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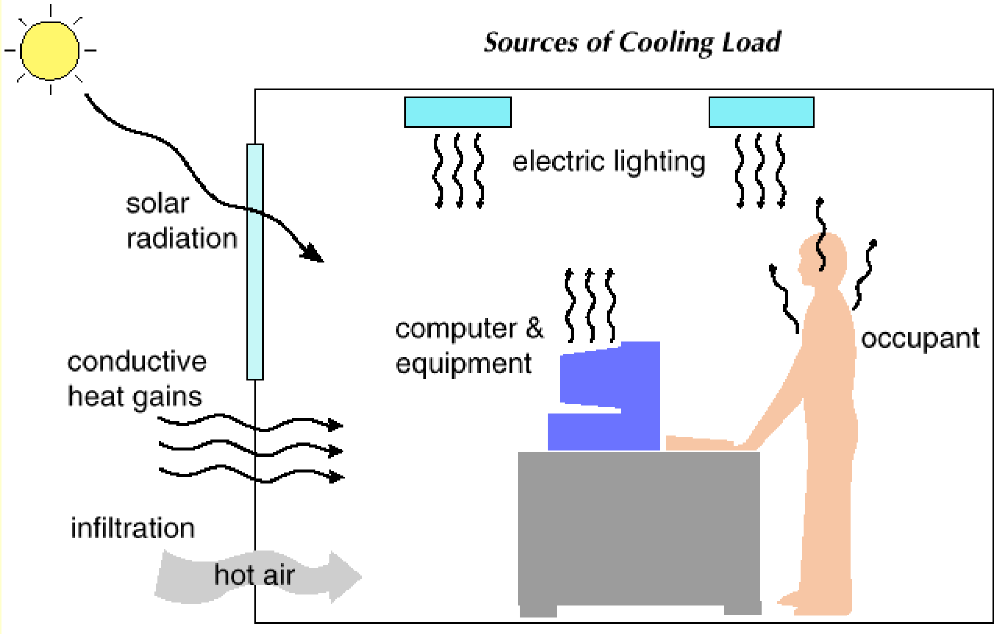

Energy Calculations

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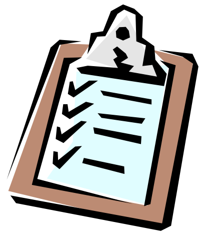

- Objectives
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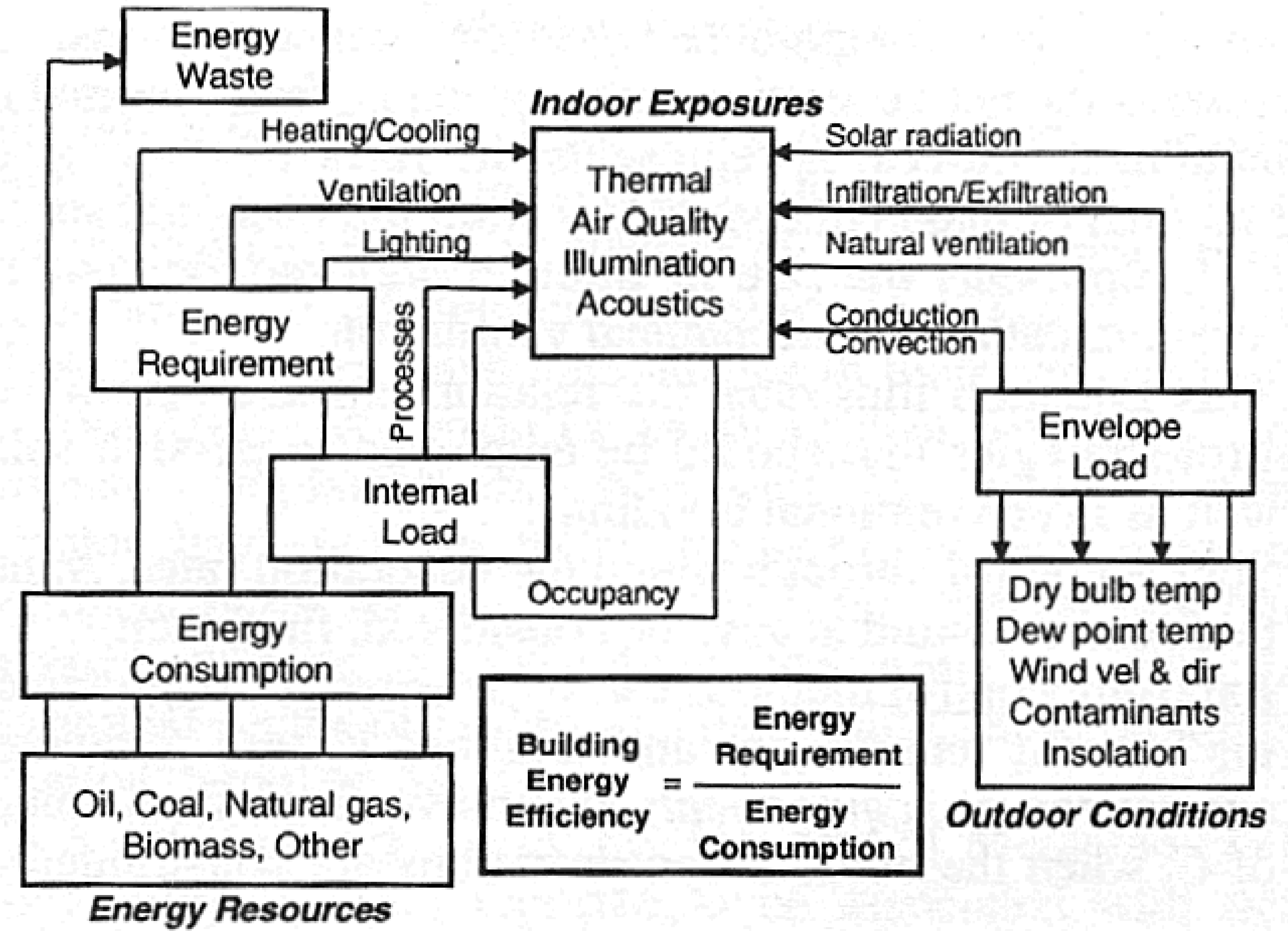
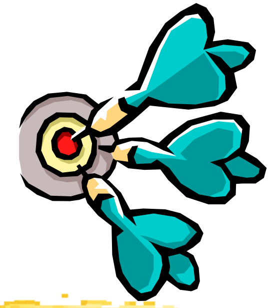
- Transfer Function Method
- Energy Calculation Methods
- Building Energy Simulation



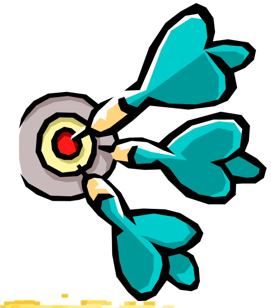
Energy flow and concept in buildings

Objectives



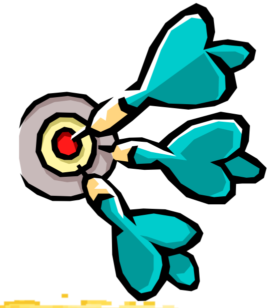
- From *load estimation* to *energy calculations*
  - Only determine peak design loads is not enough
  - Need to evaluate HVAC and building energy consumption
    - To support design decisions (e.g. evaluate design options)
    - To enhance system design and operation
    - To compile with building energy code
- Energy calculations
  - More complicated than design load estimation
  - Form the basis of building energy and economic analysis

Objectives



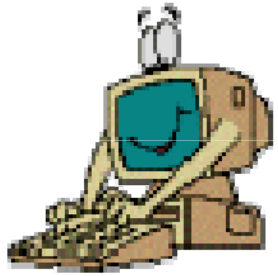
- Load estimation and energy calculations
  - Based on the same principles
  - But, with different purposes & approaches
- Design (peak) load estimation
  - Focus on maximum load or worst conditions
  - For a particular hour or period (e.g. peak summer)
- Energy calculations
  - Focus on average or typical conditions
  - On whole year (annual) performance or multiple years consumption
  - May involve analysis of energy costs & life cycle costs

Objectives



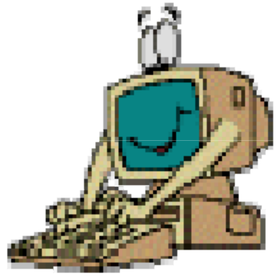
- Tasks at different building design stages
  - Conceptual design stage:
    - Rules of thumb + check figures (rough estimation)
  - Outline/Scheme design:
    - Load estimation (approximation)
    - Design evaluations (e.g. using simplified tools/models)
  - Detailed design:
    - Load calculations (complete)
    - Energy calculations + building energy simulation

Calculation Methodology

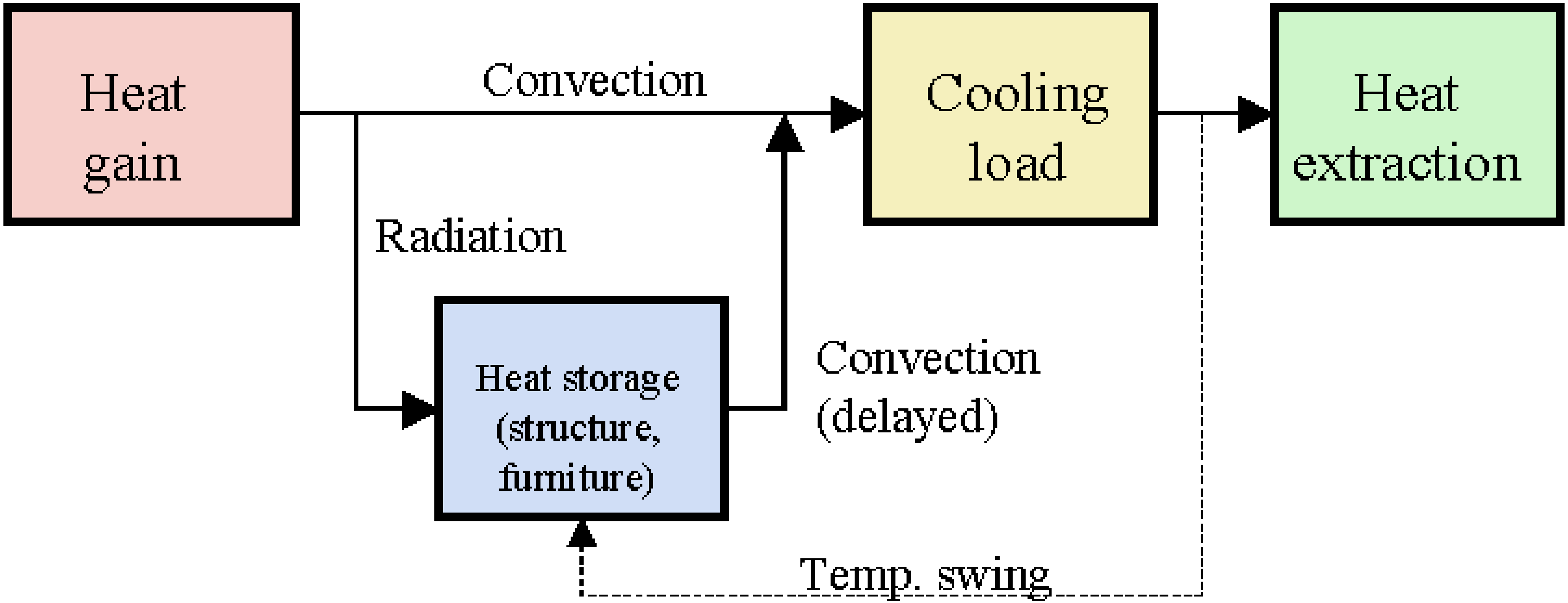


- Basic considerations
  - 1. Peak load calculations
    - Evaluate max. load to size/select equipment
  - 2. Energy analysis
    - Calculate energy use and compare design options
  - 3. Space cooling load $Q = V \rho c_p (t_r - t_s)$
    - To calculate supply air volume flow rate (*V*) and size the air system, ducts, terminals
  - 4. Cooling coil's load
    - To size cooling coil and refrigeration system

Calculation Methodology



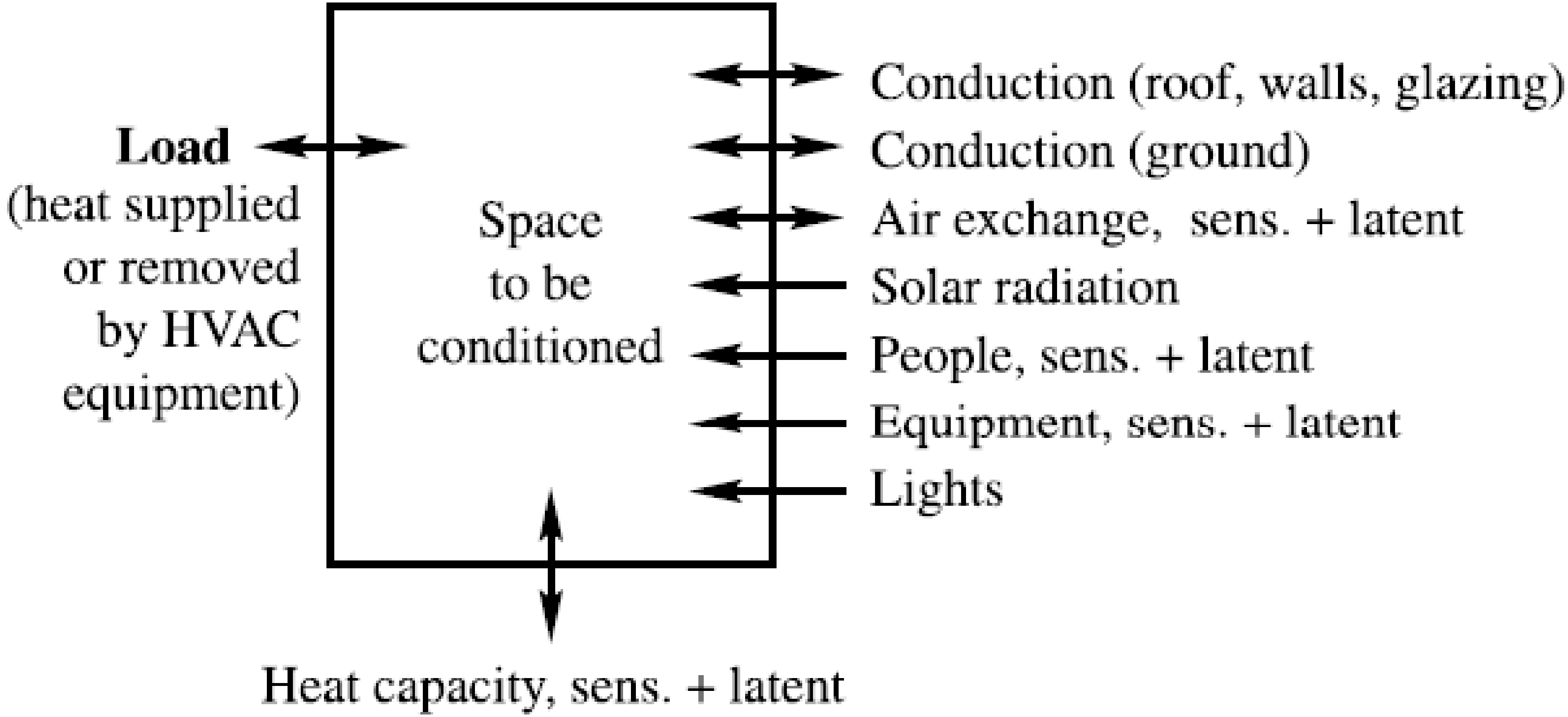
- Basic considerations (cont'd)
  - Assumptions:
    - Heat transfer equations are linear within a time interval (superposition principle holds)
      - Total load = sum of individual ones
    - Convective heat, latent heat & sensible heat gains from infiltration are all equal to cooling load instantaneously
  - Main difference in various methods
    - How to convert space radiative heat gains into space cooling loads



