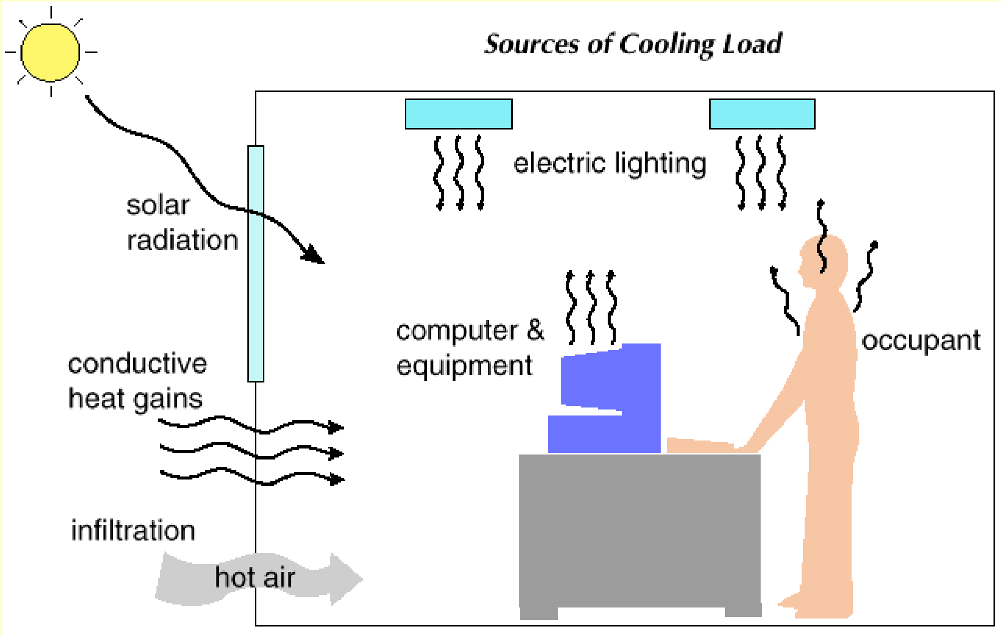
MEBS7012 Air conditioning and refrigeration

http://ibse.hk/MEBS7012/



Energy Calculations

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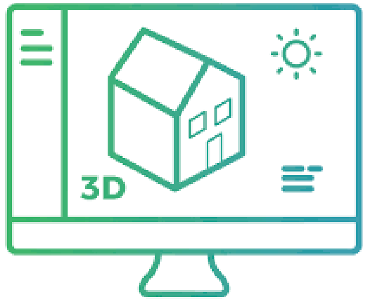
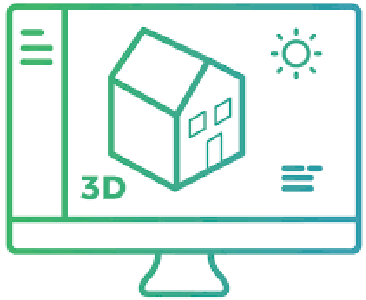
- Transfer Function Method
- Energy Calculation Methods
- Building Energy Simulation
- Simulation Software Tools

Basic Concepts



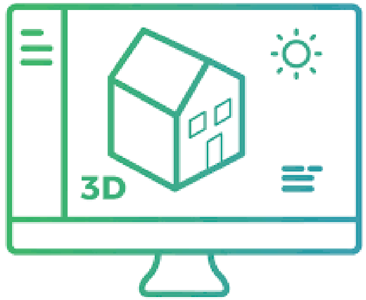
- From *load estimation* to *energy calculations*
  - Only determine peak design loads is not enough
  - Need to evaluate HVAC & building energy consumption
    - To support design decisions (e.g. evaluate design options)
    - To enhance system design and operation
    - To compile with building energy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

Basic Concepts



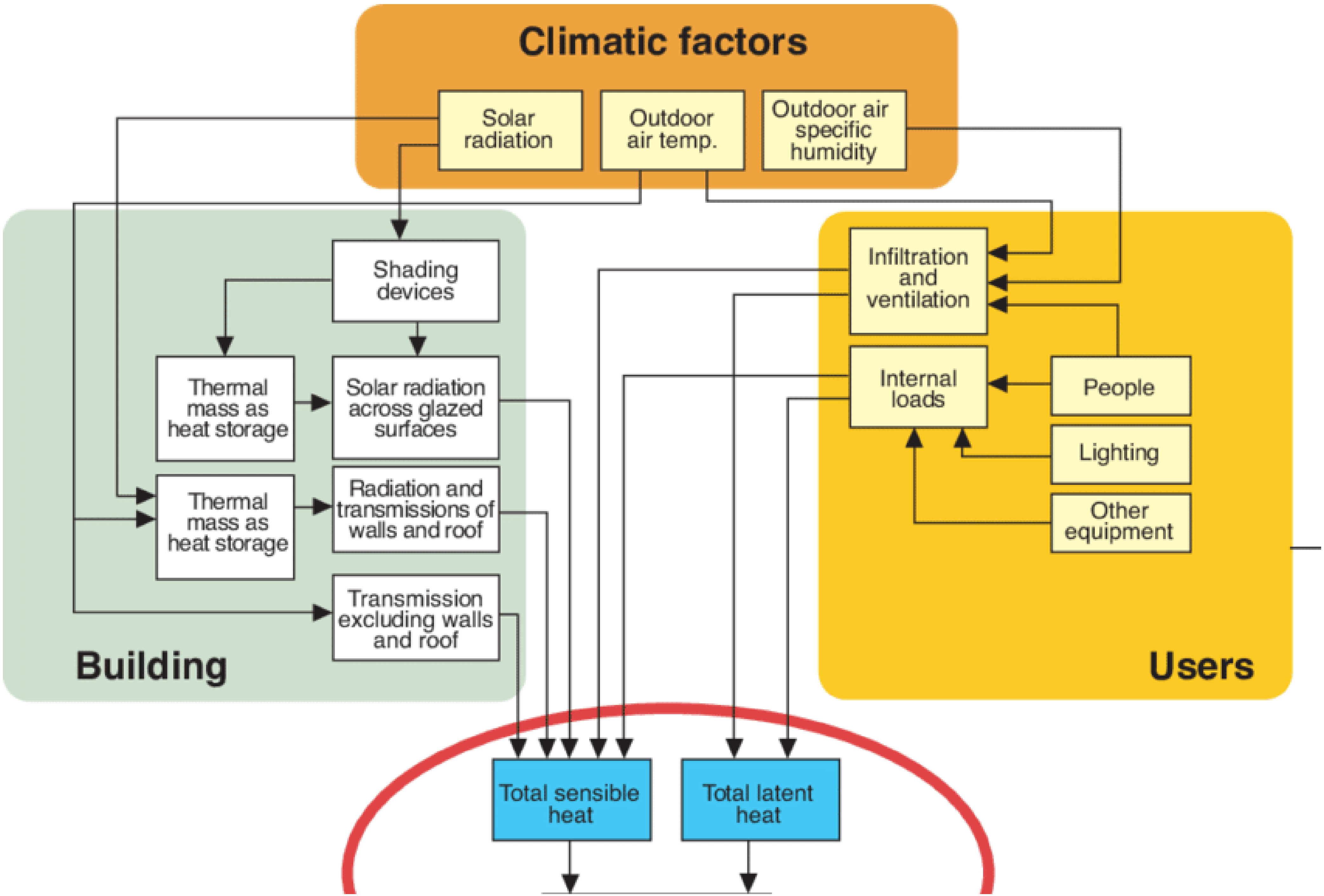
- Load estimation and energy calculations
  - Based on the same principles
  - But, with different purposes & approaches
- Design (peak) load estimation
  - Focus on maximum load or worst conditions
  - For a particular hour or period (e.g. peak summer)
- Energy calculations
  - Focus on average or typical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

