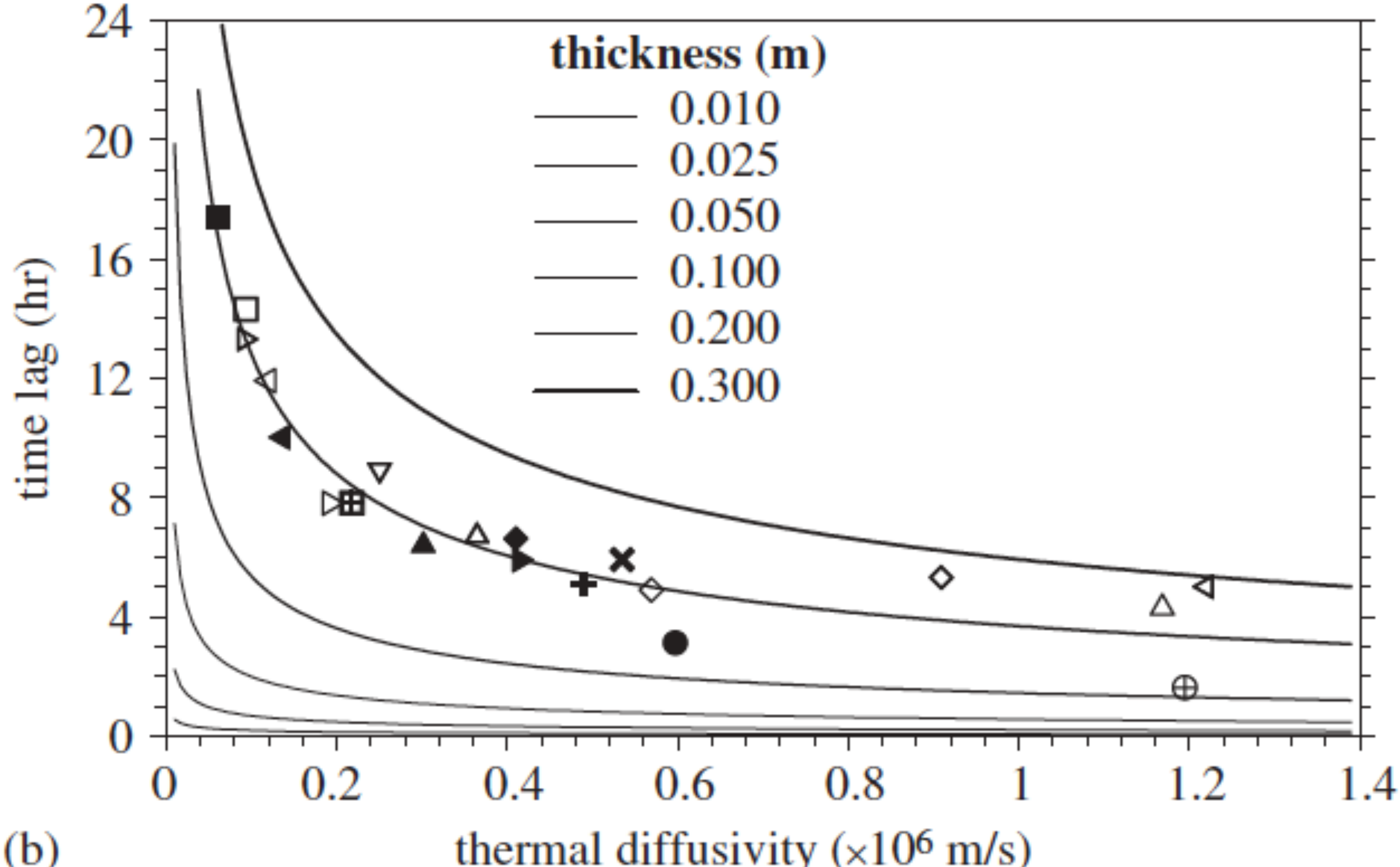
Asan, H. 2006. Numerical computation of time lags an decrement factors for different building materials. *Building and Environment* 41:615-620.

Material properties for thermal mass



Asan, H. 2006. Numerical computation of time lags an decrement factors for different building materials. *Building and Environment* 41:615-620.

Modeled time lag of several materials with varying thickness



Asan, H. 2006. Numerical computation of time lags an decrement factors for different building materials. *Building and Environment* 41:615-620.