Conversion of heat gain into cooling load

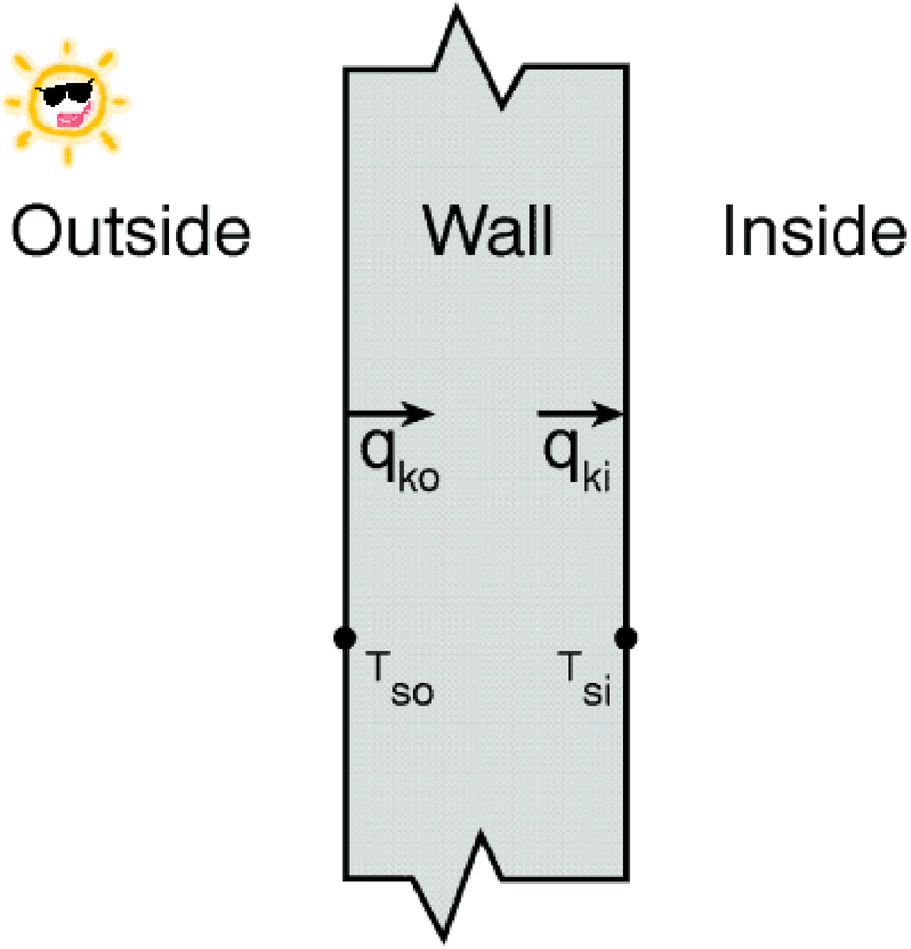
(Source: ASHRAE Handbook Fundamentals 2005)

Thermal Load **Heat Gains/Losses**



Heat storage

(Source: ASHRAE Handbook Fundamentals 2005)



q_{ko} = convective flux into the wall, W/m^2
q_{ki} = convective flux through the wall, W/m^2
T_{so} = wall surface temperature outside, ºC
T_{si} = wall surface temperature outside, ºC

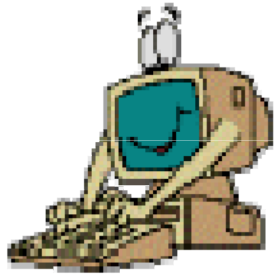
Possible ways to model this process:

1. Numerical finite difference
2. Numerical finite element
3. Transform methods
4. Time series methods

Wall conduction process

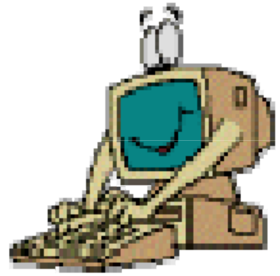
(Source: ASHRAE Handbook Fundamentals 2005)

Calculation Methodology



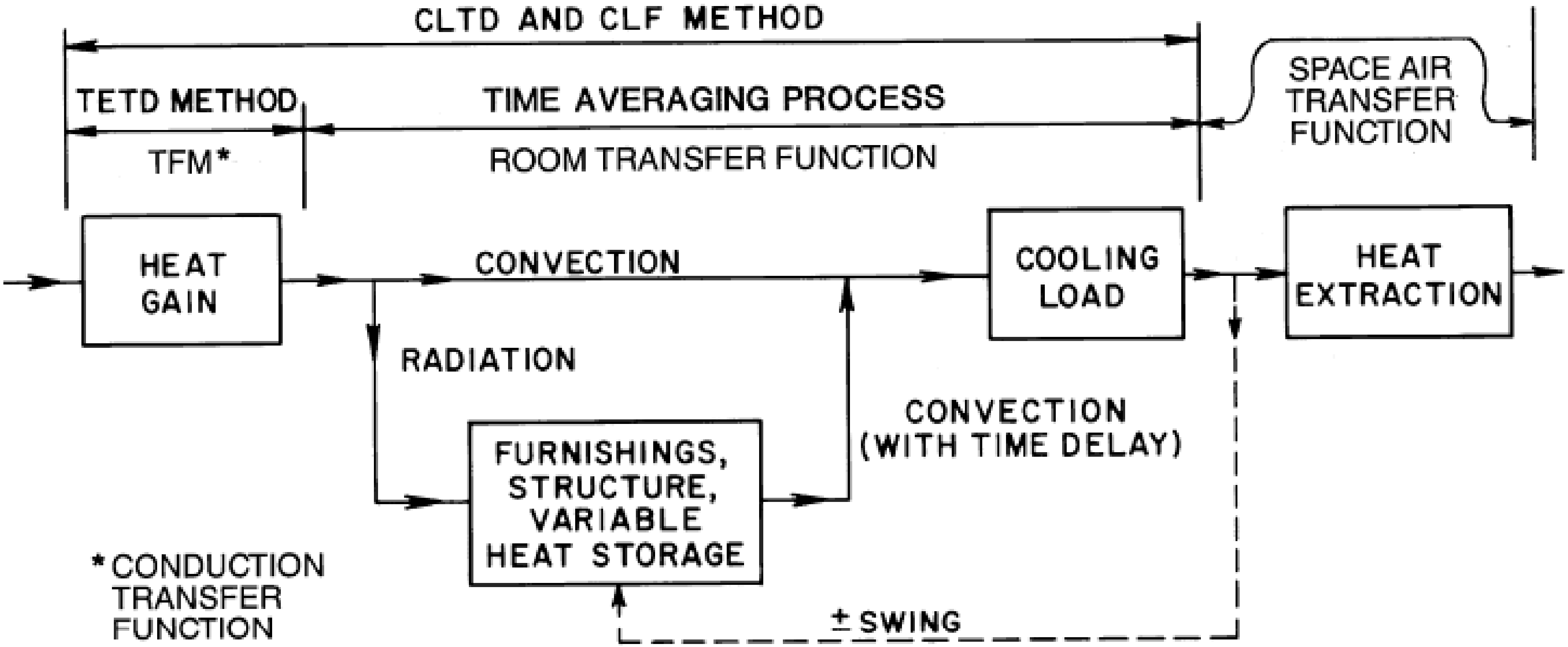
- Common methods:
  - Transfer function method (TFM)
  - Cooling load temperature difference/cooling load factor (CLTD/CLF) method
  - Total equivalent temp. differential/time averaging (TETD/TA) method
- Other existing methods:
  - Finite difference method (FDM)
  - CIBSE method (based on admittance)

Calculation Methodology



- Transfer Function Method (TFM)
  - Laplace transform and *z*-transform of time series
- CLTD/CLF method
  - A one-step simplification of TFM
- TETD/TA method
  - Heat gains calculated from Fourier series solution of 1-dimensional transient heat conduction
  - Average heat gains to current and successive hours according to thermal mass & experience

Basic concepts of TFM, CLTD/CLF and TETD/TA methods



(Source: ASHRAE Handbook Fundamentals 2005)

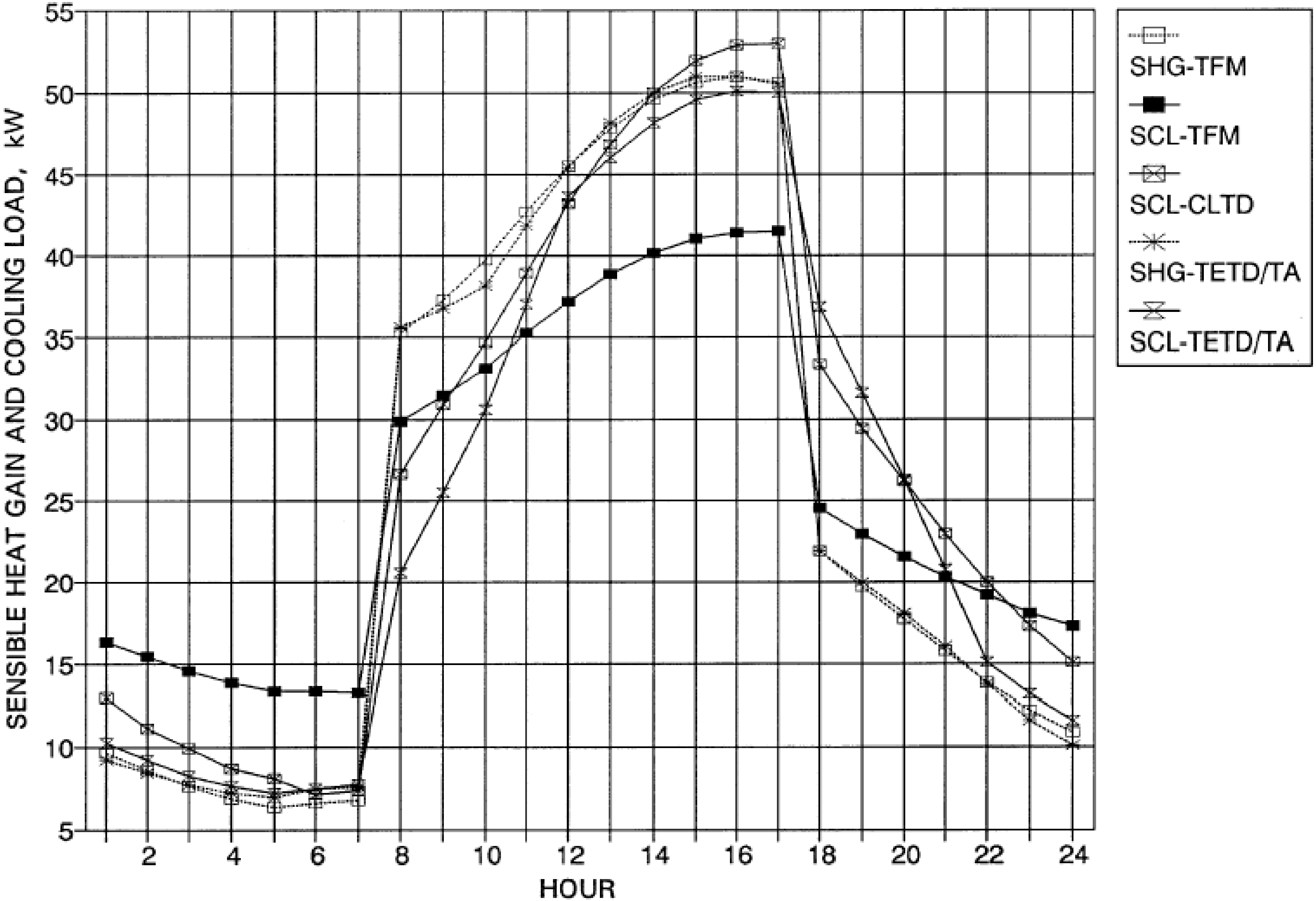
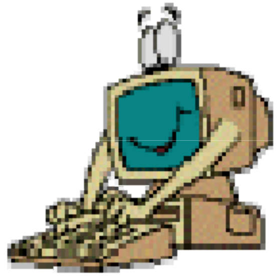


Fig. 5 TFM versus CLTD/SCF/CLF Versus TETD/TA Methods of Calculating Sensible Heat Gain and Cooling Load

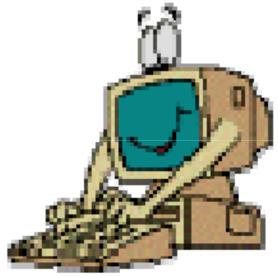
(Source: ASHRAE Handbook Fundamentals 2005)

Calculation Methodology



- Other methods:
  - Heat balance (HB) method
    - The rigorous approach (mainly for research use)
    - Requires solving of partial differential equations and often involves iteration
  - Radiant time series (RTS) method
    - A simplified method derived from HB procedure
  - Finite difference/element method (FDM or FEM)
    - Solve transient simultaneous heat & moisture transfer

Calculation Methodology



- Heat Balance (HB) Method
  - Use heat balance equations to calculate:
    - Surface-by-surface conductive, convective & radiative heat balance for each room surface
    - Convective heat balance for the room air
  - Calculation process
    - Find the inside surface temperatures of building structures due to heat balance
    - Calculate the sum of heat transfer from these surfaces and from internal loads