Basic Concepts



- 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

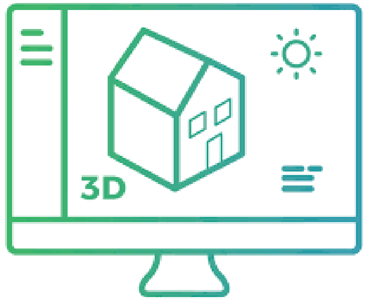
Climatic, building & users factors on load & energy calculations



Basic Concepts

- Typical HVAC design tasks:
  - 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 & refrigeration system

Basic Concepts

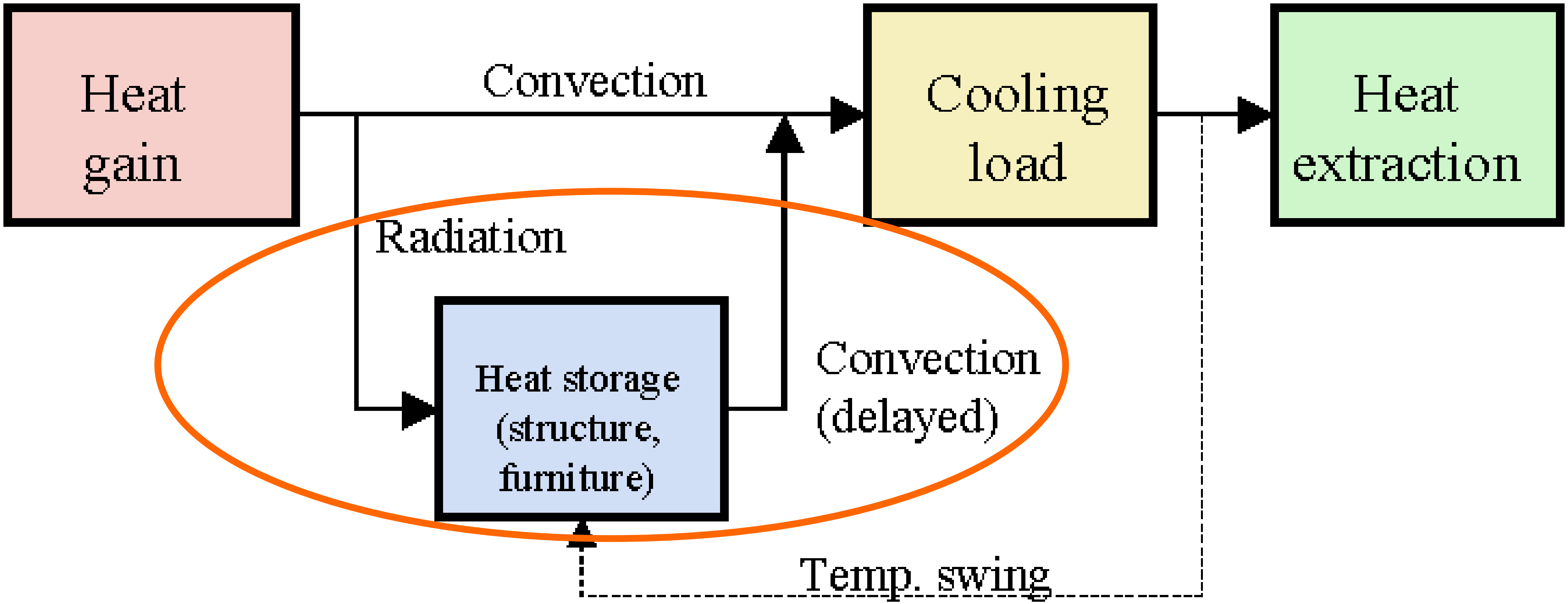


- Typical applications of energy calculations
  - Comparison: to compare the estimated performance of design alternatives for new buildings or to compare retrofit alternatives for existing buildings
  - Compliance: for energy code compliance or green building rating system credit/certification
  - Prediction: to predict energy consumption & evaluate energy targets; support real-time building control & operation

Basic Concepts

- 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

Different methods have different ways to convert space radiative heat gains into space cooling loads