Computed time lags and decrement factors for materials

Table 1

Thickness	$L = 0.001$ m		$L = 0.010$ m		$L = 0.025$ m		$L = 0.050$ m		$L = 0.100$ m		$L = 0.200$ m		$L = 0.300$ m		$L = 1.000$ m	
Building material	ϕ (h)	f	ϕ (h)	f	ϕ (h)	f	ϕ (h)	f	ϕ (h)	f	ϕ (h)	f	ϕ (h)	f	ϕ (h)	f
Cement layer	0.01	0.730	0.09	0.647	0.26	0.544	0.69	0.426	1.89	0.284	5.12	0.128	8.23	0.054	>24	≈0
Concrete block	0.01	0.733	0.16	0.672	0.44	0.588	1.14	0.477	2.88	0.312	6.81	0.118	10.31	0.043	>24	≈0
Brick block	0.01	0.735	0.17	0.683	0.46	0.609	1.15	0.506	2.83	0.343	6.65	0.137	9.86	0.053	>24	≈0
Gypsum plastering	0.01	0.732	0.12	0.660	0.28	0.564	0.89	0.450	2.34	0.299	5.93	0.123	9.27	0.048	>24	≈0
Granite (red) block	0.02	0.739	0.24	0.726	0.59	0.701	1.28	0.646	2.62	0.515	5.01	0.288	6.95	0.166	>24	≈0
Marble (white) block	0.02	0.739	0.22	0.721	0.56	0.689	1.25	0.626	2.66	0.487	5.31	0.255	7.56	0.136	>24	≈0
Sandstone block	0.02	0.737	0.16	0.720	0.40	0.688	0.92	0.633	2.03	0.519	4.47	0.306	6.45	0.176	21.77	≈0
Clay layer	0.02	0.736	0.17	0.698	0.45	0.639	1.10	0.551	2.61	0.396	5.98	0.178	8.84	0.078	>24	≈0
Soil layer	0.03	0.732	0.40	0.669	1.31	0.569	2.93	0.409	6.12	0.184	12.08	0.036	18.65	0.001	>24	≈0
Asphalt layer	0.04	0.738	0.41	0.706	1.03	0.647	2.31	0.526	4.62	0.309	8.82	0.100	12.00	0.034	>24	≈0
Steel slab	0.04	0.741	0.38	0.736	0.89	0.719	1.79	0.658	3.05	0.516	4.41	0.313	5.09	0.227	8.95	0.031
Aluminum slab	0.02	0.741	0.23	0.739	0.55	0.733	1.13	0.708	2.09	0.631	3.43	0.459	4.14	0.352	5.86	0.113
Cork board	0.00	0.656	0.08	0.323	0.32	0.174	1.10	0.097	3.66	0.044	10.02	0.008	15.77	0.001	>24	≈0
Wood board	0.02	0.717	0.24	0.559	0.79	0.403	2.27	0.259	5.89	0.103	13.31	0.014	20.28	0.000	>24	≈0
Glass block	0.02	0.735	0.39	0.692	0.73	0.624	1.64	0.517	3.77	0.329	7.74	0.116	11.65	0.041	>24	≈0
Plastic board	0.01	0.733	0.10	0.671	0.27	0.587	0.73	0.482	1.90	0.339	4.94	0.162	7.84	0.073	>24	≈0
Bakelite board	0.01	0.724	0.34	0.603	0.96	0.466	2.32	0.315	5.76	0.136	12.53	0.022	19.49	0.001	>24	≈0
Rubber board	0.03	0.728	0.39	0.629	1.17	0.501	3.01	0.331	6.76	0.127	14.34	0.017	21.82	0.000	>24	≈0
PVC board	0.01	0.717	0.20	0.559	0.65	0.406	1.90	0.265	5.11	0.116	11.92	0.019	18.01	0.002	>24	≈0
Asbestos layer	0.03	0.716	0.37	0.557	1.23	0.396	3.39	0.230	7.97	0.069	17.41	0.004	>24	0.000	>24	≈0
Formaldehyde board	0.00	0.632	0.01	0.271	0.06	0.139	0.23	0.077	0.84	0.040	3.19	0.018	5.96	0.008	>24	≈0
Fiberglass	0.00	0.656	0.01	0.322	0.10	0.174	0.52	0.099	1.71	0.051	5.70	0.018	9.92	0.006	>24	≈0
Thermalite board	0.01	0.721	0.09	0.582	0.28	0.439	0.81	0.309	2.36	0.181	6.52	0.064	10.43	0.021	>24	≈0
Fiberboard layer	0.00	0.682	0.06	0.379	0.24	0.234	0.80	0.138	2.66	0.069	7.86	0.019	12.54	0.005	>24	≈0
Siporex board	0.01	0.710	0.09	0.517	0.26	0.355	0.92	0.231	2.81	0.123	7.81	0.035	12.31	0.009	>24	≈0
Polyurethane board	0.00	0.632	0.01	0.271	0.03	0.139	0.12	0.077	0.42	0.040	1.63	0.020	3.36	0.120	17.31	≈0

Asan, H. 2006. Numerical computation of time lags an decrement factors for different building materials. *Building and Environment* 41:615-620.

Why are these important?

- Time lag
  - Doesn't impact energy use directly
    - But impacts time of energy use
  - Can shift peak loads
  - Meaningful for peak loads on aggregate basis
    - Also for energy markets with dynamic pricing

- Decrement factor
  - Directly impacts energy use
    - Dampens rate of conduction through enclosure
  - Can allow for smaller HVAC equipment
    - Lower upfront costs
    - Important in design phase

Thermal time constant (*TTC*)

- The thermal time constant is defined as the sum of the product of the heat capacity of a layer i and the cumulative thermal resistance up to layer i

$$TTC = \sum_i \rho_i C_{pi} L_i R_{o \to i, cumulative}$$

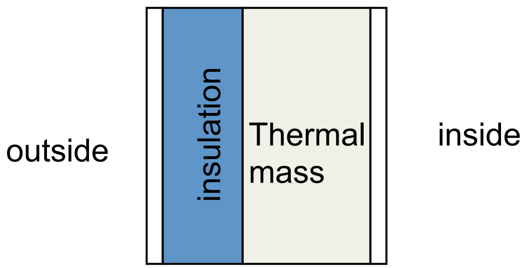
Units of time [sec]

- *TTC* is a measure of time it takes heat to propagate through the wall and is a kind of "effective" thermal insulating capability
  - The higher the TTC, the lower the overall heat transfer through the structure

Example TTC calculation: insulation placement

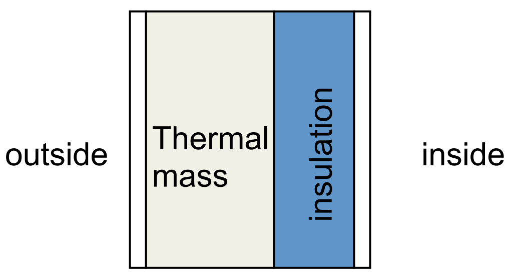
$$\sum_i \rho_i C_{pi} L_i R_{o \to i, cumulative}$$