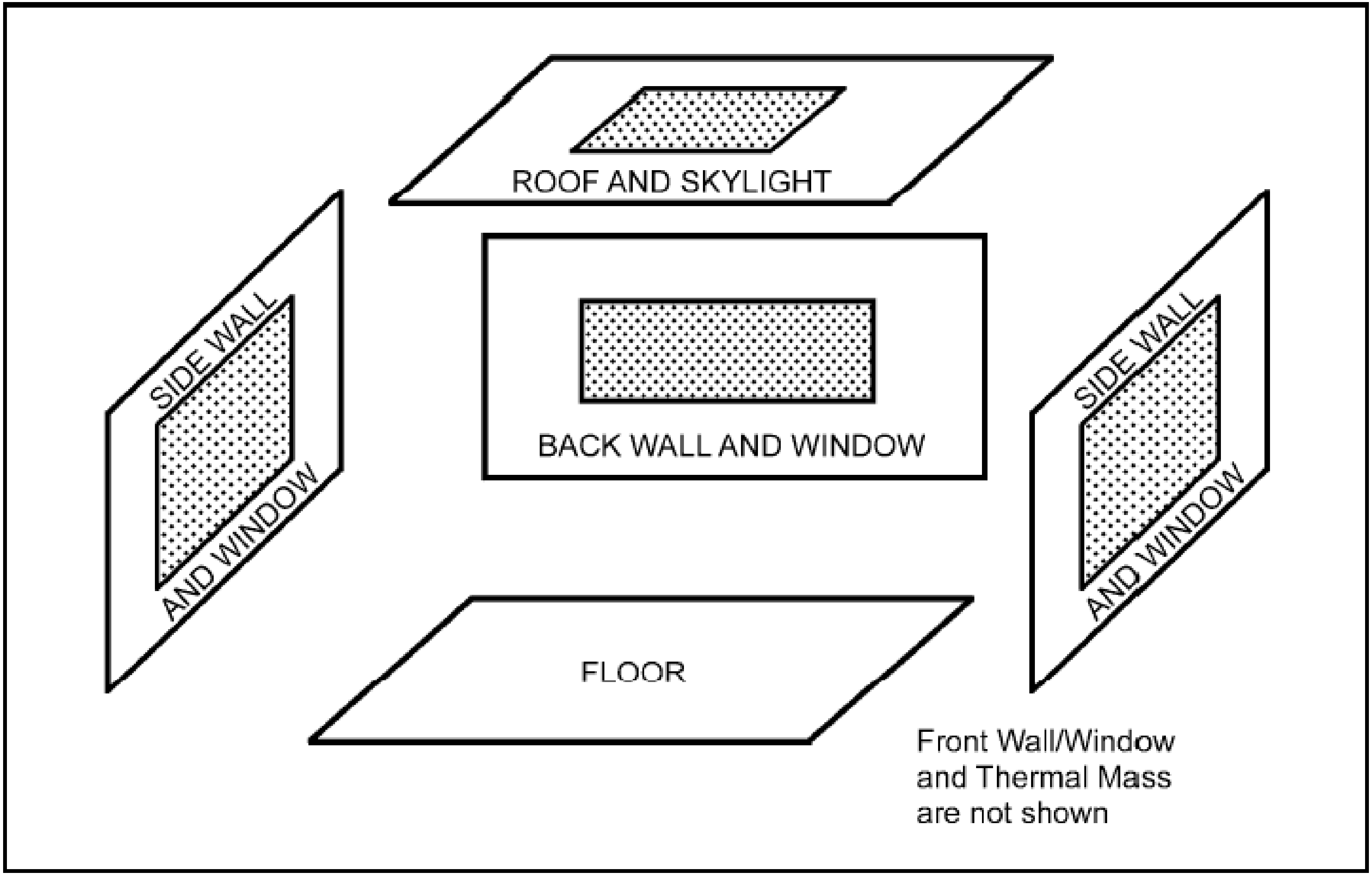
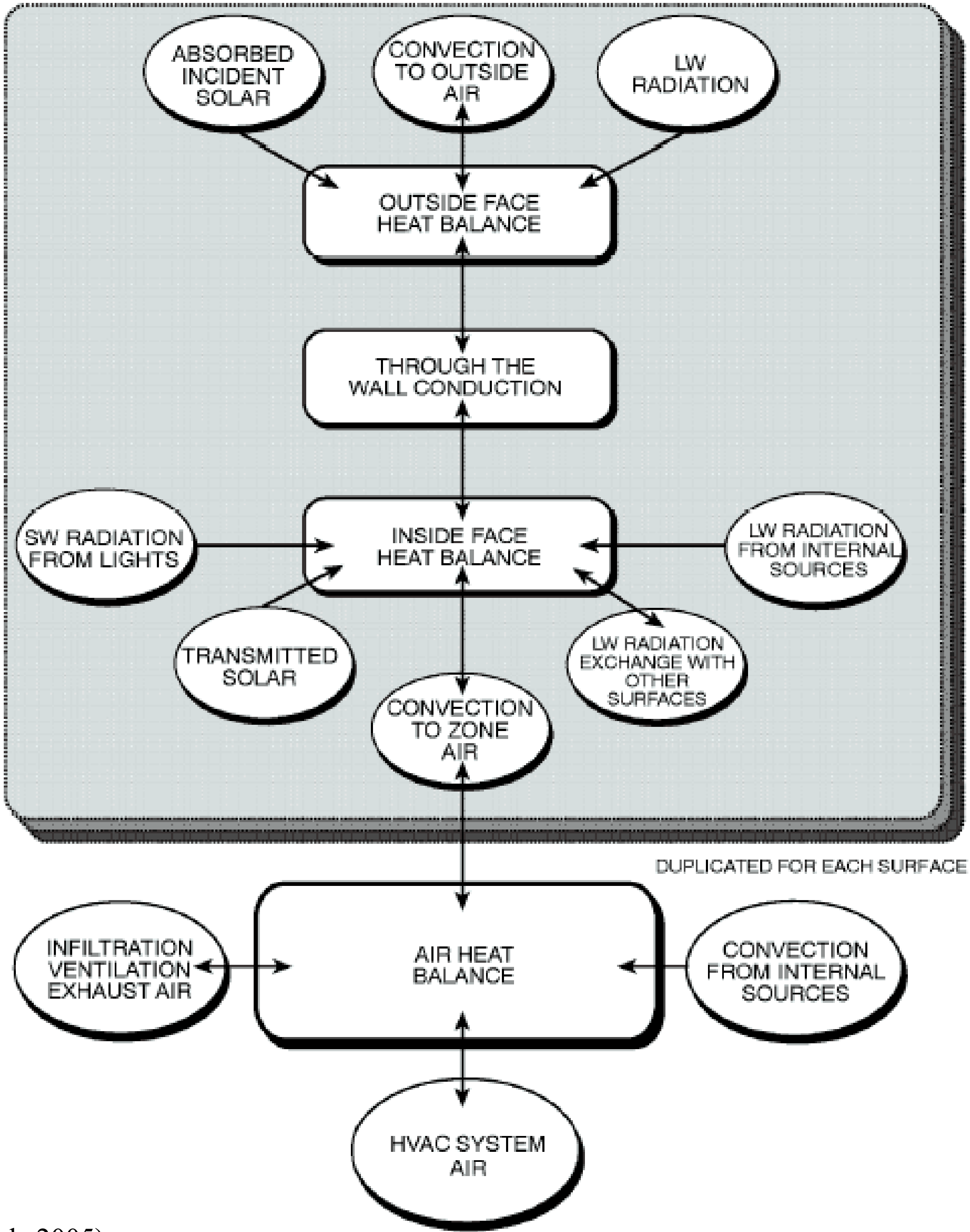


Fig. 7 Schematic View of General Heat Balance Zone

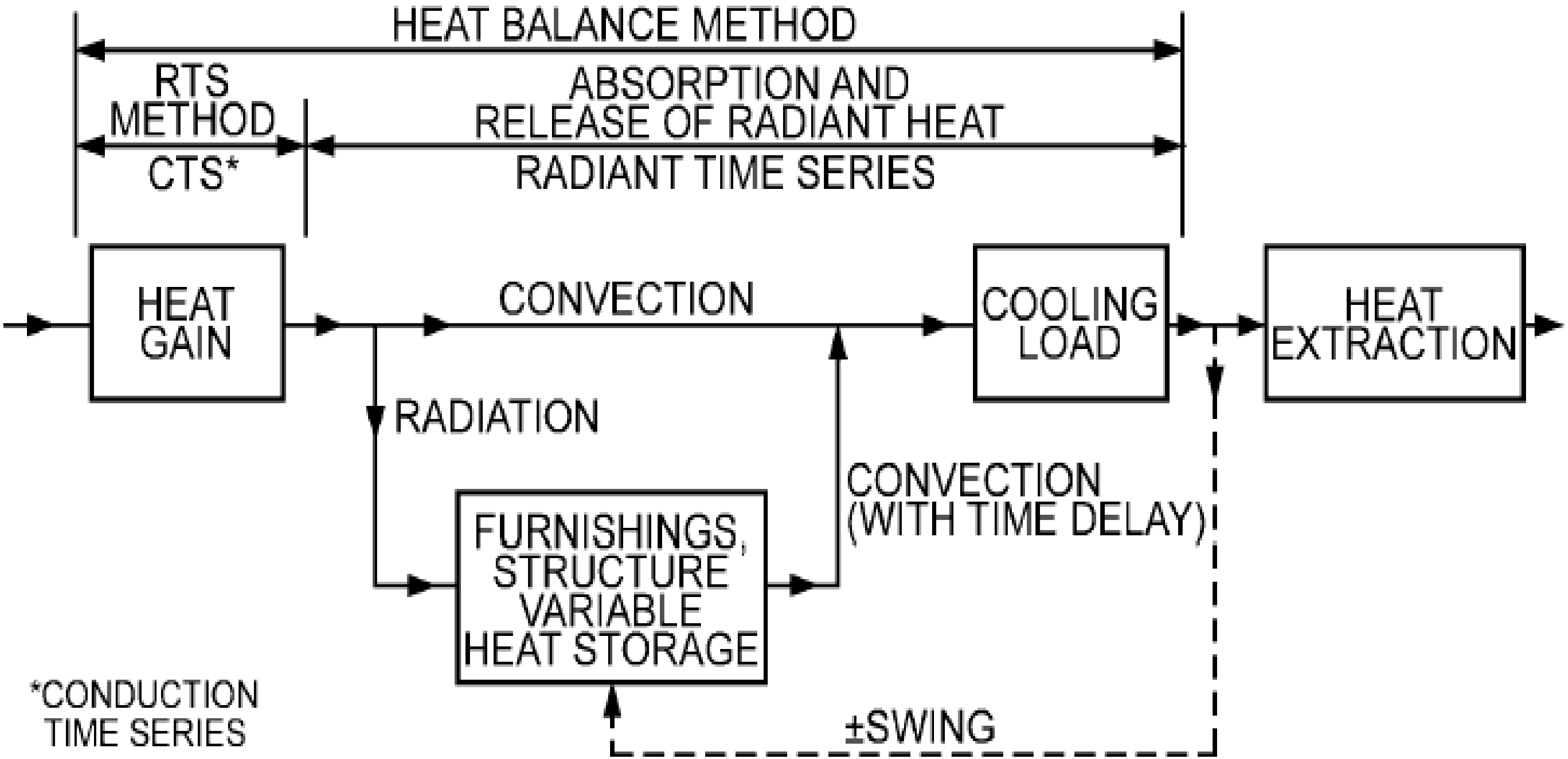
(Source: ASHRAE Handbook Fundamentals 2005)

Heat balance process in a zone



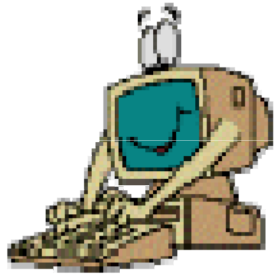
(Source: ASHRAE Handbook Fundamentals 2005)

Basic concepts of heat balance and radiant time series methods



(Source: ASHRAE Handbook Fundamentals 2005)

Calculation Methodology



- Radiant time series (RTS) method
  - A simplified method directly related to and derived from the HB calculation procedure
  - Does not require iterative calculations
  - Can quantify each component contribution to the total cooling load
  - Suitable for peak design load calculations, but not for annual energy simulations

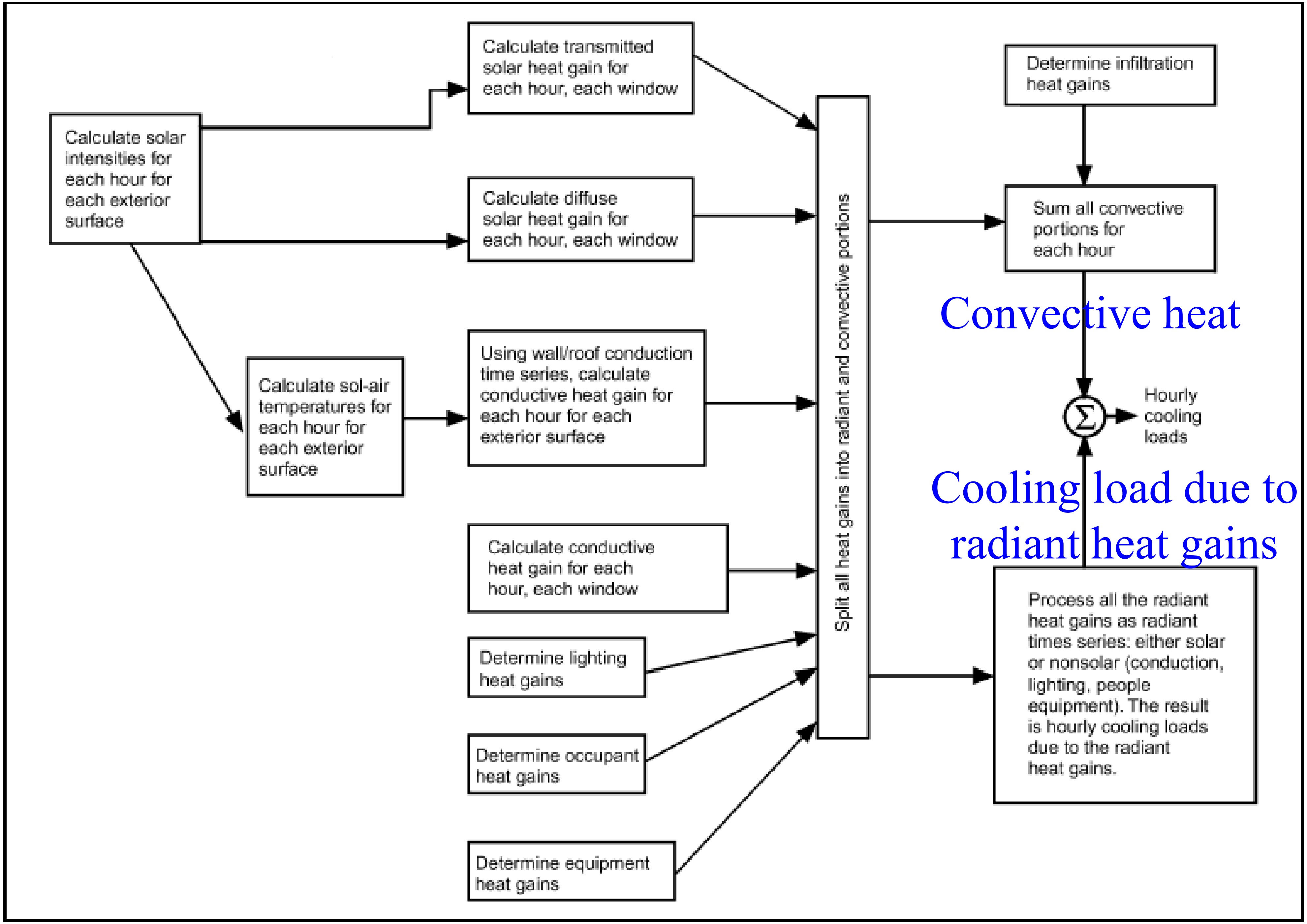
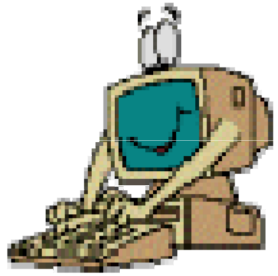


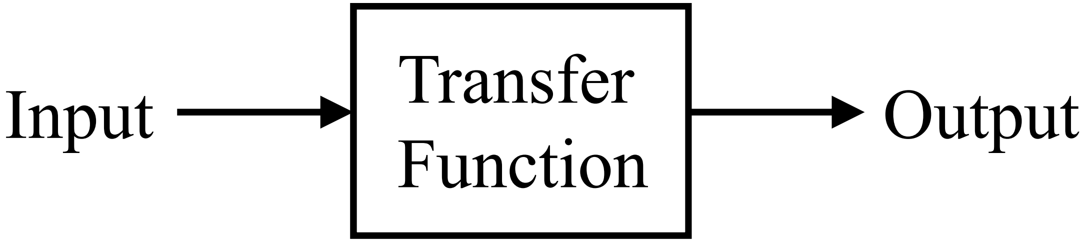
Fig. 8 Overview of Radiant Time Series Method

(Source: ASHRAE Handbook Fundamentals 2005)

Transfer Function Method



- Transfer Function Method (TFM)
  - Most commonly adopted for energy calculations
  - Three components:
    - Conduction transfer function (CTF)
    - Room transfer function (RTF)
    - Space air transfer function (SATF)
  - Implemented numerically using weighting factors
    - Transfer function coefficients, to weight the importance of current & historical values of heat gain & cooling load on currently calculated loads