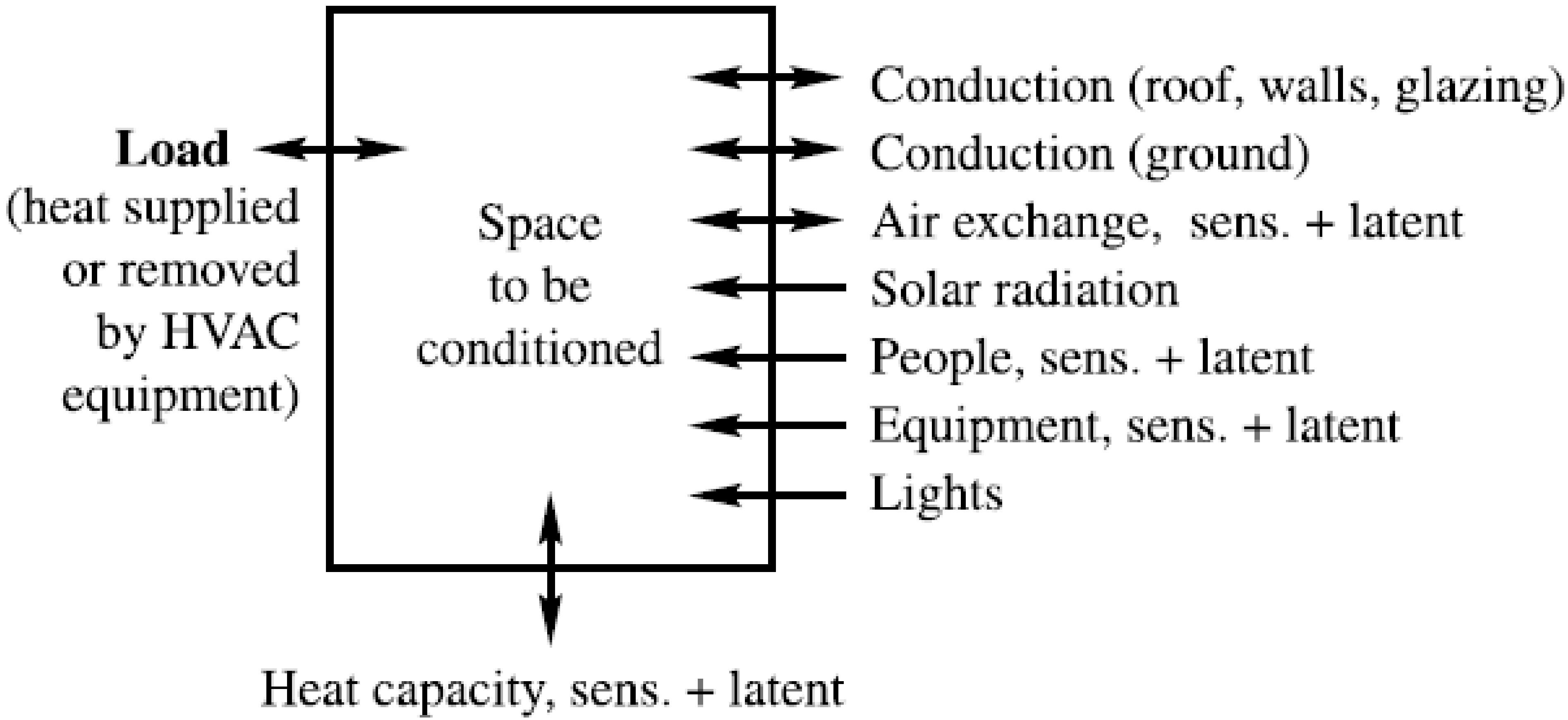


Conversion of heat gain into cooling load

(Source: ASHRAE Handbook Fundamentals 2005)

Thermal Load

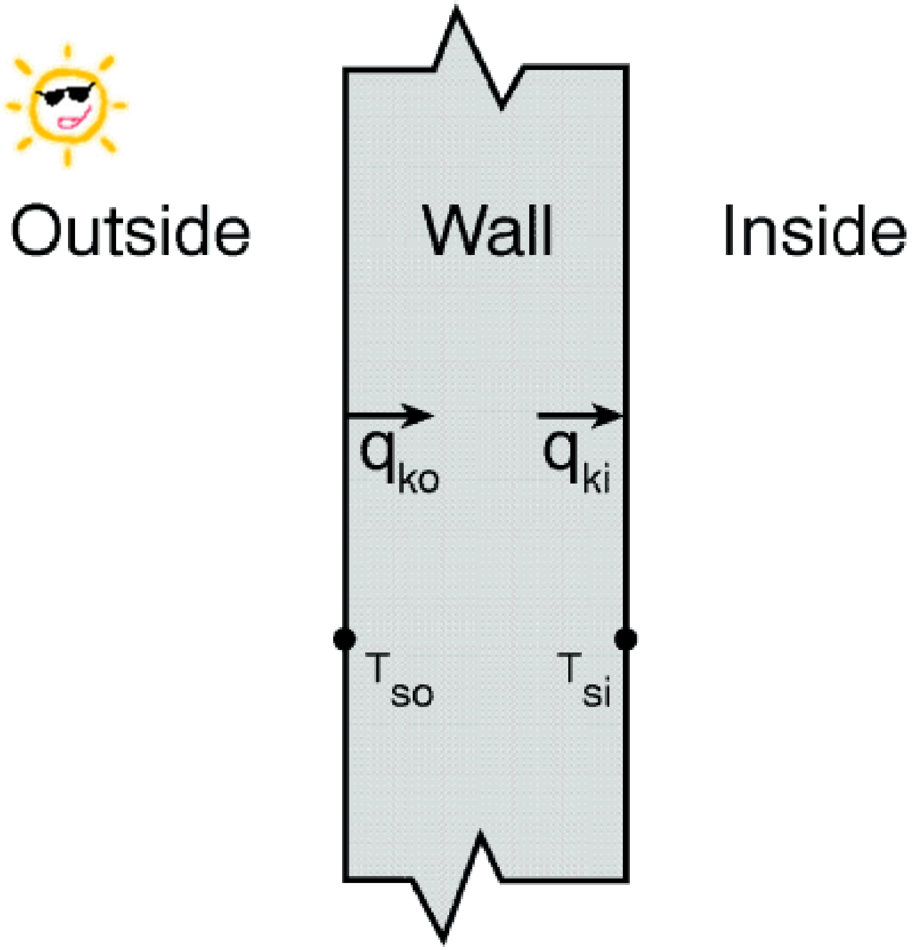
Heat Gains/Losses



Heat storage

(Source: ASHRAE Handbook Fundamentals 2005)