Wall 1: exterior insulation



TTC = 43.8

Wall 2: interior insulation



TTC = 7.8

TABLE 3-8. CALCULATION OF THE THERMAL TIME CONSTANT OF 2 WALLS (METRIC)

Wall #1

LAYER	THICK l_i(m)	DENSITY ρ_i(Kg/m³)	RESIST. r_i	CUMULAT. RESIST.	HC ρ*c	QR_i Hr
Ext. surface						0.03
Ext. plaster	0.02	1800	0.025	0.0425	414	0.35
Polystyrene	0.025	30	0.71	0.41	12	0.12
Concrete	0.10	2200	0.06	0.795	506	40.2
Int. plaster	0.01	1600	0.014	0.832	368	3.1
Wall's TTC						43.8

Wall #2

LAYER	THICK l_i(m)	DENSITY ρ_i(Kg/m³)	RESIST. r_i	CUMULAT. RESIST.	HC ρ*c	QR_i Hr
Ext. surface						0.03
Ext. plaster	0.02	1800	0.025	0.0425	414	0.35
Concrete	0.10	2200	0.06	0.085	506	4.3
Polystyrene	0.025	30	0.71	0.47	12	0.14
Int. plaster	0.01	1600	0.014	0.832	368	3.1
Wall's TTC						7.8

TTC example

- The Thermal Time Constant (TTC) of the concrete wall with exterior insulation is nearly 5x larger than the concrete wall with interior insulation
  - This means the wall with exterior insulation will be a better thermal mass

- The assembly with the interior insulation has the large thermal mass directly exposed to the large temperature swings of the outdoors
  - By placing the insulation between the exterior air and the thermal mass, it takes longer to “charge” and “discharge” the thermal mass with heat
  - **To take advantage of thermal mass, the mass should be in contact with the indoor environment**

Finishing building energy modeling…

BEOPT AND ENERGYPLUS

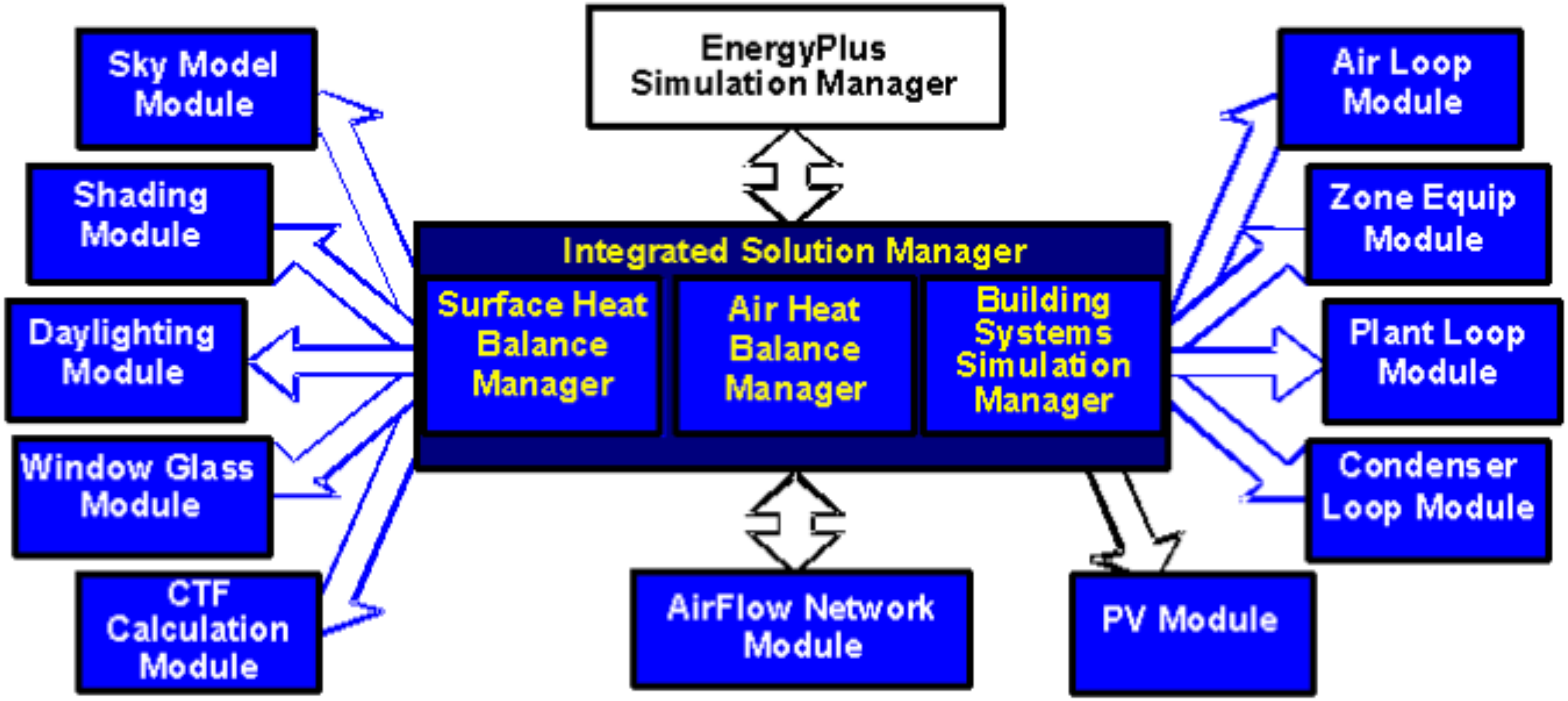
EnergyPlus

- EnergyPlus is an extremely powerful building energy simulation tool
  - Uses hourly or sub-hourly time steps
  - Models nearly all physical phenomena well
    - Including transient heat conduction (thermal mass)
  - Combined heat and mass (air) transfer modeling
  - Excellent system models
  - Thermal comfort modeling
  - Modular for future extensions