Transfer function (K)

Polynominals of z-transform

$$K = Y/G = \left(v_o + v_1 z^{-1} + v_2 z^{-2} + \ldots\right) \Big/ \left(1 + w_1 z^{-1} + w_2 z^{-2} + \ldots\right)$$

Y = Laplace transform of the output
G = Laplace transform of the input or driving force

When a continuous function $f(t)$ is represented at regular intervals Δt and its magnitude are $f(0)$, $f(\Delta)$, $f(2\Delta)$,…, $f(n\Delta)$, the Laplace transform is given by a polynominal called “z-transform”:

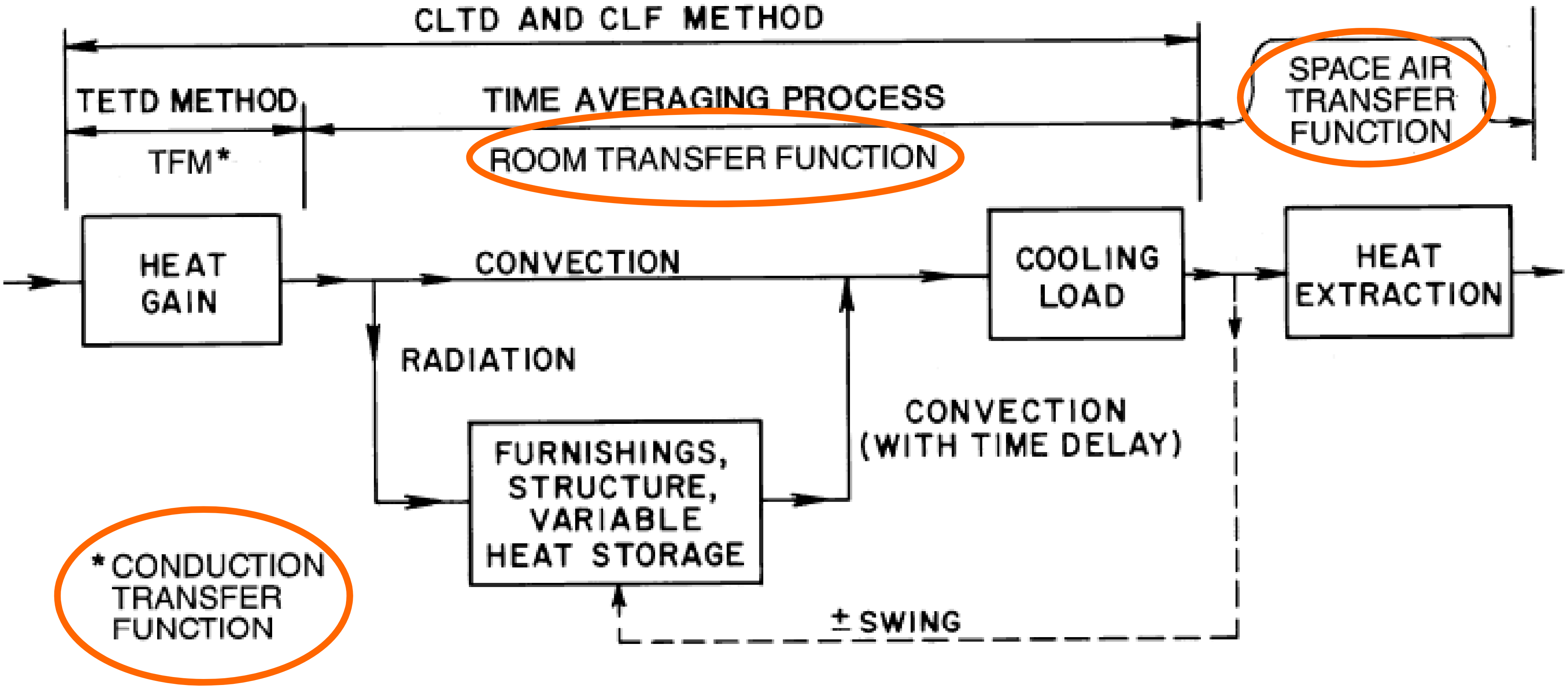
$$\varphi(z) = f(0) + f(\Delta)\, z^{-1} + f(2\Delta)\, z^{-2} + \ldots + f(n\Delta)\, z^{-n}$$

where Δ = time interval, hour

$$z = e^{t\Delta}$$

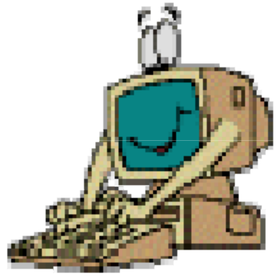
v_0, v_1, v_2, … & w_1, w_2, … are weighting factors for the calculations

Three components of transfer function method (TFM)



(Source: ASHRAE Handbook Fundamentals 2005)

Transfer Function Method



- Sol-air temperature (t_e)
  - A fictitious outdoor air temperature that gives the rate of heat entering the outer surface of walls and roofs due to the combined effect of incident solar radiation, radiative heat exchange with the sky vault and surroundings, and convective heat exchange with the outdoor air

$$t_e = t_o + \frac{\alpha E_t}{h_o} - \frac{\varepsilon \Delta R}{h_o}$$

Outdoor air temp

Surface absorptance

Surface emittance

Heat balance at a sunlit surface, heat flux is equal to:

$$\frac{q}{A} = \alpha E_t + h_o(t_o - t_s) - \varepsilon \Delta R$$

where

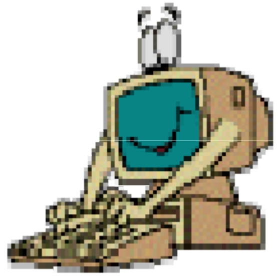
α = absorptance of surface for solar radiation
E_t = total solar radiation incident on surface, $W/(m^2 \cdot K)$
h_o = coefficient of heat transfer by long-wave radiation and convection at outer surface, $W/(m^2 \cdot K)$
t_o = outdoor air temperature, °C
t_s = surface temperature, °C
ε = hemispherical emittance of surface
ΔR = difference between long-wave radiation incident on surface from sky and surroundings and radiation emitted by blackbody at outdoor air temperature, W/m^2

Assume the heat flux can be expressed in terms of sol-air temp. (t_e)

$$\frac{q}{A} = h_o(t_e - t_s)$$

Thus, sol-air temperature is given by: $t_e = t_o + \frac{\alpha E_t}{h_o} - \frac{\varepsilon \Delta R}{h_o}$

Transfer Function Method



- External walls and roofs:

Sol-air temperature

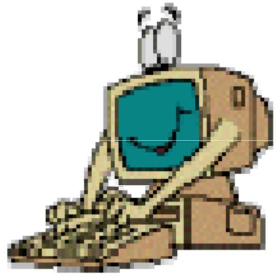
$$q_{e,t} = A\left[\sum_{n=0} b_n T_{sol,t-n\delta} - \sum_{n=1} d_n \left(q_{e,t-n\delta}/A\right)\right] - T_r \sum_{n=0} c_n$$

- Ceiling, floors & partition wall:

$$q_{aj,t} = UA\left(T_{aj} - T_r\right)$$

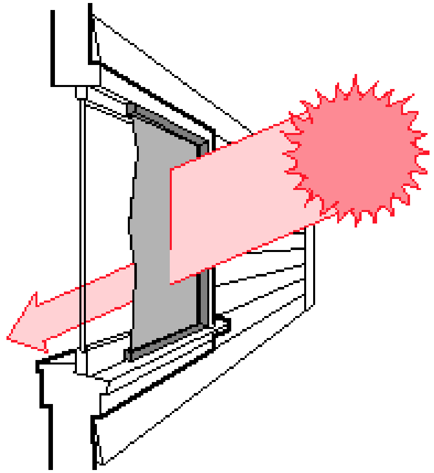
aj = adjacent

r = room



Transfer Function Method

- Window glass
  - Solar heat gain:
    - Shading coefficient (SC)
    - Solar heat gain factor (SHGF)



$$q_{\mathrm{es},t} = \left(A_{\mathrm{s}} \times \mathrm{SHGF} \times \mathrm{SC}\right) + \left(A_{\mathrm{sh}} \times \mathrm{SHGF}_{\mathrm{sh}} \times \mathrm{SC}\right)$$

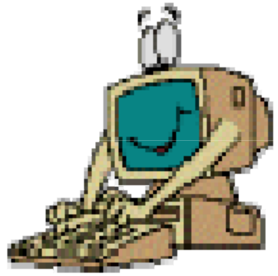
Sunlit   Shaded

  - Conduction heat gain: U-value

$$q_{\mathrm{ec},t} = U_{\mathrm{g}}\left(A_{\mathrm{s}} + A_{\mathrm{sh}}\right)\left(T_{\mathrm{o},t} - T_{\mathrm{r}}\right)$$

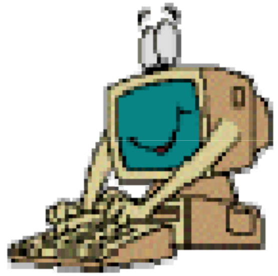
Sunlit   Shaded

Transfer Function Method



- Internal heat gains
  - People (sensible + latent)
  - Lights
  - Machine & appliances
- Infiltration (uncontrolled, via cracks/opening)
  - If positive pressure is maintained in conditioned space, infiltration is normally assumed zero

Transfer Function Method



- Convert heat gain into cooling load
  - Space sensible cooling load (from radiative):

$$q_{\text{s-e},t} = \sum_{i=1} \left(v_o q_{\text{e},t} + v_1 q_{\text{e},t-\delta} + v_2 q_{\text{e},t-2\delta} + \ldots \right) - \left(w_1 q_{\text{r},t-\delta} + w_2 q_{\text{r},t-2\delta} + \ldots \right)$$

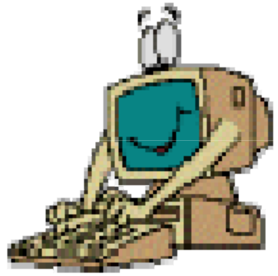
$v_0, v_1, v_2, \ldots$ & $w_1, w_2, \ldots$ are weighting factors

  - Space sensible cooling load (from convective):

$$q_{\text{s-c},t} = \sum_{k=1} q_{\text{ec},t}$$

  - Space latent cooling load: $q_{\text{rl},t} = \sum_{m=1} q_{\text{el},t}$

Transfer Function Method



- Convert heat gain into cooling load (cont'd)
  - Heat extraction rate & space air temperature

$$\sum_{i=0}^{1} p_i \left(q_{\mathrm{xs},t} - q_{\mathrm{rs},t-\mathrm{i}\delta} \right) = \sum_{i=0}^{2} g_i \left(T_{\mathrm{r}} - T_{\mathrm{r},t-\mathrm{i}\delta} \right)$$

  - Cooling coil load (sensible & latent)
    - Air mixture & air leaving the cooling coil
    - Ventilation load

Energy Calculation Methods

- Two categories
  - Steady-state methods
    - Degree-day method
    - Variable base degree-day method
    - Bin and modified bin methods
  - Dynamic methods
    - Using computer-based building energy simulation
    - Try to capture dynamic response of the building
    - Can be developed based on transfer function, heat balance or other methods

Energy Calculation Methods

- Degree-day method
  - A degree-day is the sum of the number of degrees that the average daily temperature (technically the average of the daily maximum and minimum) is above (for cooling) or below (for heating) a base temperature times the duration in days
    - Heating degree-days (HDD)
    - Cooling degree-days (CDD)
  - Summed over a period or a year for indicating climate severity (effect of outdoor air on a building)

Heating degree-day:

$$DD_h(t_{bal}) = (1\text{ day}) \sum_{\text{days}} (t_{bal} - t_o)^+$$

Cooling degree-day:

$$DD_c(t_{bal}) = (1\text{ day}) \sum_{\text{days}} (t_o - t_{bal})^+$$

$^+$ Only take the positive values

t_{bal} = base temperature (or balance point temperature)
(e.g. 18.3 °C or 65 °F); $Q_{load} = Q_{gain} + Q_{loss} = 0$
t_o = outdoor temperature (e.g. average daily max./min.)

* Degree-hours if summing over 24-hourly intervals
Degree-day = $\Sigma(\text{degree-hours})^+ / 24$

To determine the heating degree-day:

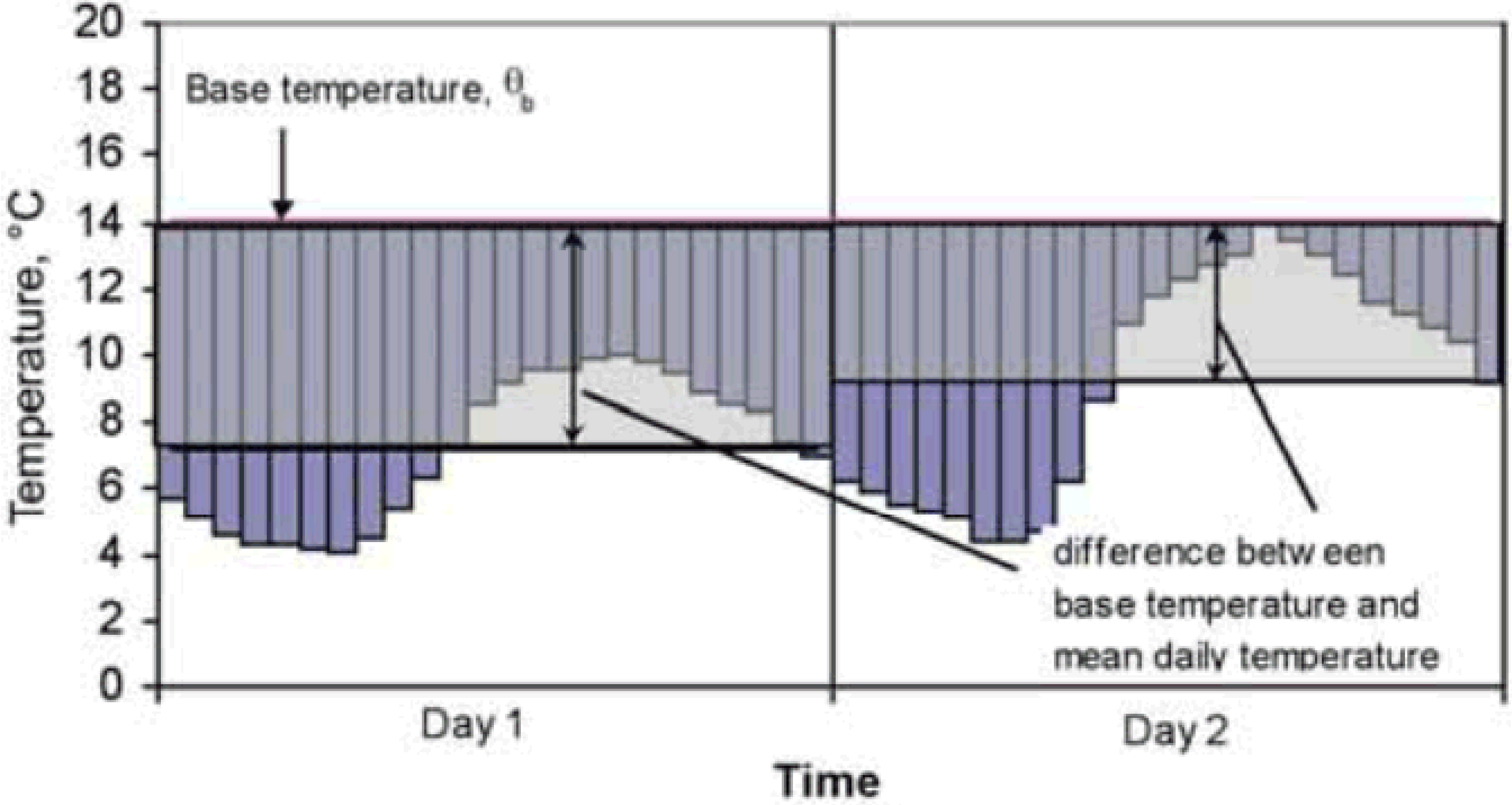


Figure 1.1 The basic definition of degree-days as the difference between the base temperature and the mean daily outdoor temperature