Wall conduction process



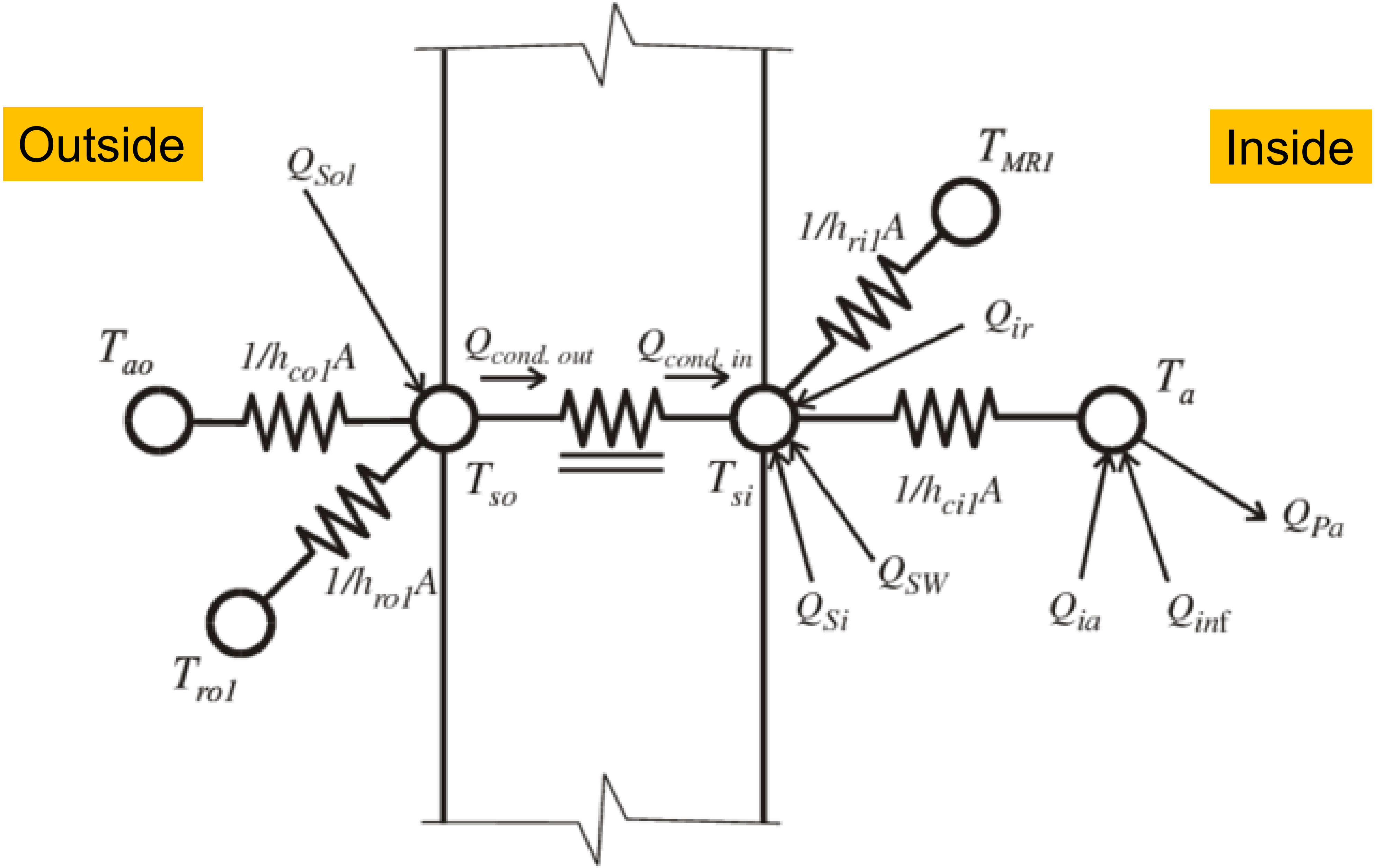
q_{ko} = convective flux into the wall, W/m^2
q_{ki} = convective flux through the wall, W/m^2
T_{so} = wall surface temperature outside, ºC
T_{si} = wall surface temperature outside, ºC

Possible ways to model this process:

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

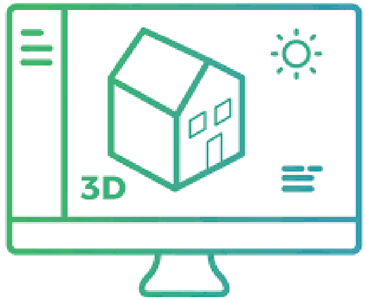
(Source: ASHRAE Handbook Fundamentals 2005)

Heat balance cooling load calculation method represented as nodal network (a single wall is shown with the outside surface on the left)