- http://apps1.eere.energy.gov/buildings/energyplus/energyplus_about.cfm

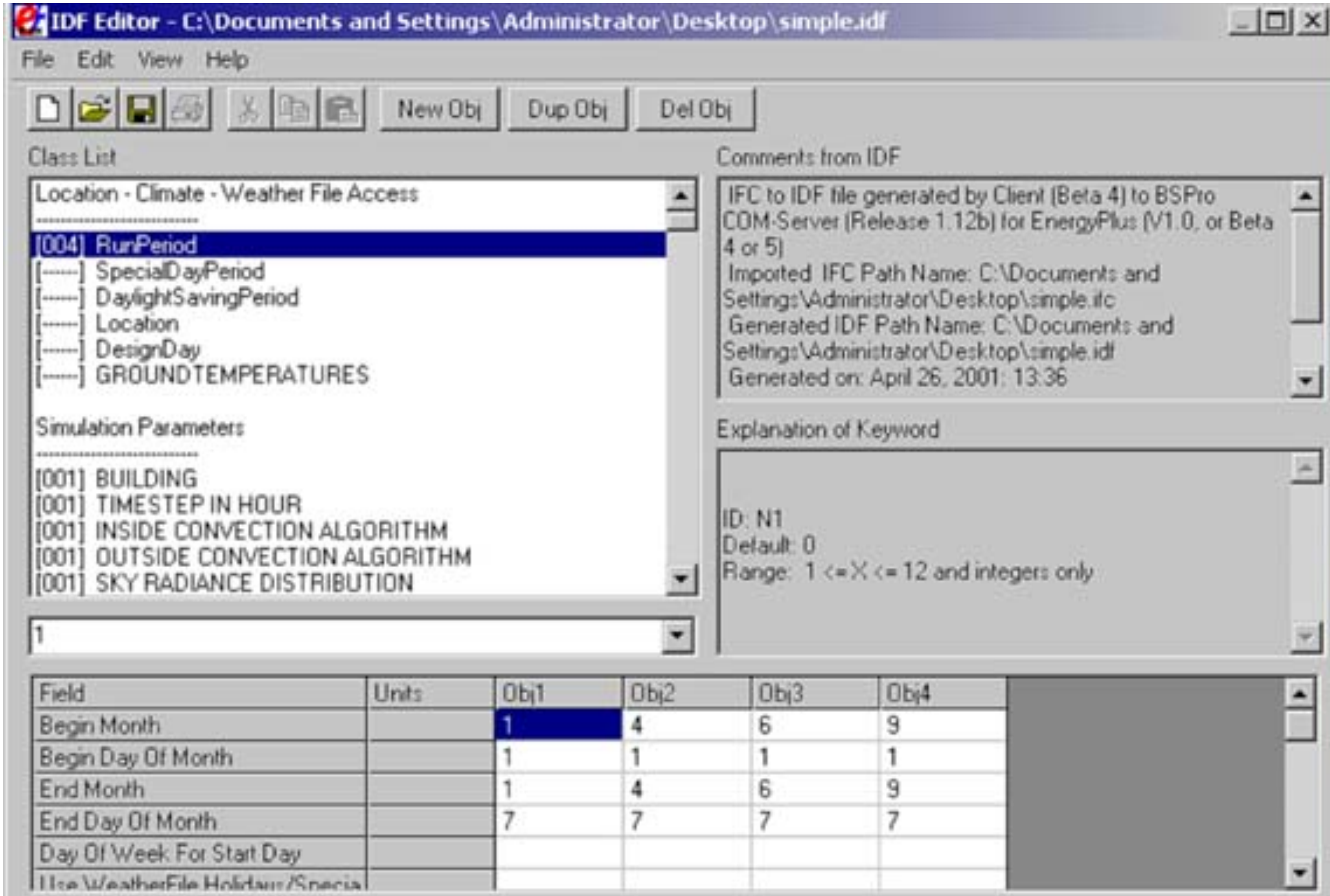
- Runs on Windows, Mac, and Linux

EnergyPlus program organization



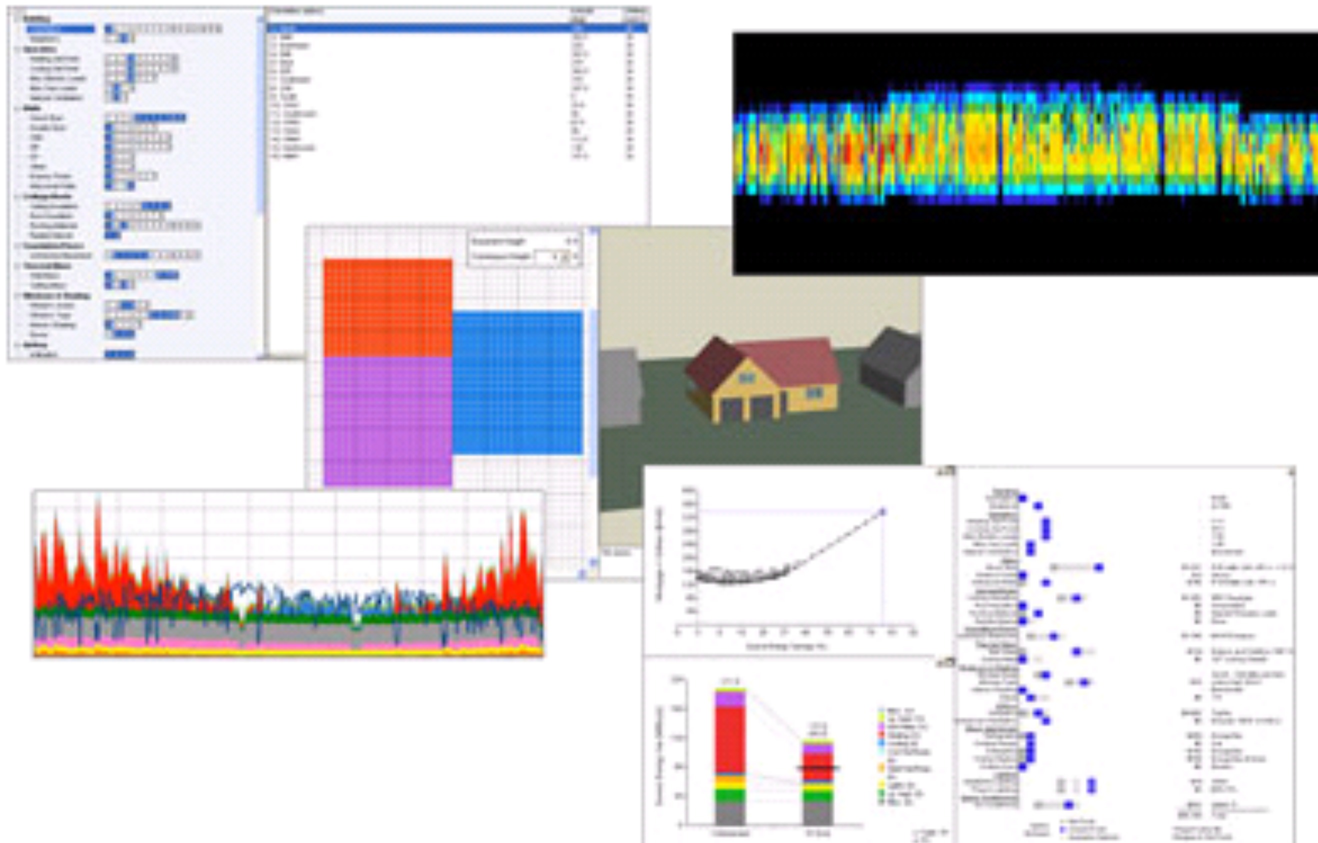
One **huge** limitation: it does not have a graphical user interface (GUI)

EnergyPlus only has a text based input file editor



We need front-end GUIs for EnergyPlus

- *OpenStudio*
- DesignBuilder
- EFEN
- AECOsim
- Hevacomp
- N++
- gEnergy
- *Simergy*
- Sefaira
- BEopt