To determine the heating degree-day (cont'd):

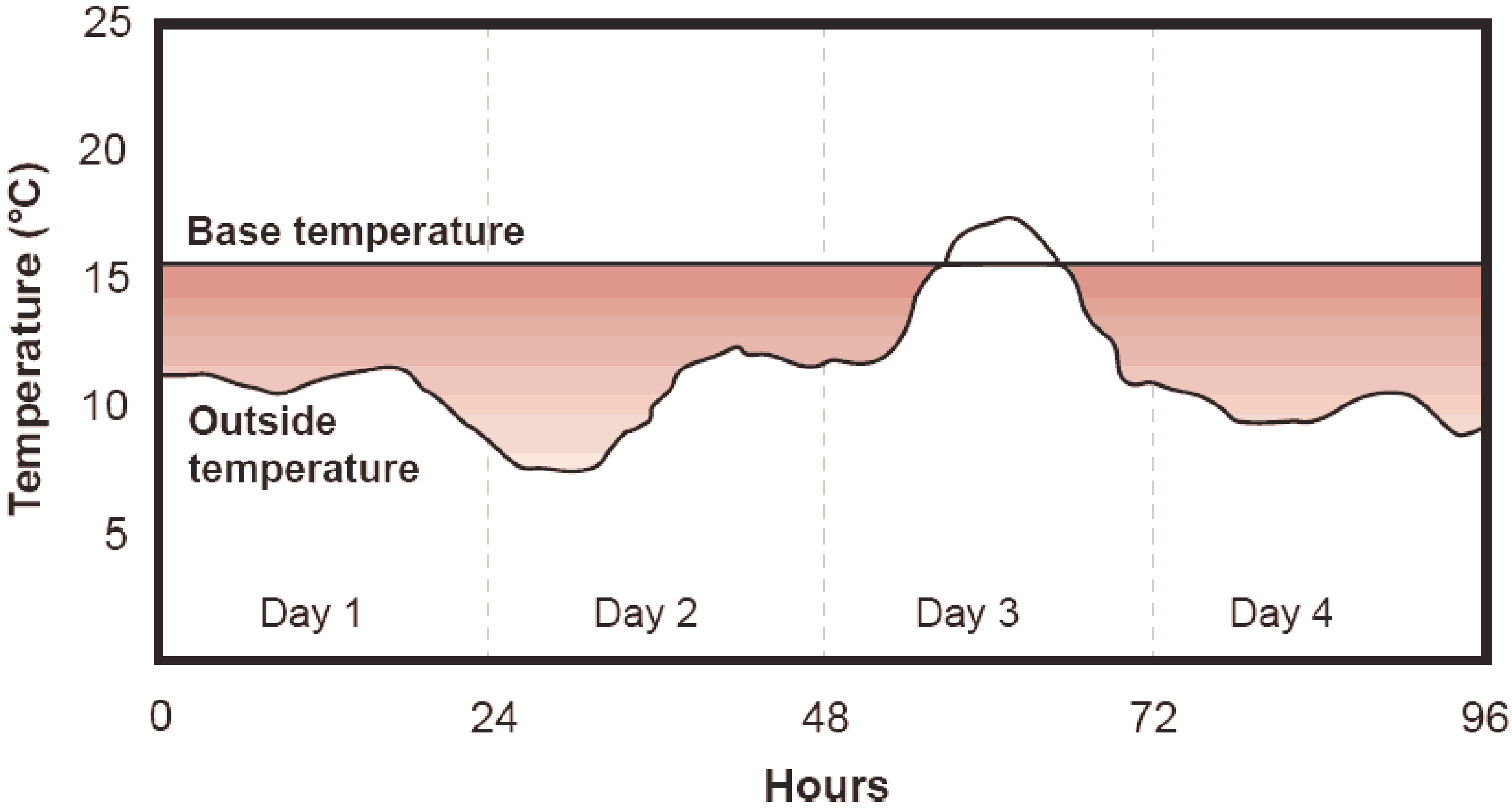
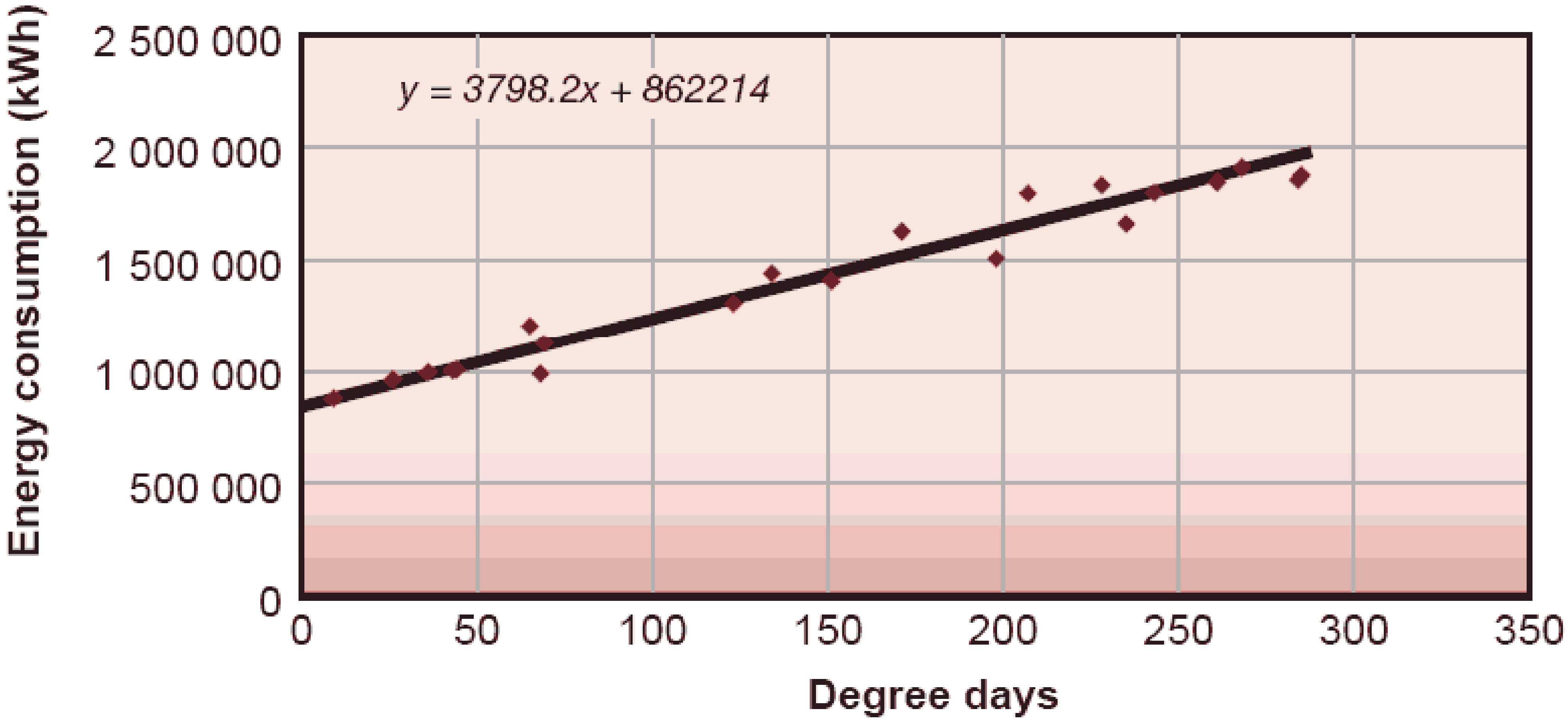


Figure 1 The shaded area is the degree-day value for the period



Correlation between energy consumption and degree days

Energy Calculation Methods

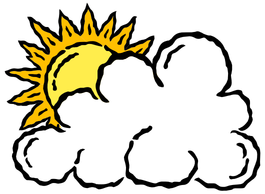
- Variable base degree-day (VBDD) method
  - Degree-day with variable reference temperatures
    - To account for different building conditions and variation between daytime and nighttime
    - First calculate the balance point temperature of a building and then the heating and cooling degree hours at that base temperature
    - Require tedious calculations and detailed processing of hourly weather data at a complexity similar to hourly simulations. Therefore, does not seem warranted nowadays (why not just go for hourly simulation)

Energy Calculation Methods

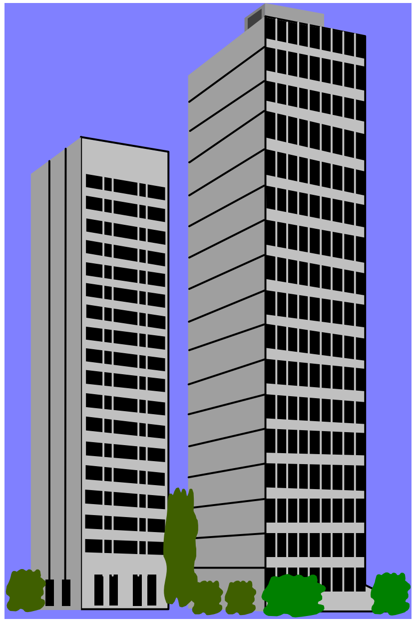
- Bin and modified bin methods
  - Evolve from VBDD method
  - Derive building annual heating/cooling loads by calculating its loads for a set of temperature “bins”
  - Multiplying the calculated loads by nos. of hours represented by each bin (e.g. 18-20, 20-22, 22-24 ^{o}C)
  - Totaling the sums to obtain the loads (cooling/heating energy)
  - Original bin method: not account of solar/wind effects
  - Modified bin method: account for solar/wind effects

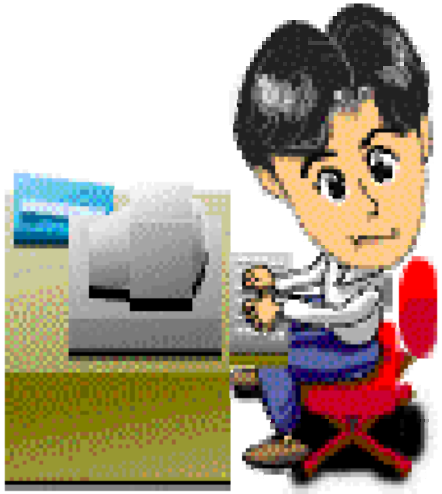
Energy Calculation Methods

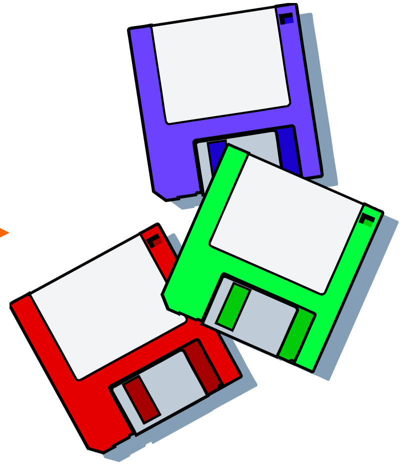
- Dynamic simulation methods
  - Usually hour-by-hour, for 8,760 hours (24 x 365)
  - Energy calculation sequence:
    - Space or building load [LOAD]
    - Secondary equipment load (airside system) [SYSTEMS]
    - Primary equipment energy requirement (e.g. chiller) [PLANT]
  - Computer software
    - Building energy simulation programs, e.g. Energy-10, DOE-2, TRACE 700, Carrier HAP



Weather data







Building description

- physical data
- design parameters

Simulation tool (computer program)

Simulation outputs

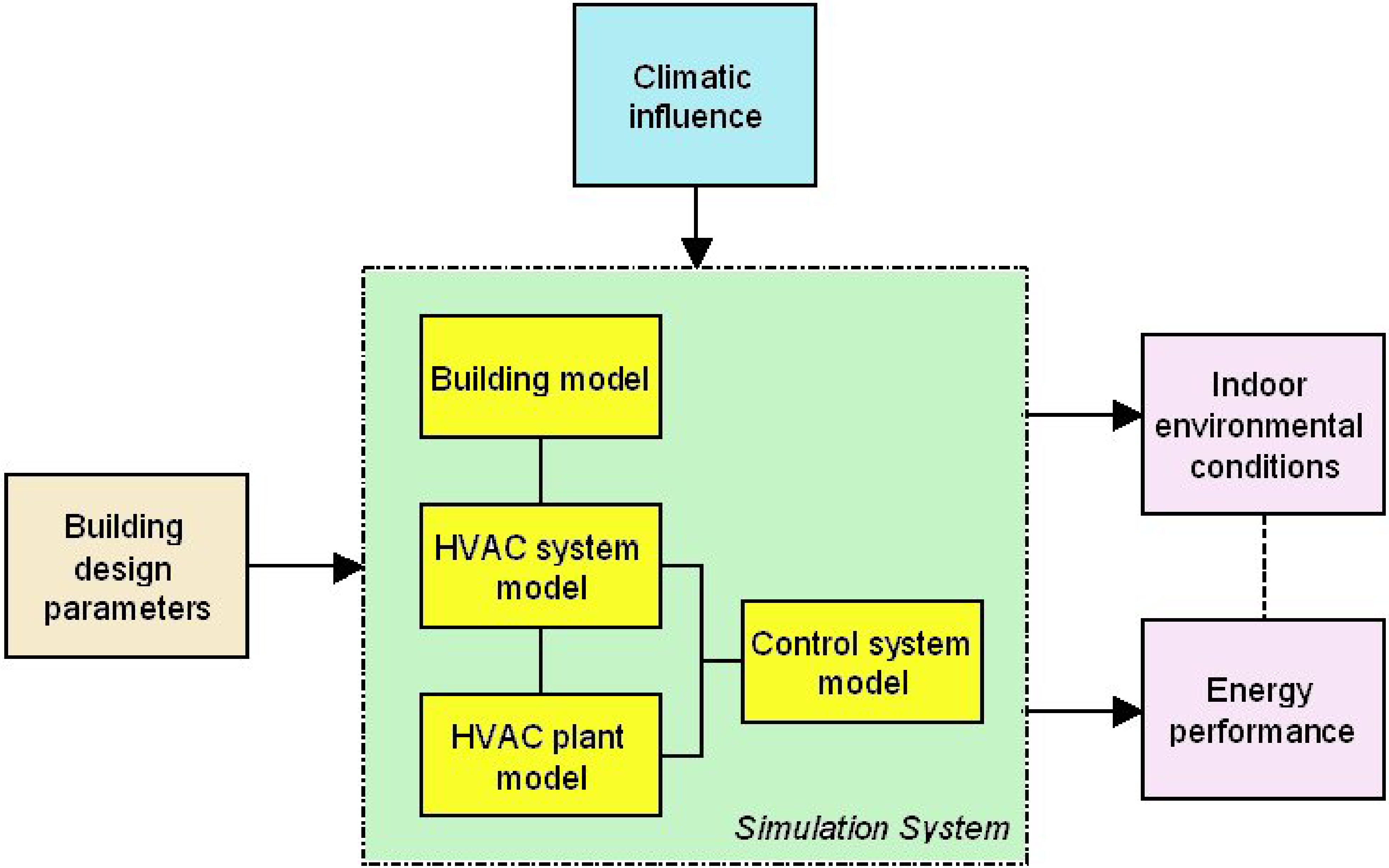
- energy consumption (MWh)
- energy demands (kW)
- environmental conditions