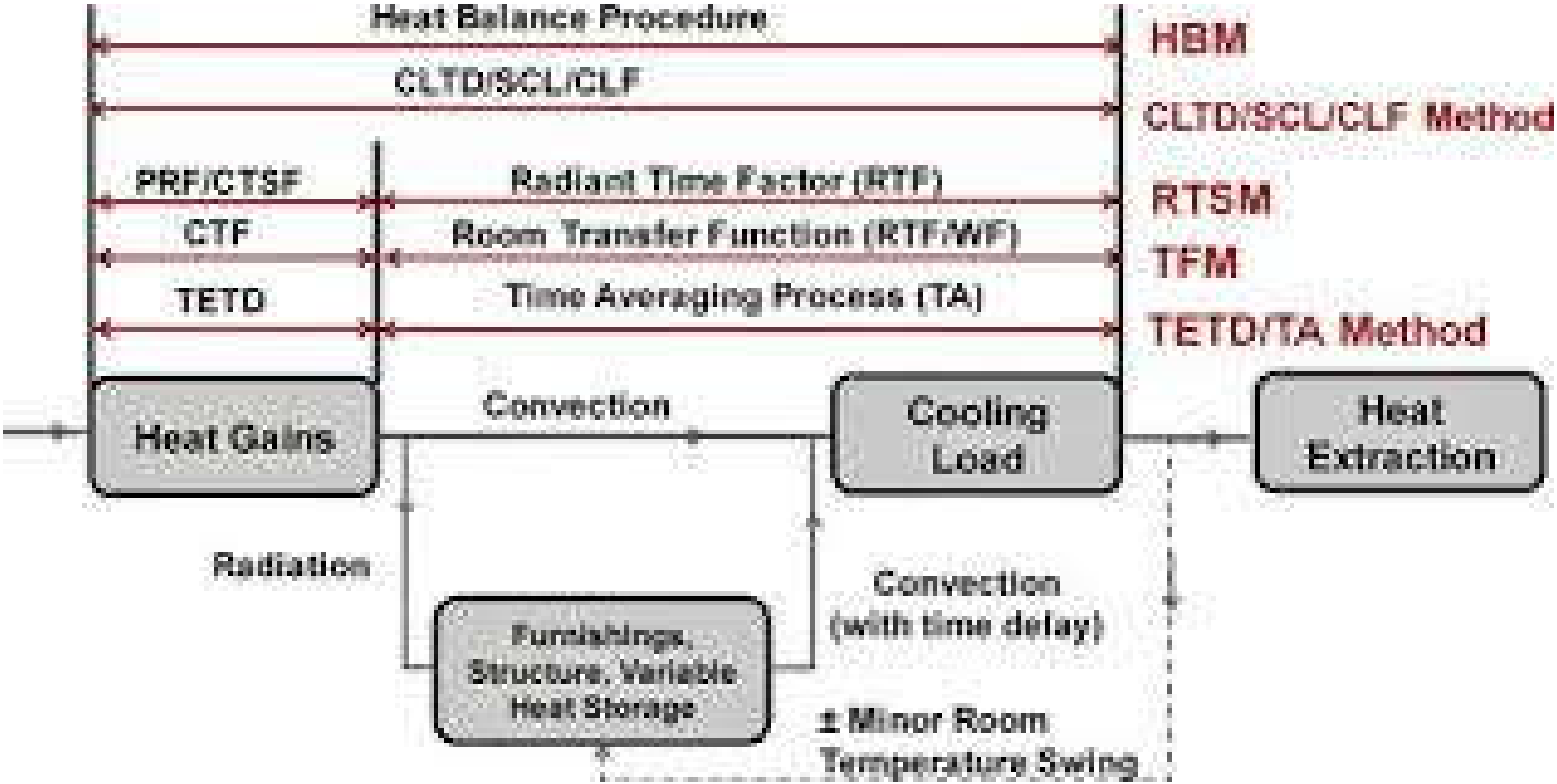
(Image Source: Rees S. J., Spitler J. D., Davies M. G. & Haves P., 2000. Qualitative comparison of North American and U.K. cooling load calculation methods, *International Journal of HVAC&R Research*, 6 (1) 75-99.)

Basic Concepts



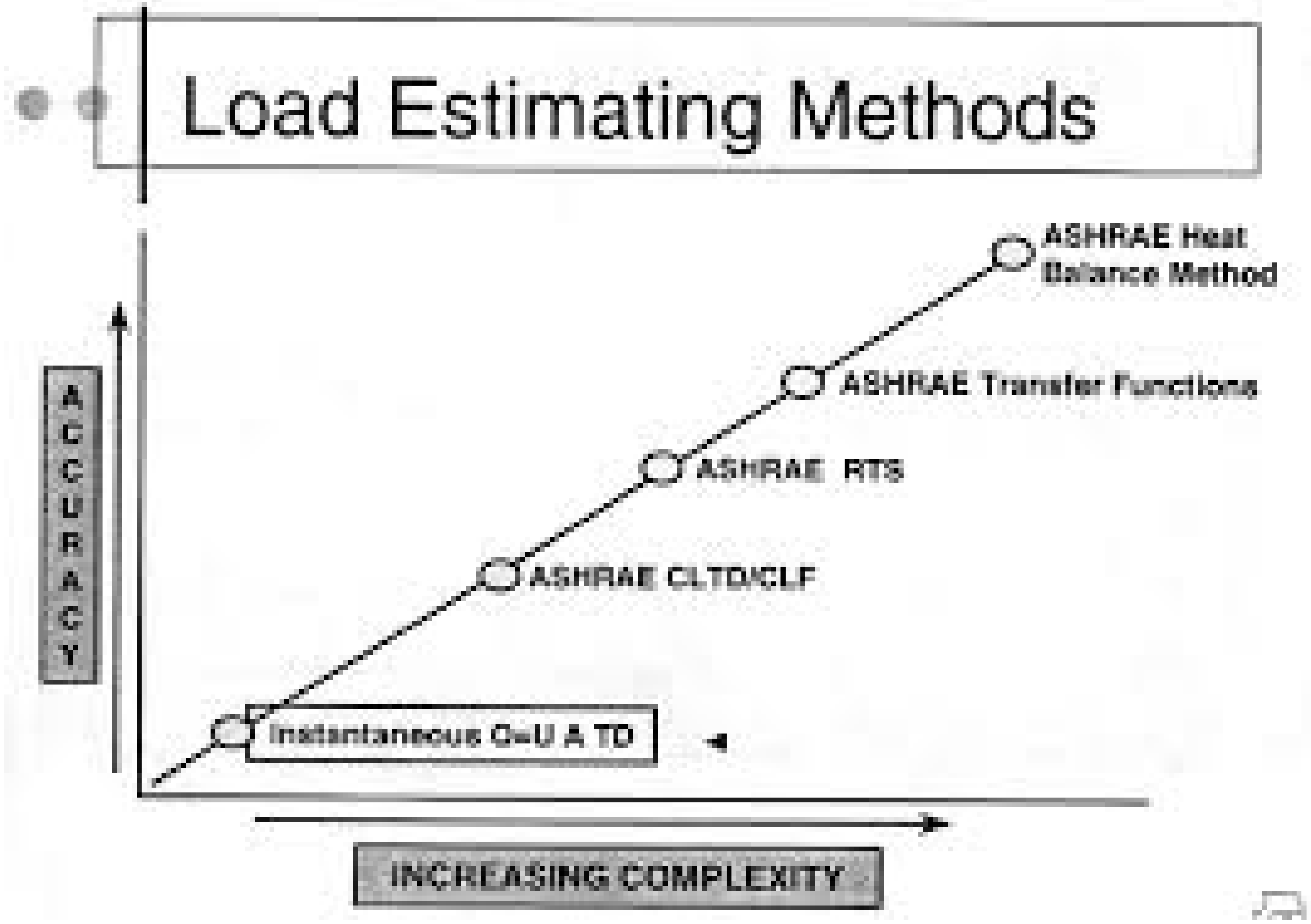
- Calculation methodologies:
  - Heat balance (HB)
  - Radiant time series (RTS)
  - Cooling load temperature difference (CLTD)
  - Transfer function method (TFM)
  - Total equivalent temp. differential/time averaging (TETD/TA) method
- Methods to calculate the cooling load in either steady state or dynamic conditions

Cooling load calculation methods



(Image Source: Mao C., Baltazar J.-C. & Haberl J. S., 2018. Literature review of building peak cooling load methods in the United States, *Science and Technology for the Built Environment*, 24 (3) 228-237.)