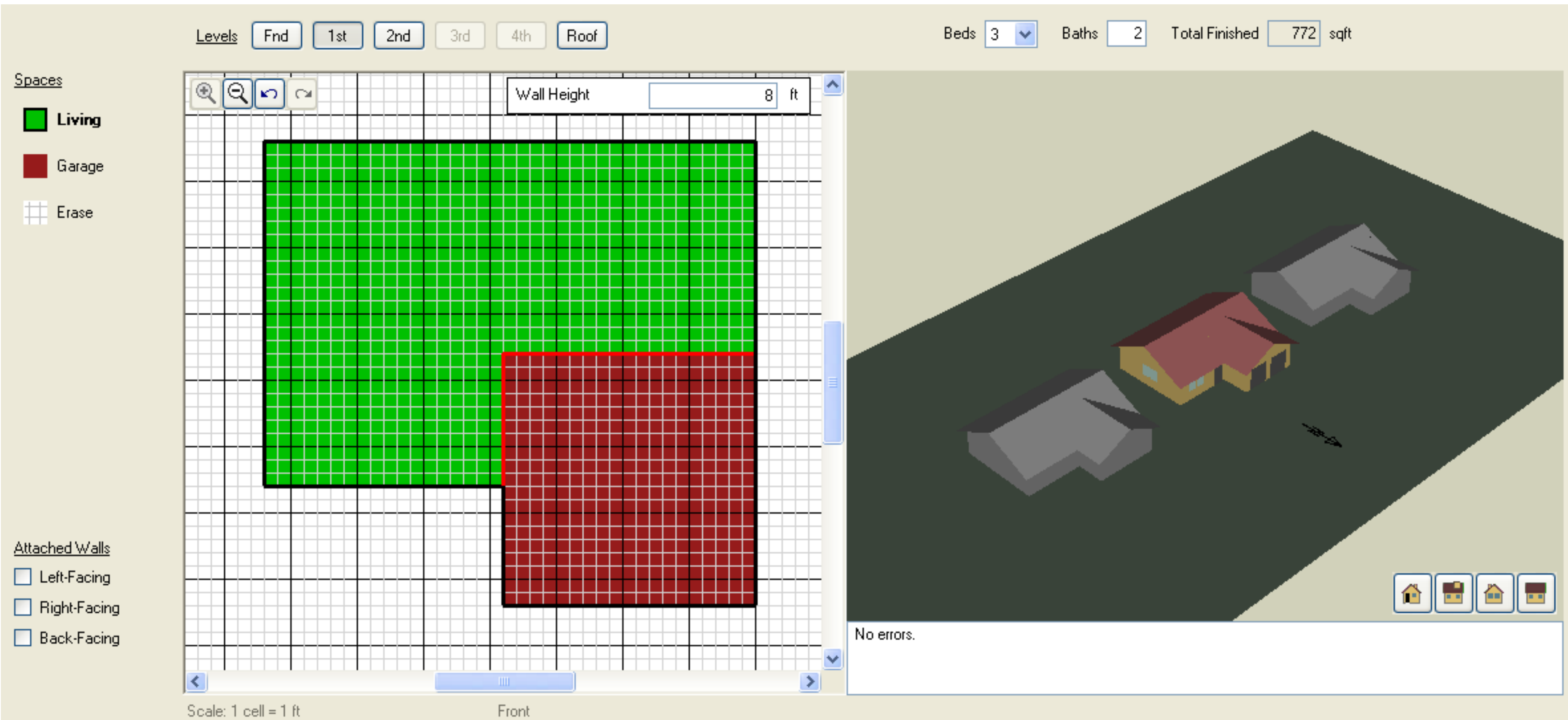


BEopt

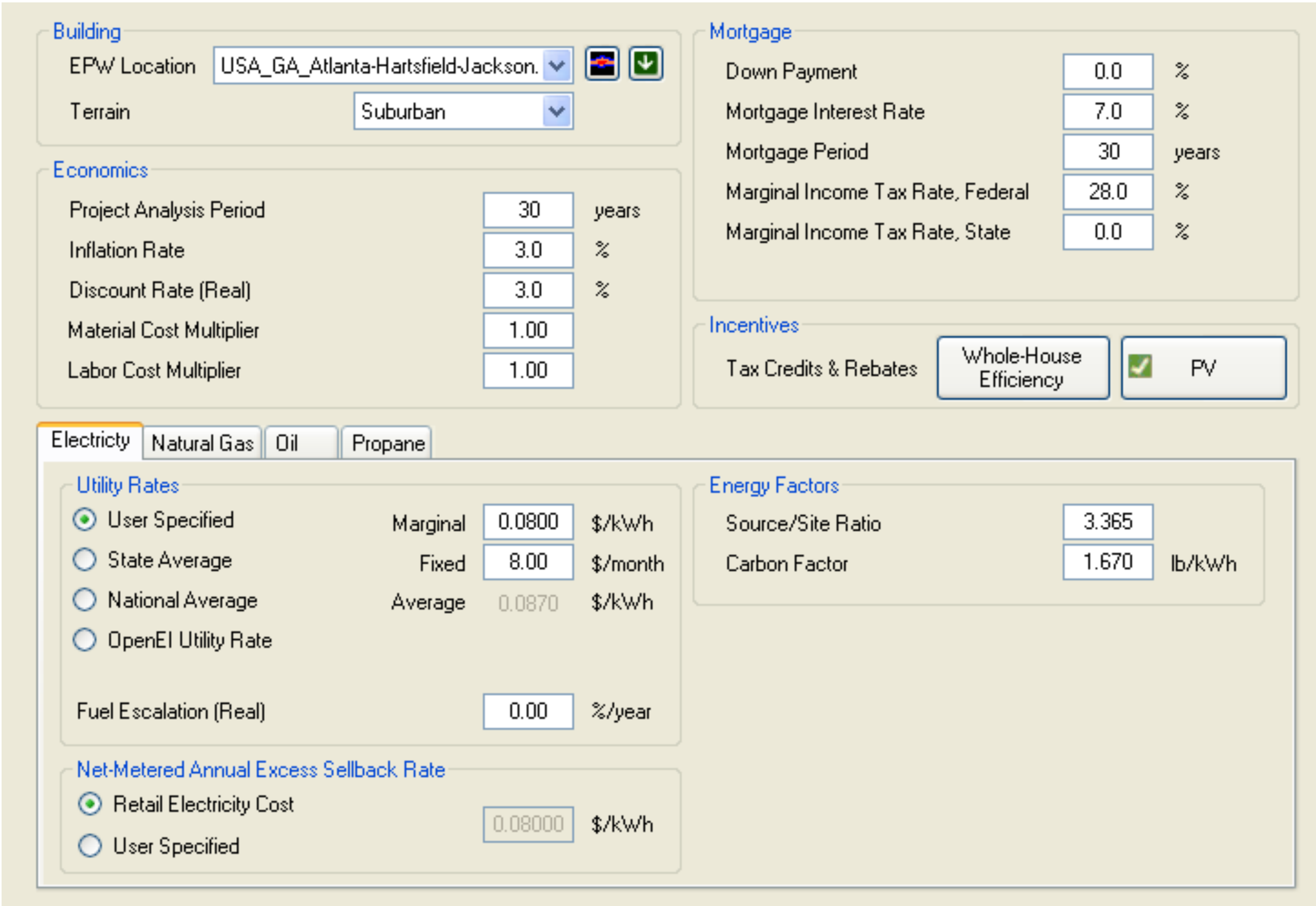
- BEopt (Building Energy Optimization) combines a user-friendly GUI for building model geometry and specifying enclosure details, systems, etc. with both parametric analysis and an optimization engine for identifying cost-optimal efficiency packages
  - Includes annual energy costs/savings, construction costs, and material/equipment costs
  - https://beopt.nrel.gov

- Strictly limited to residential buildings
- Only runs on Windows
- Uses either EnergyPlus or DOE-2.2 as the simulation engine
  - eQUEST uses DOE-2.2
  - We will use EnergyPlus (more robust)