Building Energy Simulation

- Building energy simulation
  - Analysis of energy performance of building using computer modelling and simulation techniques
- Many issues can be studied, such as:
  - Thermal performance (e.g. bldg. fabric, glazing)
  - Comfort and indoor environment
  - Ventilation and infiltration
  - Daylighting and overshadowing
  - Energy consumption of building systems

Building Energy Simulation

- Four major elements
  - Building model
  - HVAC system model
  - HVAC plant model
  - Control system model
- An economic model may be added for life cycle costing



Major elements of building energy simulation

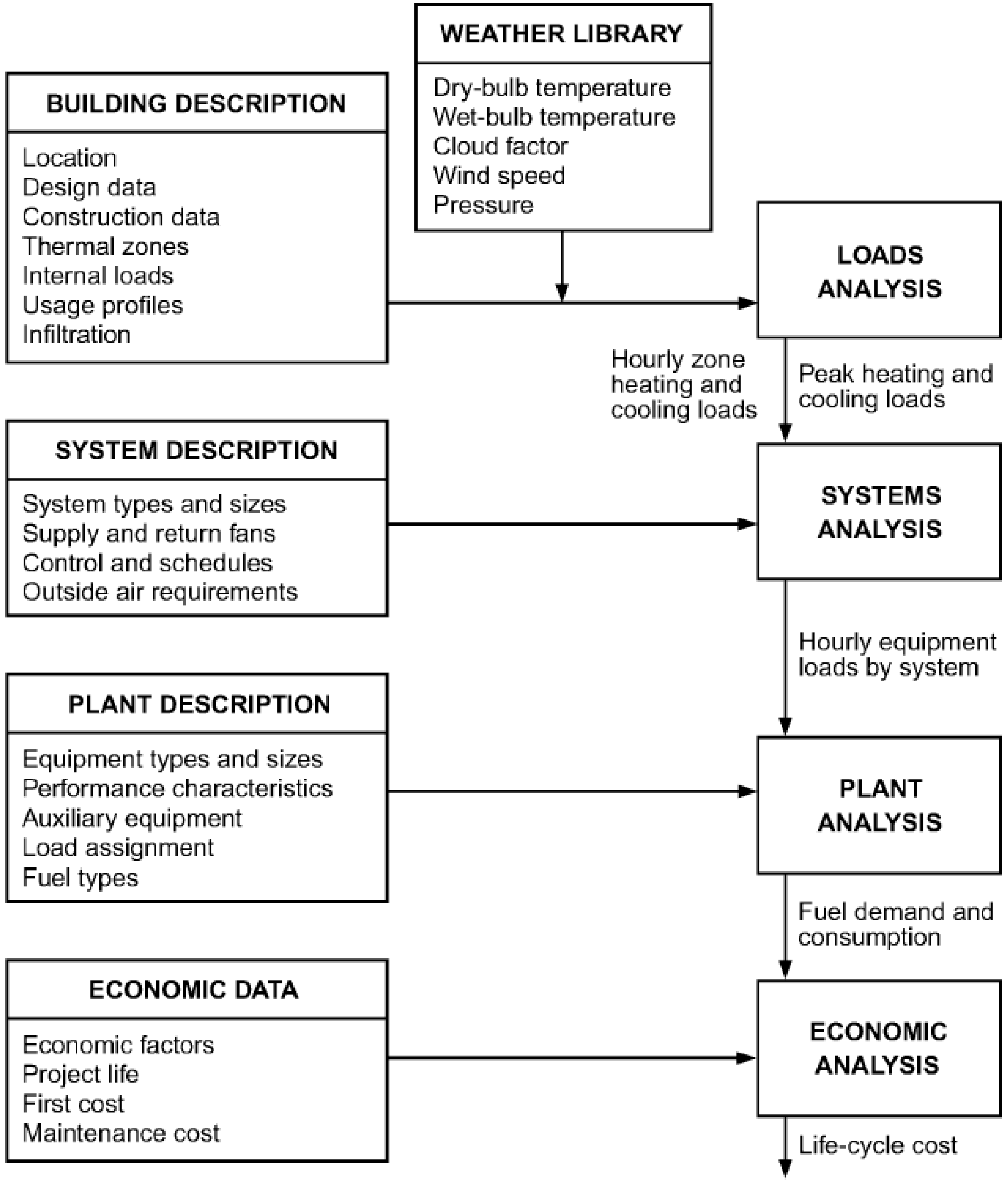
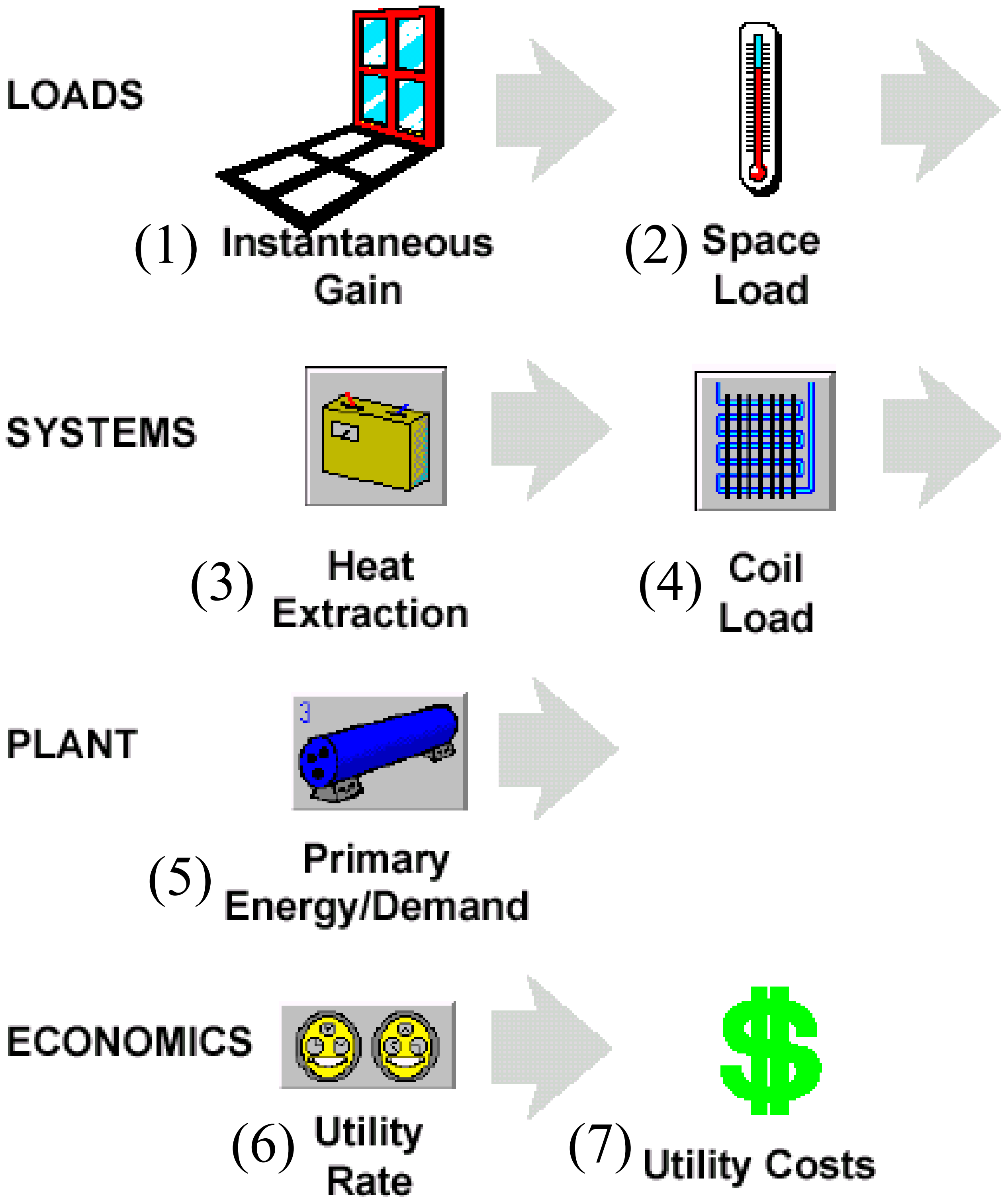


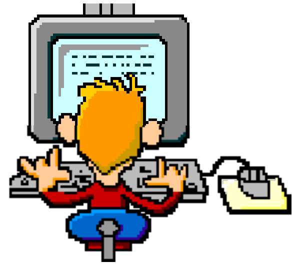
Fig. 1 Flow Chart for Building Energy Simulation Program

(Source: ASHRAE Handbook Fundamentals 2005)

“Seven steps” of simulation output



Building Energy Simulation



- Examples of building energy simulation tools
  - Simplified
    - Energy-10, ENER-WIN, Solar-5, Energy Scheming
  - Detailed
    - DOE-2, BLAST, ESP-r, TRNSYS, EnergyPlus
  - Commercial (proprietary)
    - Carrier HAP, TRACE 700

ENERGY-10

blast

EnergyPlus

DOE-2

Solar-5

ESP-r

ENER-WIN©

Hourly Energy Simulation Program for Buildings

Building Energy Simulation Software

TRNSYS

Carrier

E-20-II & HAP

HOT2000

TRANE

TRACE 700

ADELINE

Tas

Building Energy Simulation

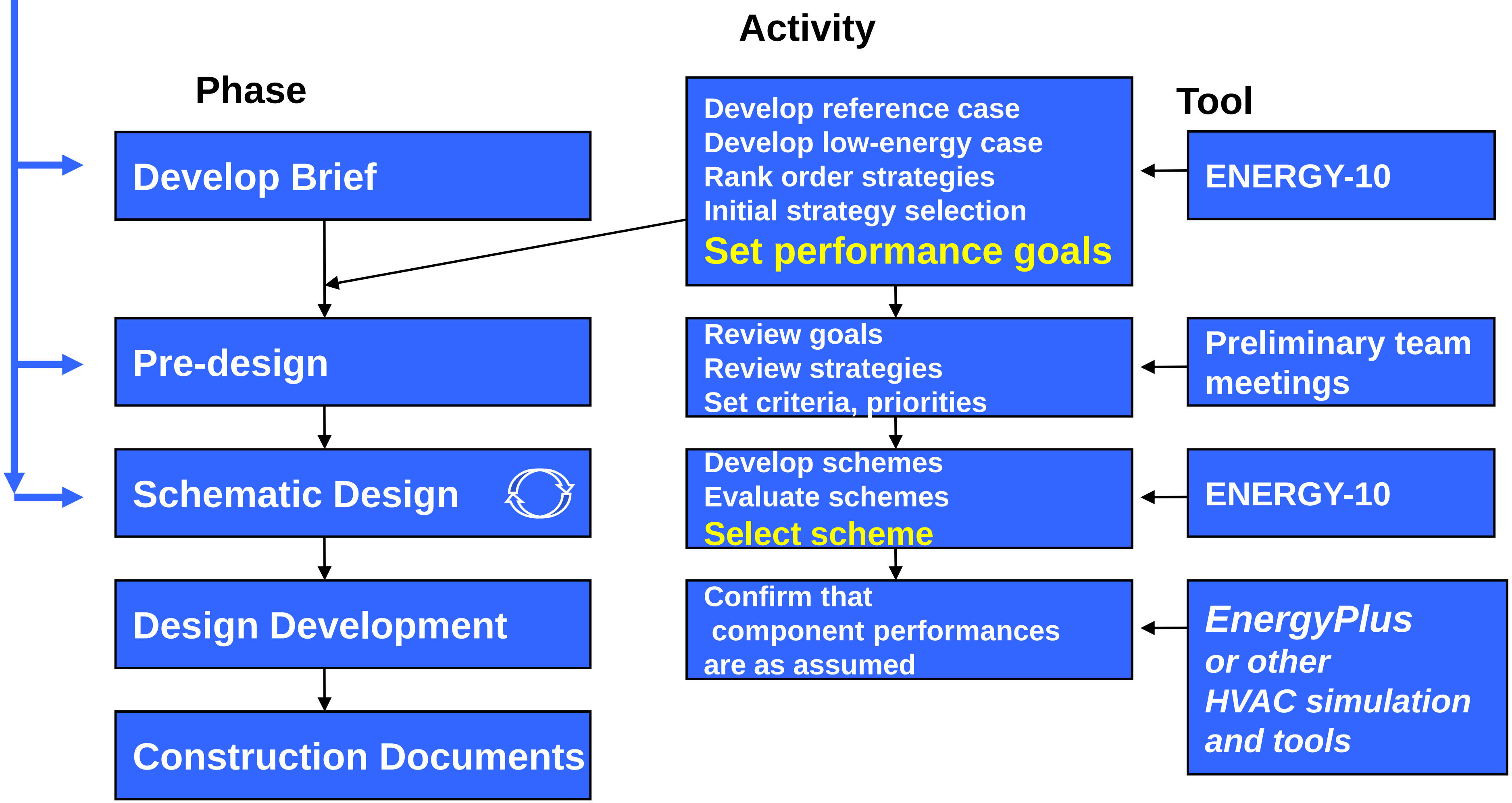
- Software examples:
  - Energy-10
    - http://www.nrel.gov/buildings/energy10.html
    - http://www.energy-10.com/
  - DOE-2 (VisualDOE 4.1)
    - http://gundog.lbl.gov/dirsoft/d2whatis.html
    - http://www.archenergy.com/products/visualdoe/

Building Energy Simulation

- Energy software example:
  - Energy-10
    - A software tool that helps architects and engineers quickly identify the most cost-effective, energy-saving measures to take in designing a low-energy building
    - Suitable for small commercial and residential buildings that are characterized by one, or two thermal zones (less than 10,000 ft^2 or 1,000 m^2)
    - http://www.nrel.gov/buildings/energy10.html
    - http://www.energy-10.com/

Example: Energy-10

ENERGY-10 **focuses on the first phases (conceptual design)**



Example: Energy-10

- Creates two building descriptions based on five inputs and user-defined defaults.