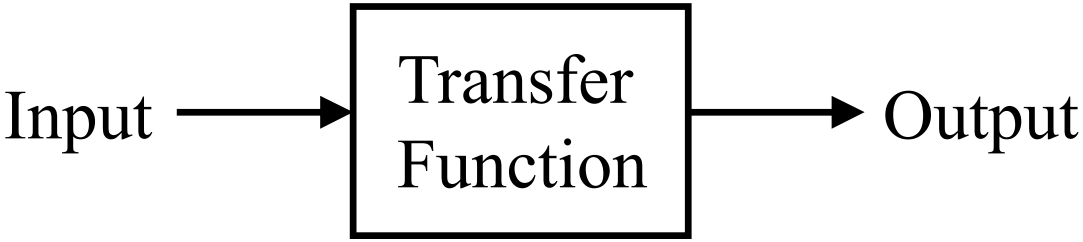
Comparison of load estimating methods



(Image Source: http://built-envi.com/wp-content/uploads/cae331_513_11_17_2015.pdf)

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 $f(0), f(\Delta), f(2\Delta), \ldots, f(n\Delta)$, the Laplace transform is given by a polynominal called "z-transform":

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

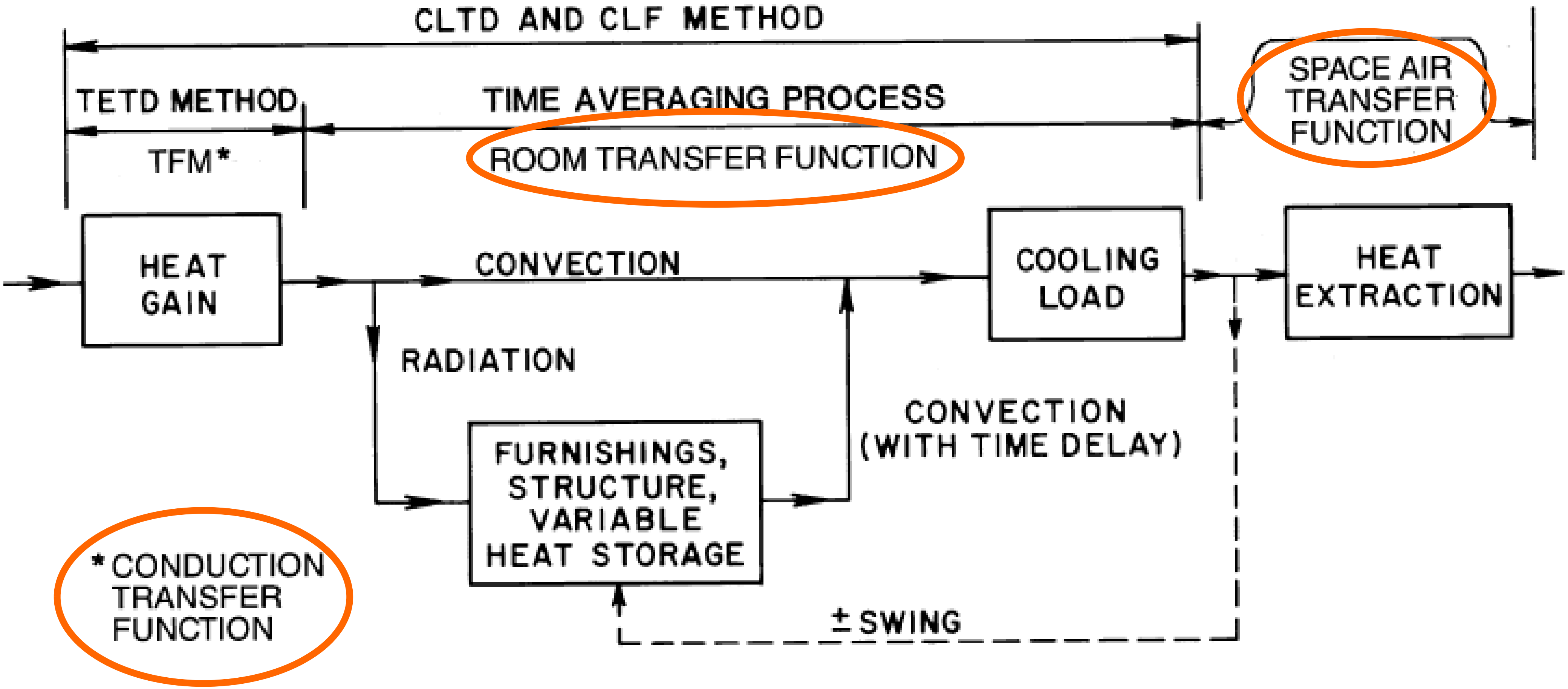
where Δ = time interval, hour

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

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

Three main components of transfer function method (TFM)

- Conduction transfer function (CTF)
- Room transfer function (RTF)
- Space air transfer function (SATF)



(Source: ASHRAE Handbook Fundamentals 2005)

Transfer Function Method

- External walls and roofs:

Sol-air temperature

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

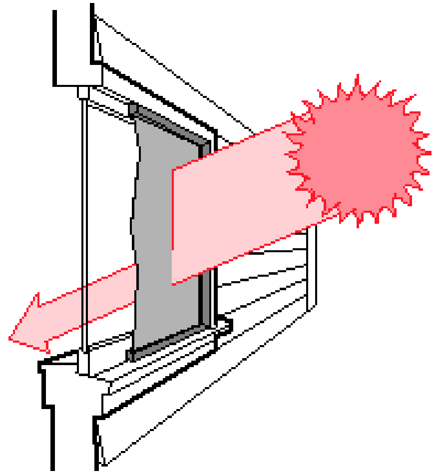
- Ceiling, floors & partition wall:

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

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):

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

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

  - Space sensible cooling load (from convective):

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

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

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:

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

+ Only take the positive values

Cooling degree-day:

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

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:

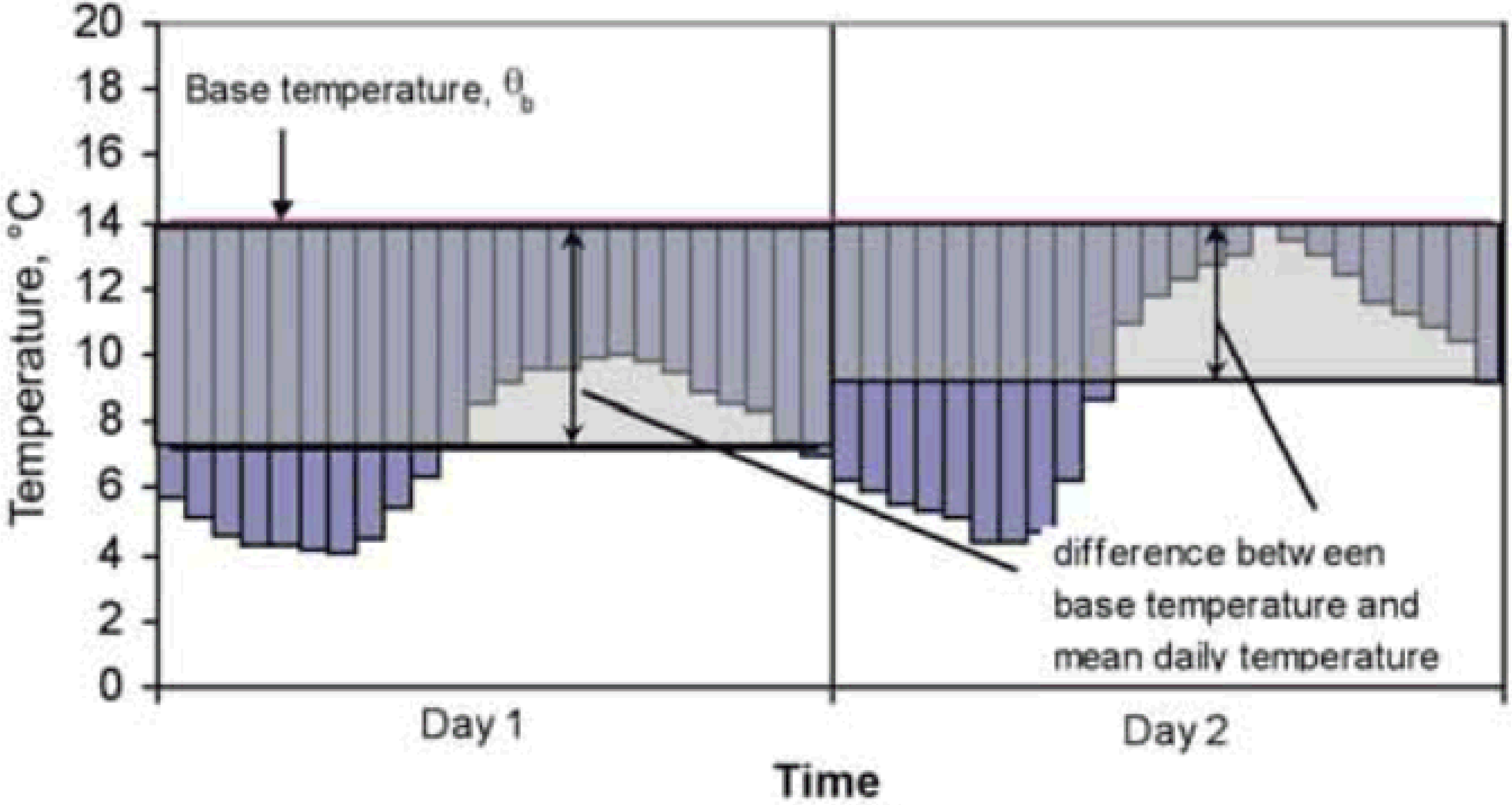


Figure 1.1 The basic definition of degree-days as the difference between the base temperature and the mean daily outdoor temperature