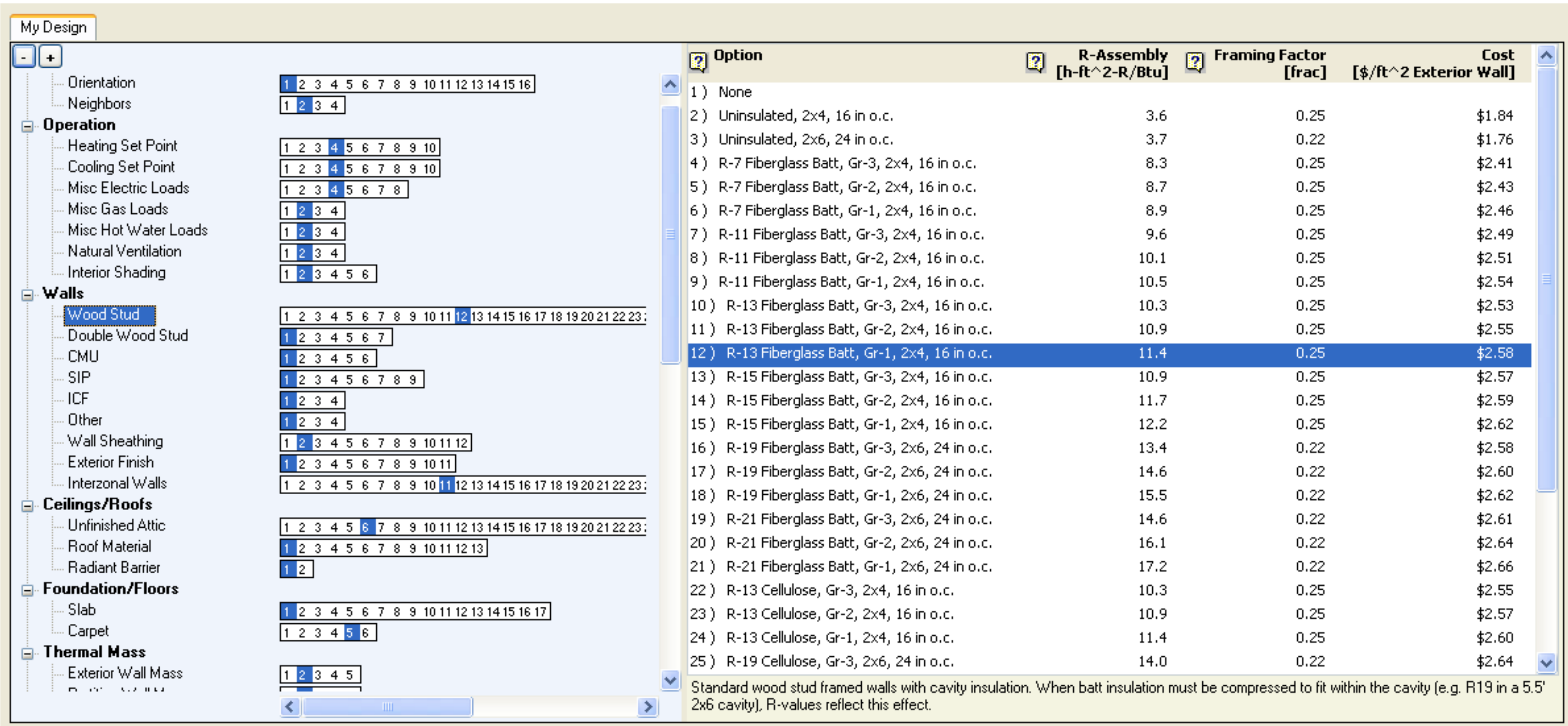
BEopt: Start with building geometry



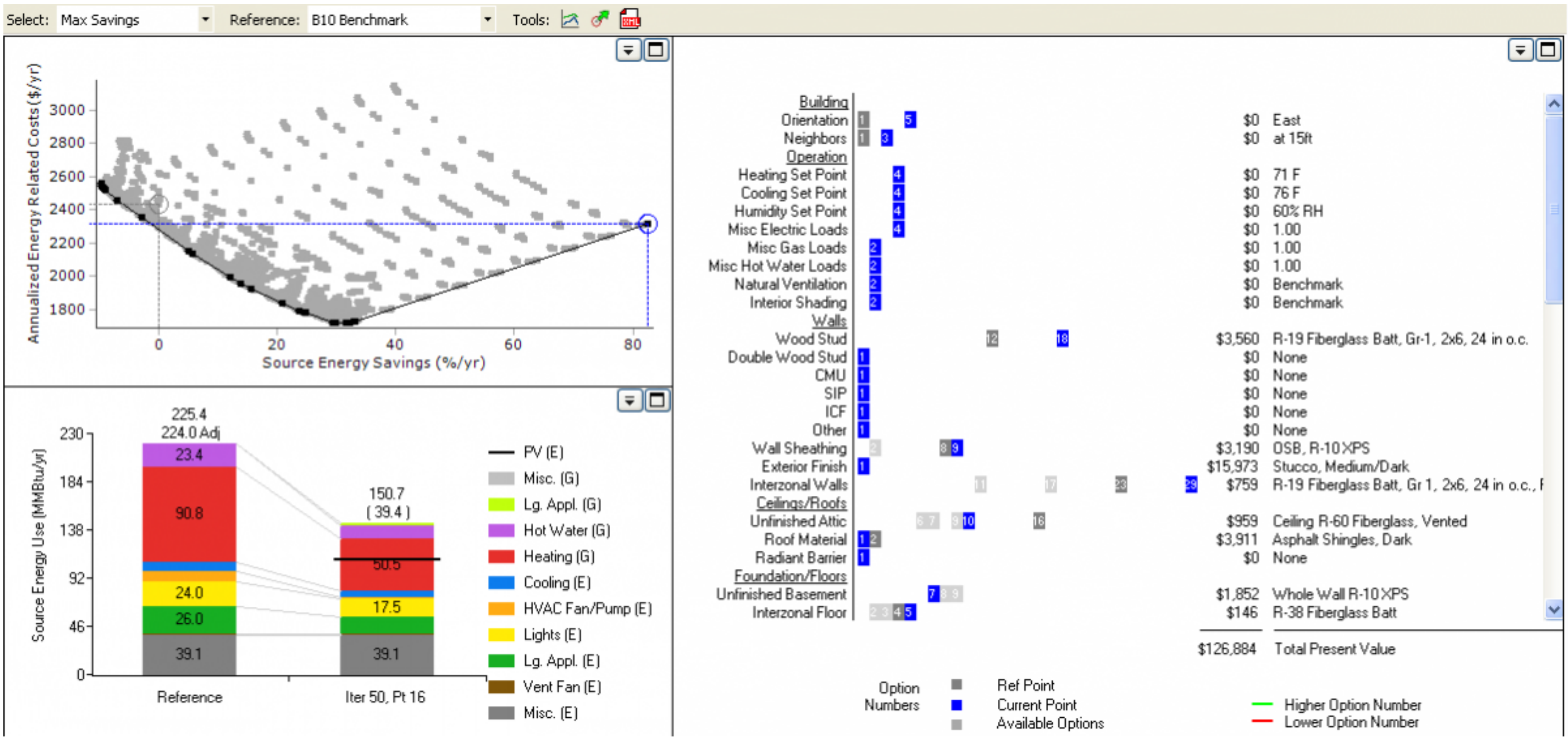
BEopt: Then pick basic characteristics



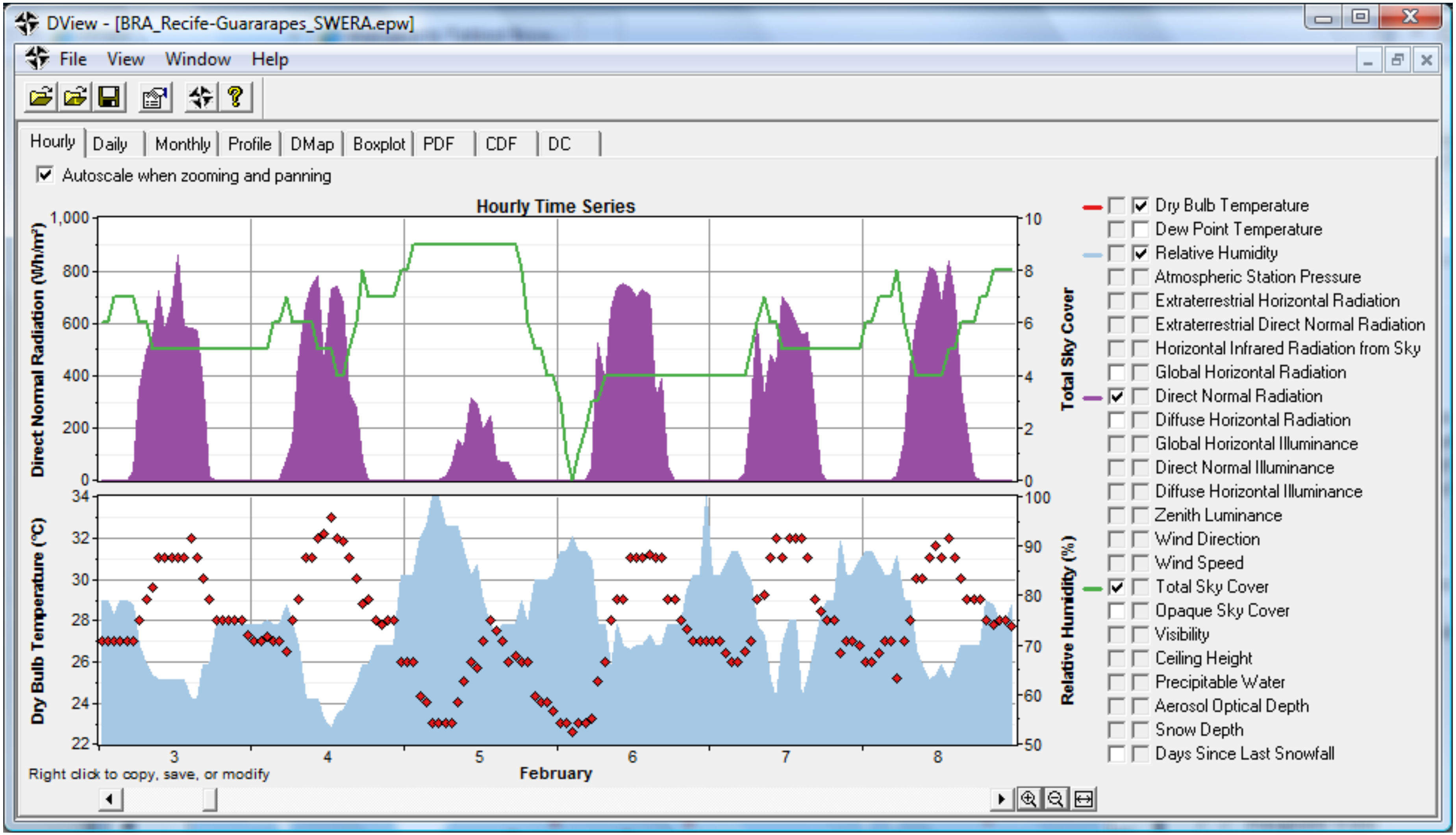
BEopt: Then pick basic characteristics



BEopt: Simulate and compare results



BEopt: Can also download DView for detailed results



BEopt + EnergyPlus demonstration

- HW 5
  - Similar to HW 4
  - Explores enclosure trade-offs with a single-family home using BEopt and EnergyPlus

- Assigned today
  - Due next week