•Location
•Building Use
•Floor area
•Number of stories
•HVAC system

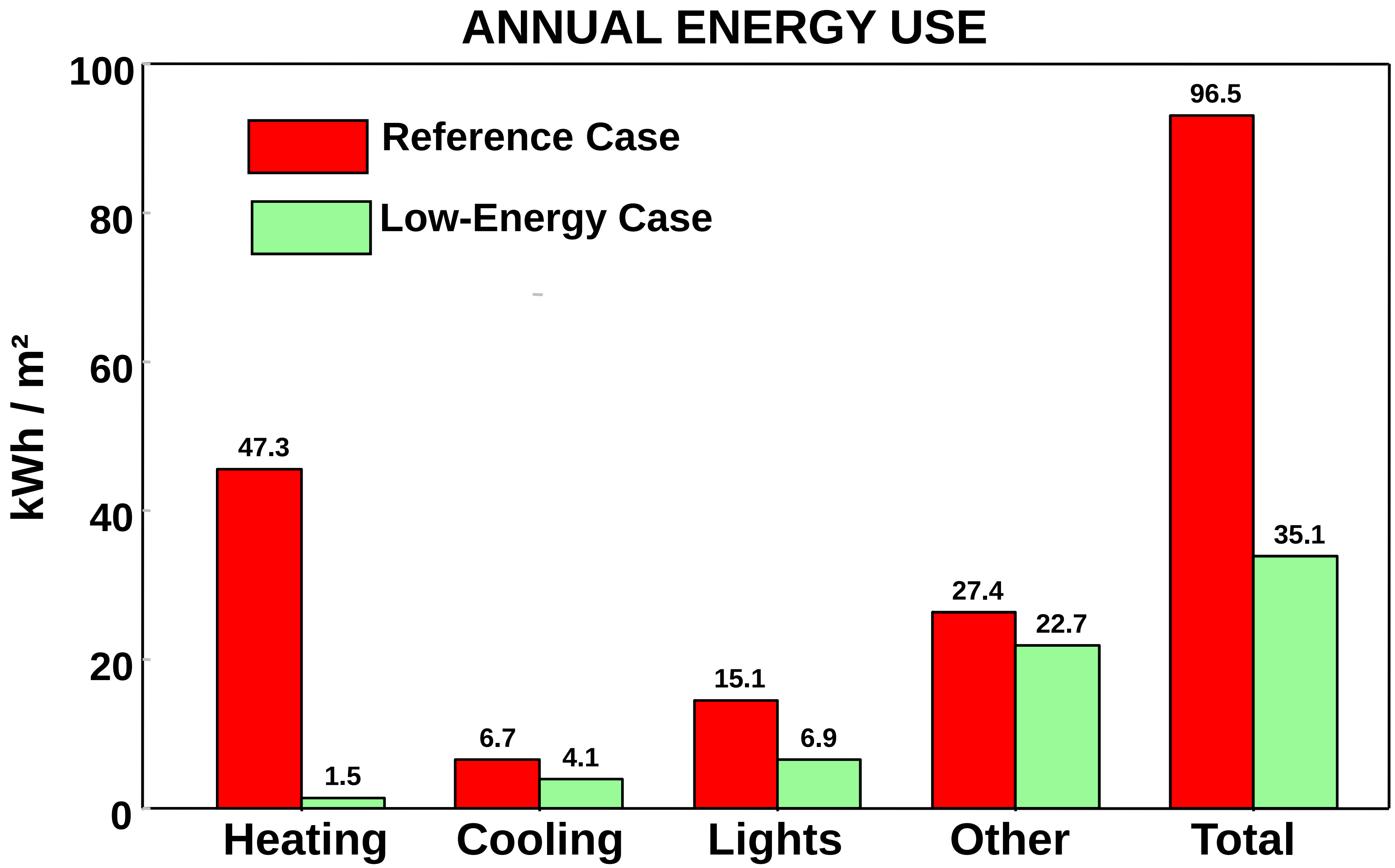
For example:

Reference Case	Low Energy Case
R-8.9 walls (4" steel stud)	R-19.6 Walls (6" steel stud with 2" foam)
R-19 roof	R-38 roof
No perimeter insulation	R-10 perimeter insulation
Conventional double windows	Best low-e double windows
Conventional lighting	Efficient lights with daylight dimming
Conventional HVAC	High efficiency HVAC
Conventional air-tightness	Leakage reduced 75%
Uniform window orientation	Passive solar orientation
Conventional HVAC controls	Improved HVAC controls
Conventional duct placement	Ducts located inside, tightened

Gets you started quickly.

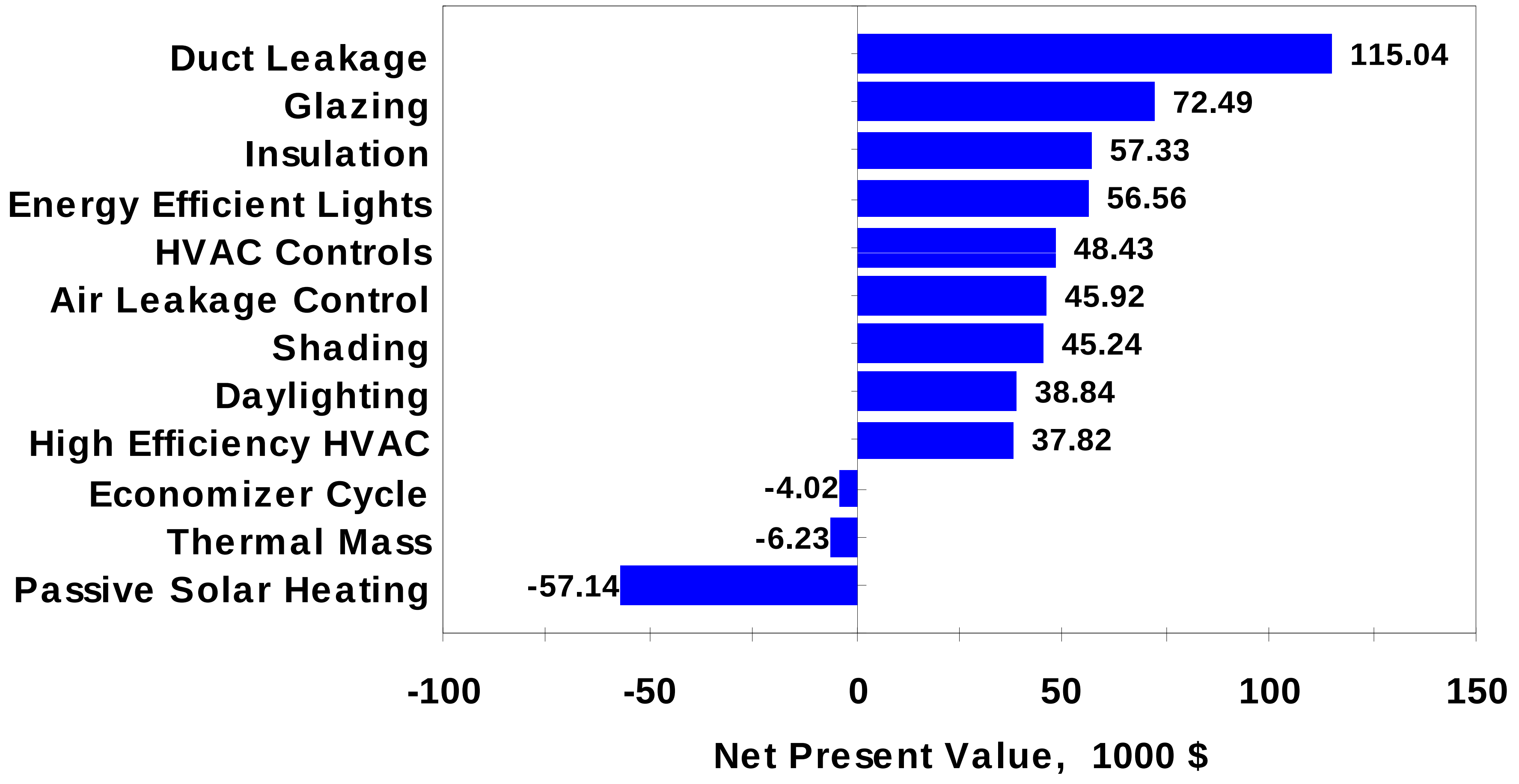
Example: Energy-10

2,000 m^2 office building

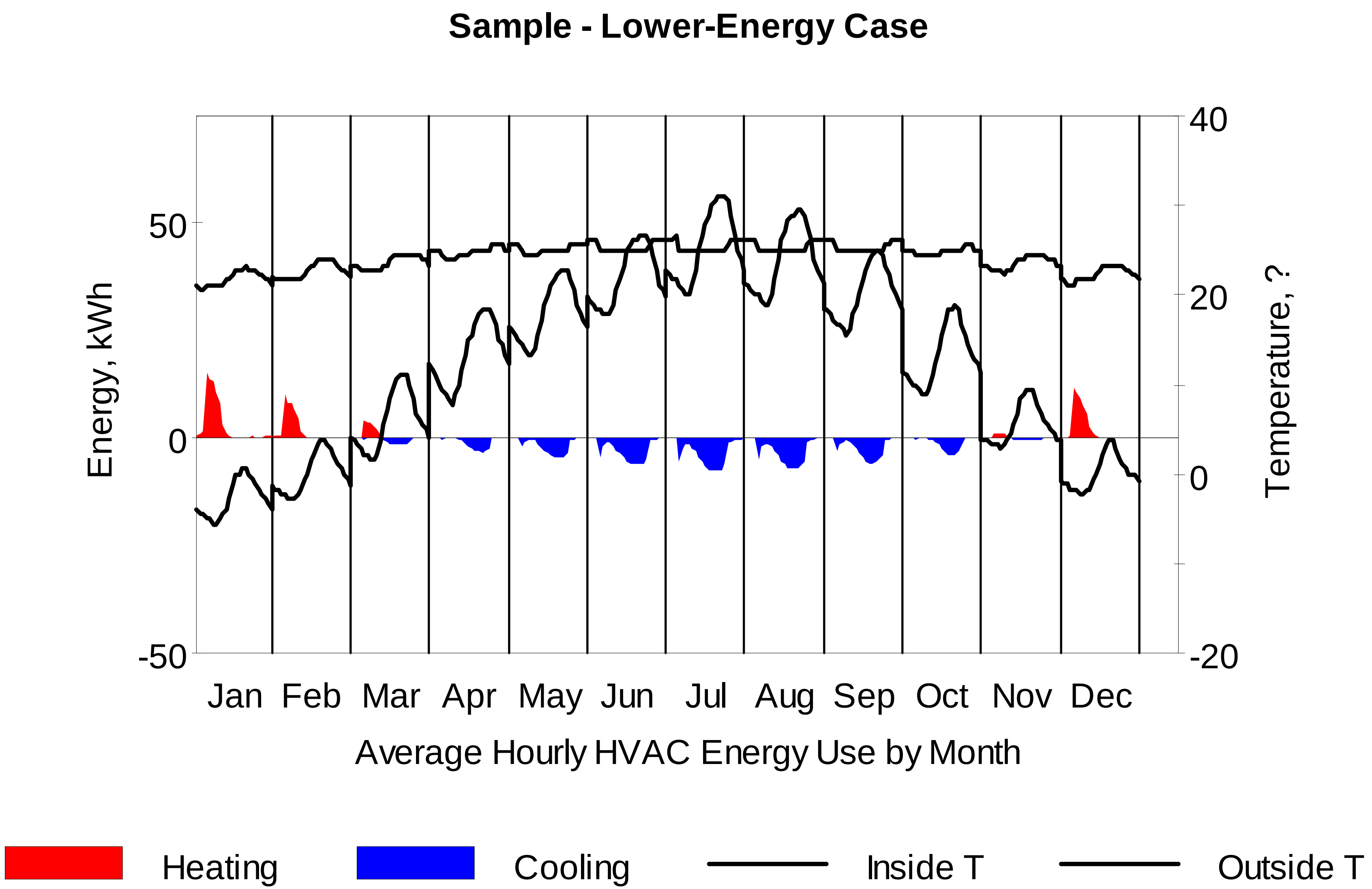


Example: Energy-10

RANKING OF ENERGY-EFFICIENT STRATEGIES

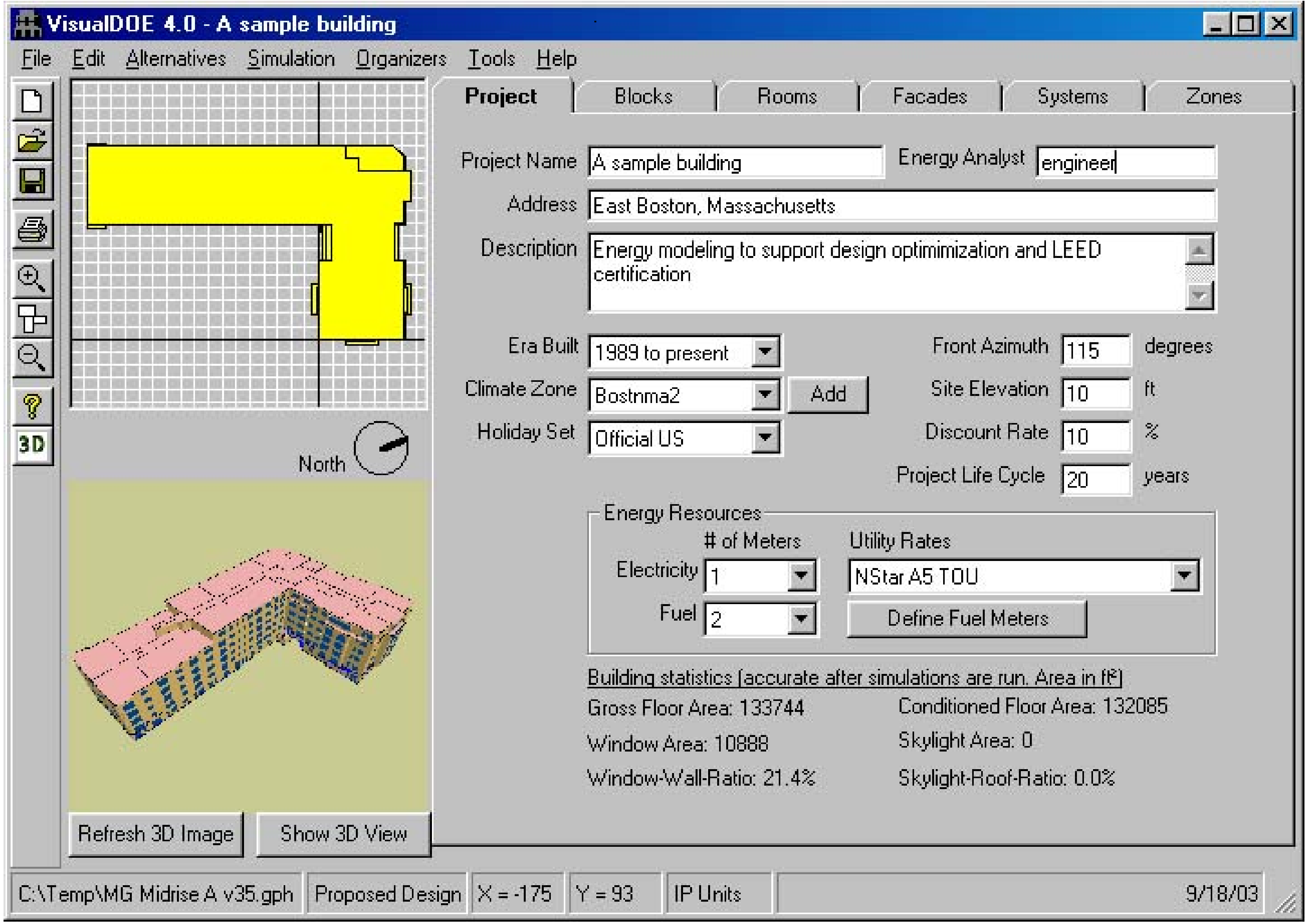


Example: Energy-10



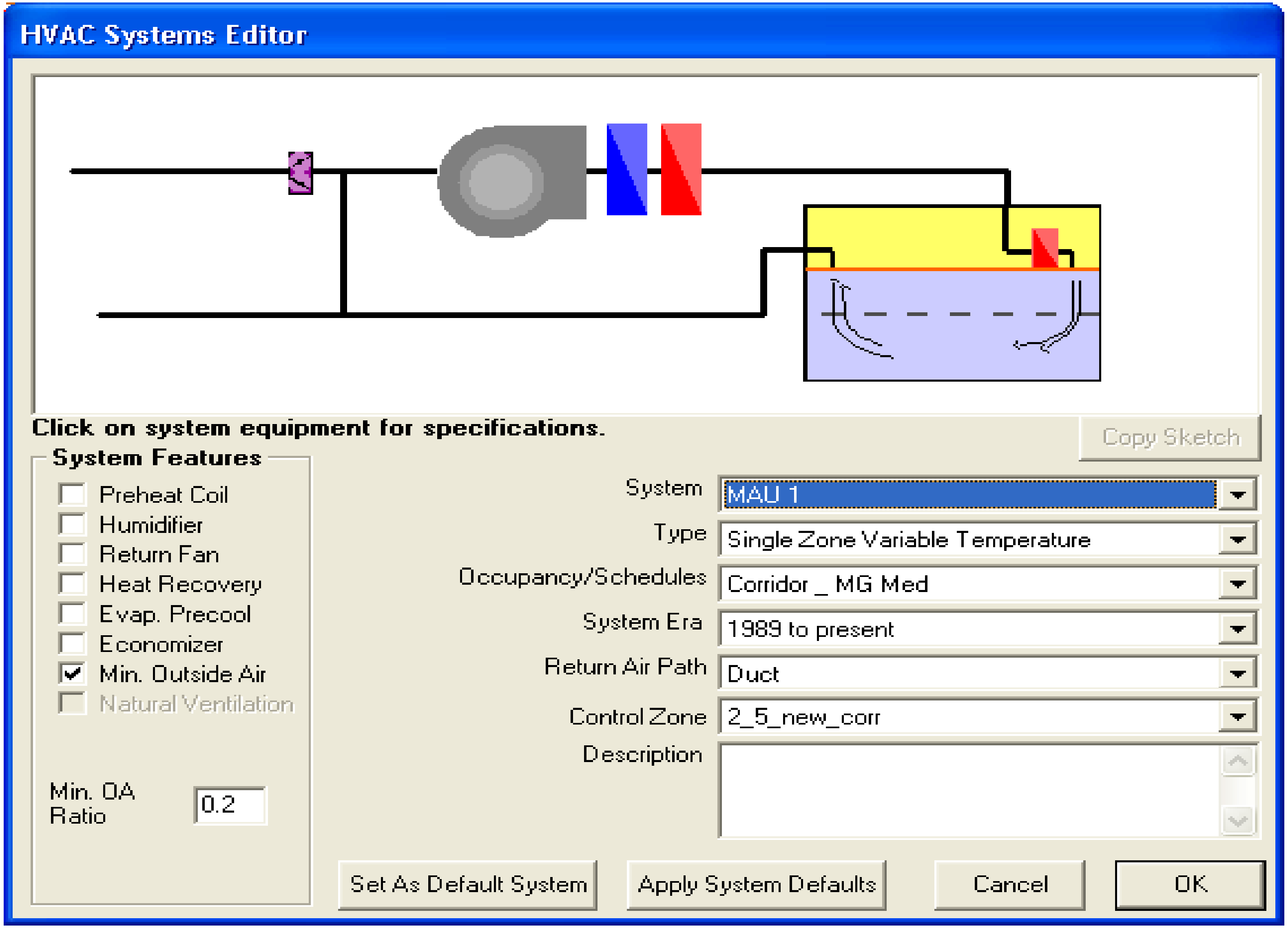
Example: VisualDOE

DOE-2



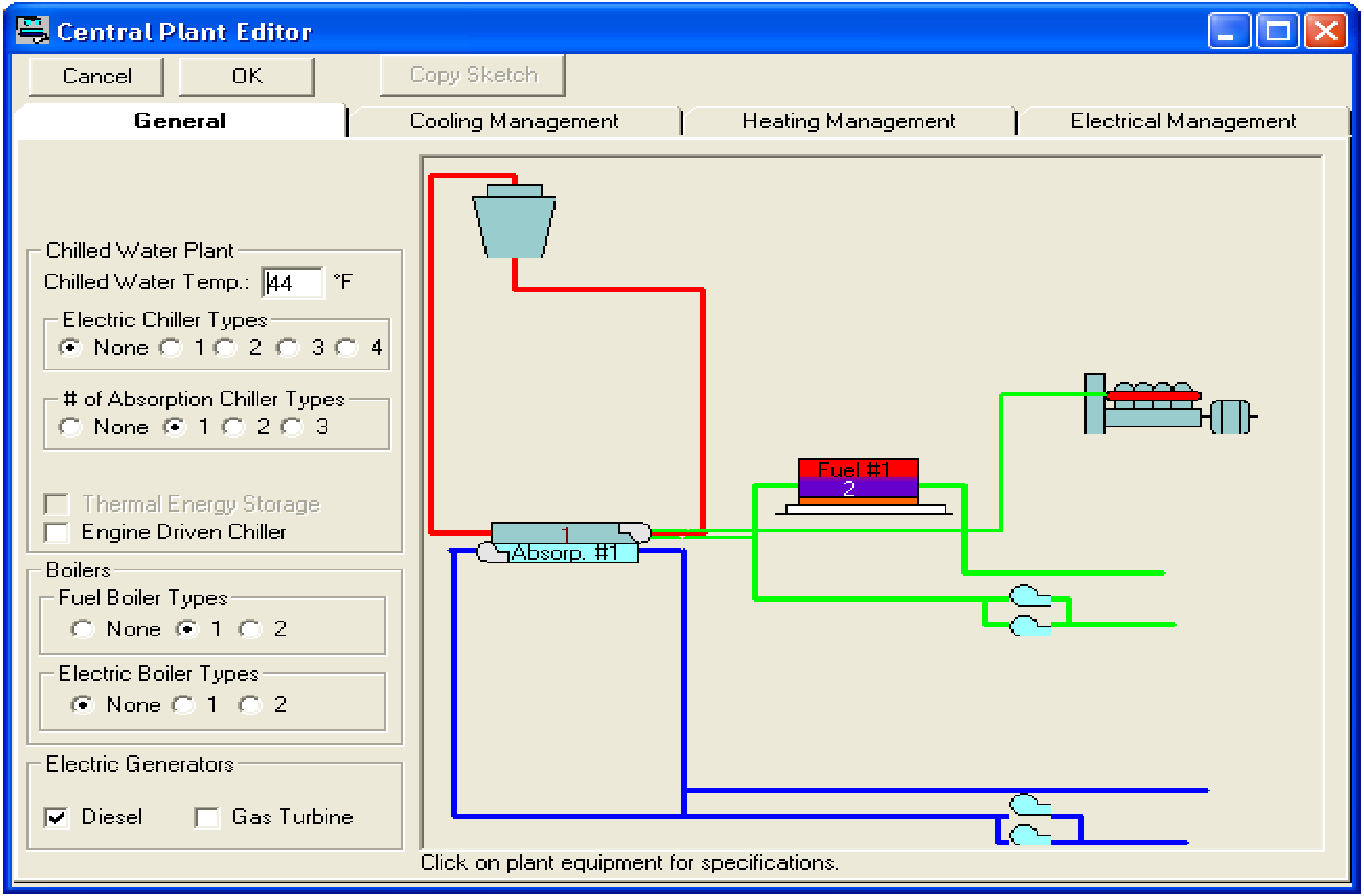
Example: VisualDOE

DOE-2



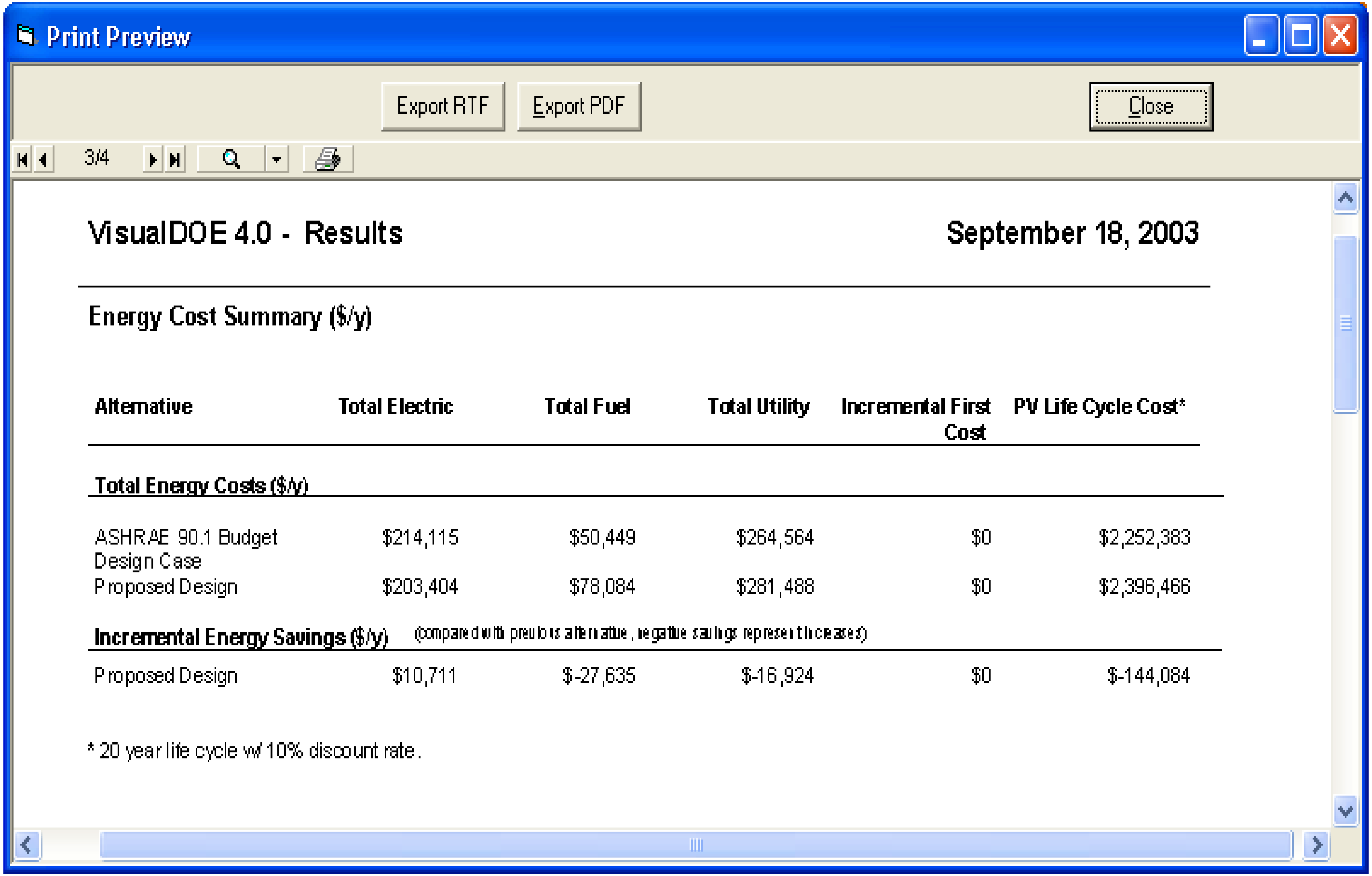
Example: VisualDOE

DOE-2



Example: VisualDOE

DOE-2



VisualDOE 4.0 - Results

September 18, 2003

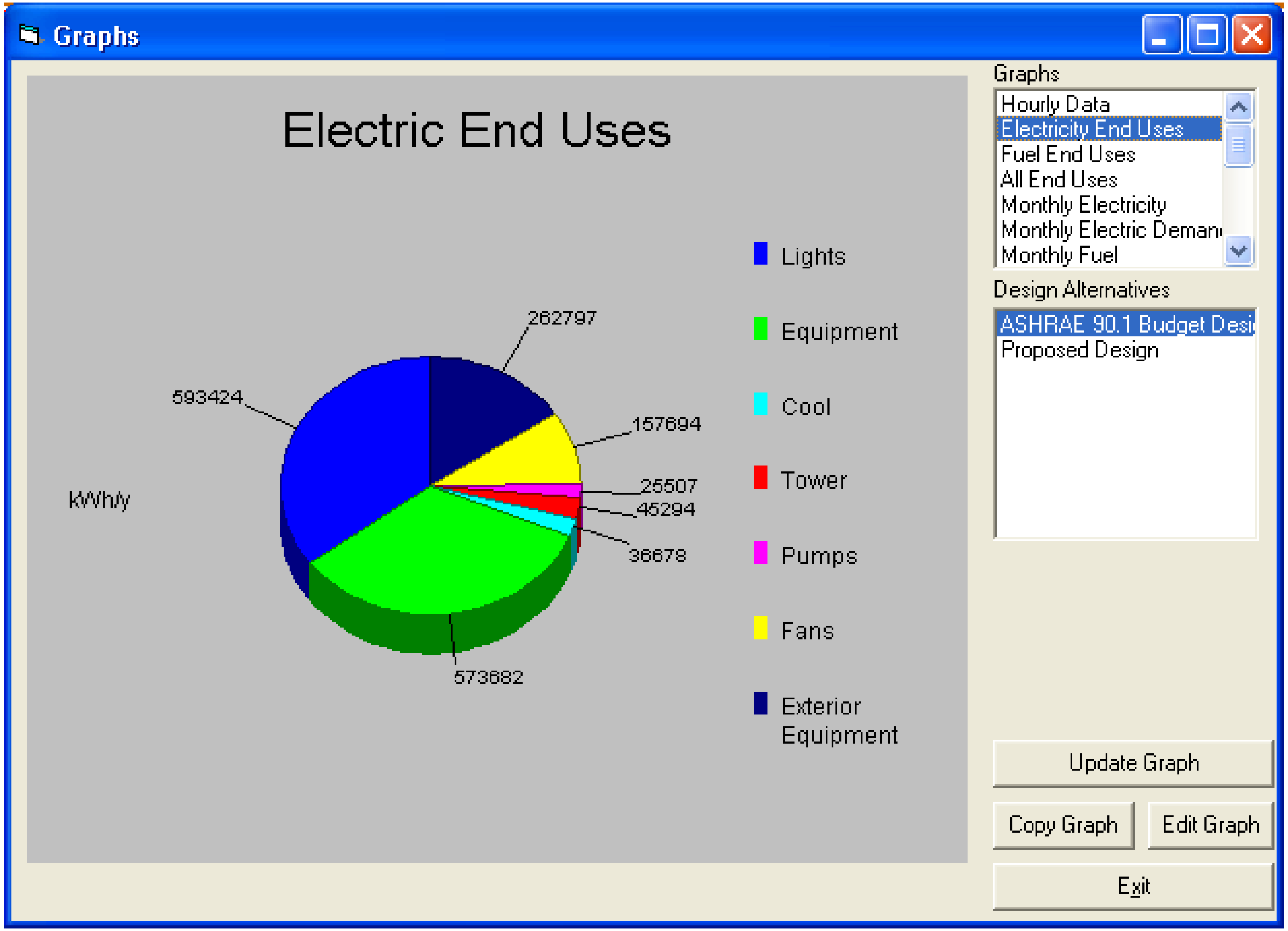
Energy Cost Summary ($/y)

Alternative	Total Electric	Total Fuel	Total Utility	Incremental First Cost	PV Life Cycle Cost*
Total Energy Costs ($/y)					
ASHRAE 90.1 Budget Design Case	$214,115	$50,449	$264,564	$0	$2,252,383
Proposed Design	$203,404	$78,084	$281,488	$0	$2,396,466
Incremental Energy Savings ($/y) (compared with previous alternative, negative savings represent increases)					
Proposed Design	$10,711	$-27,635	$-16,924	$0	$-144,084

* 20 year life cycle w/ 10% discount rate.

Example: VisualDOE

DOE-2



Example: VisualDOE

DOE-2