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

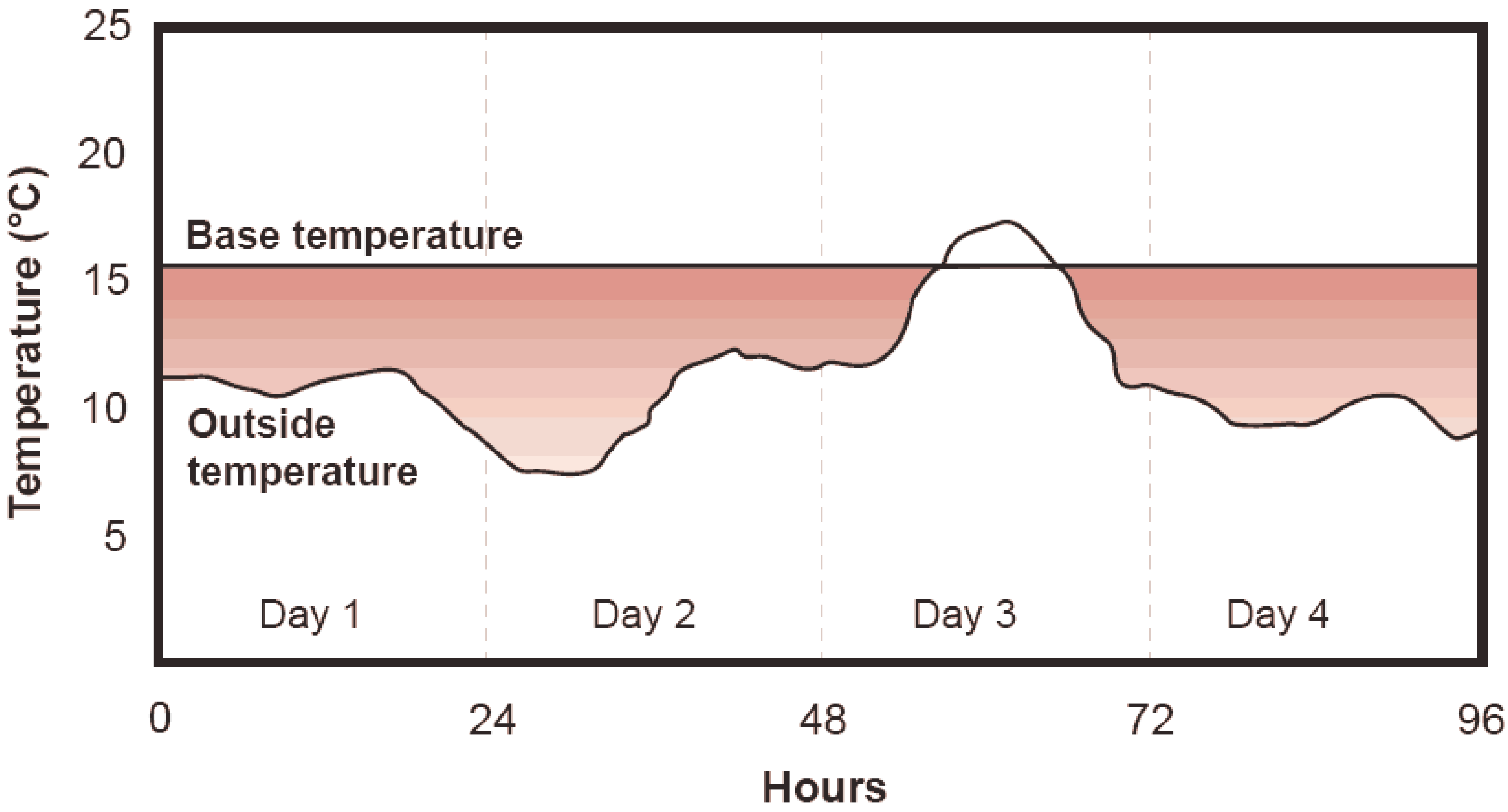
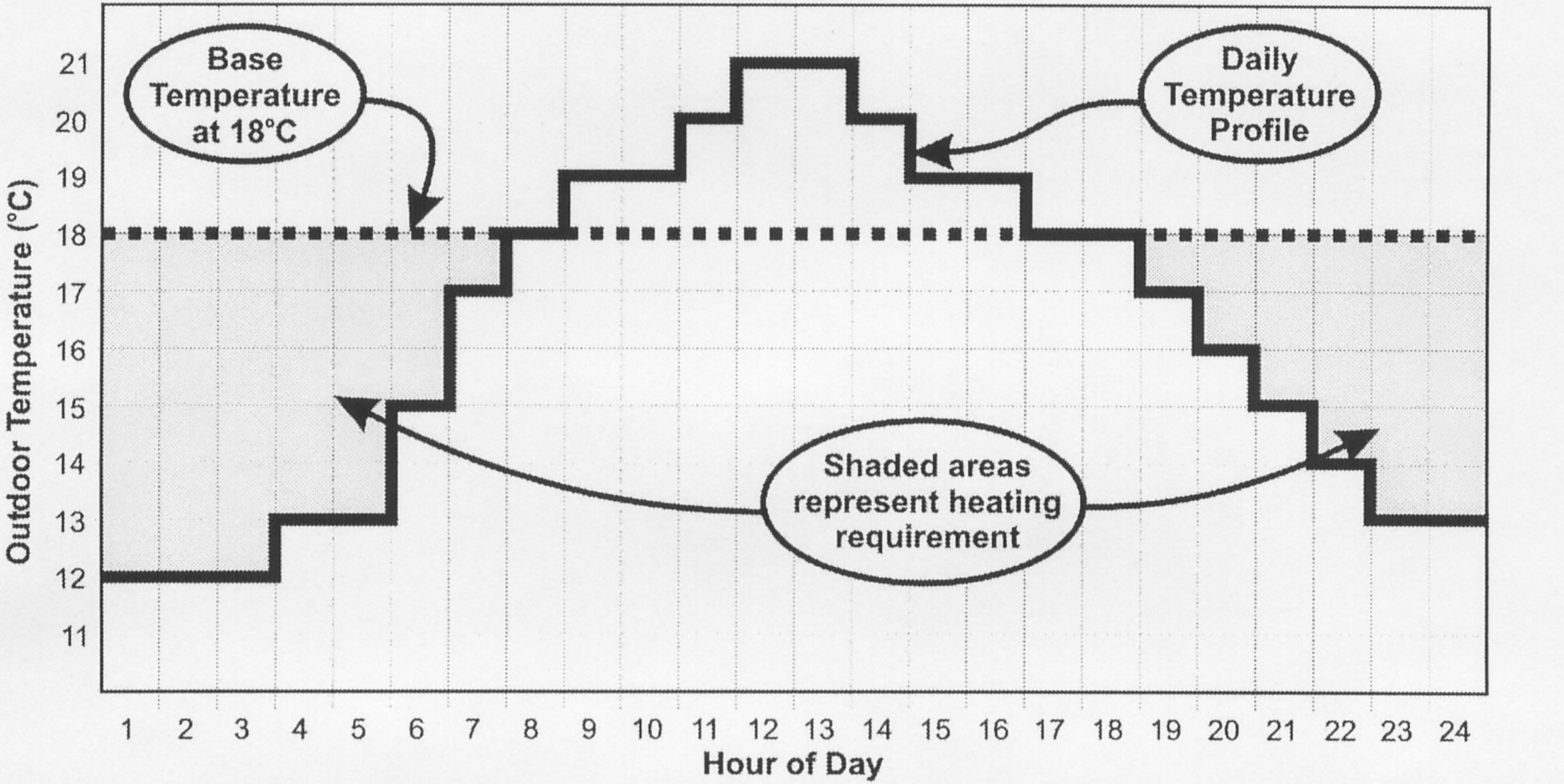


Figure 1 The shaded area is the degree-day value for the period

Example of calculating the heating degree-day



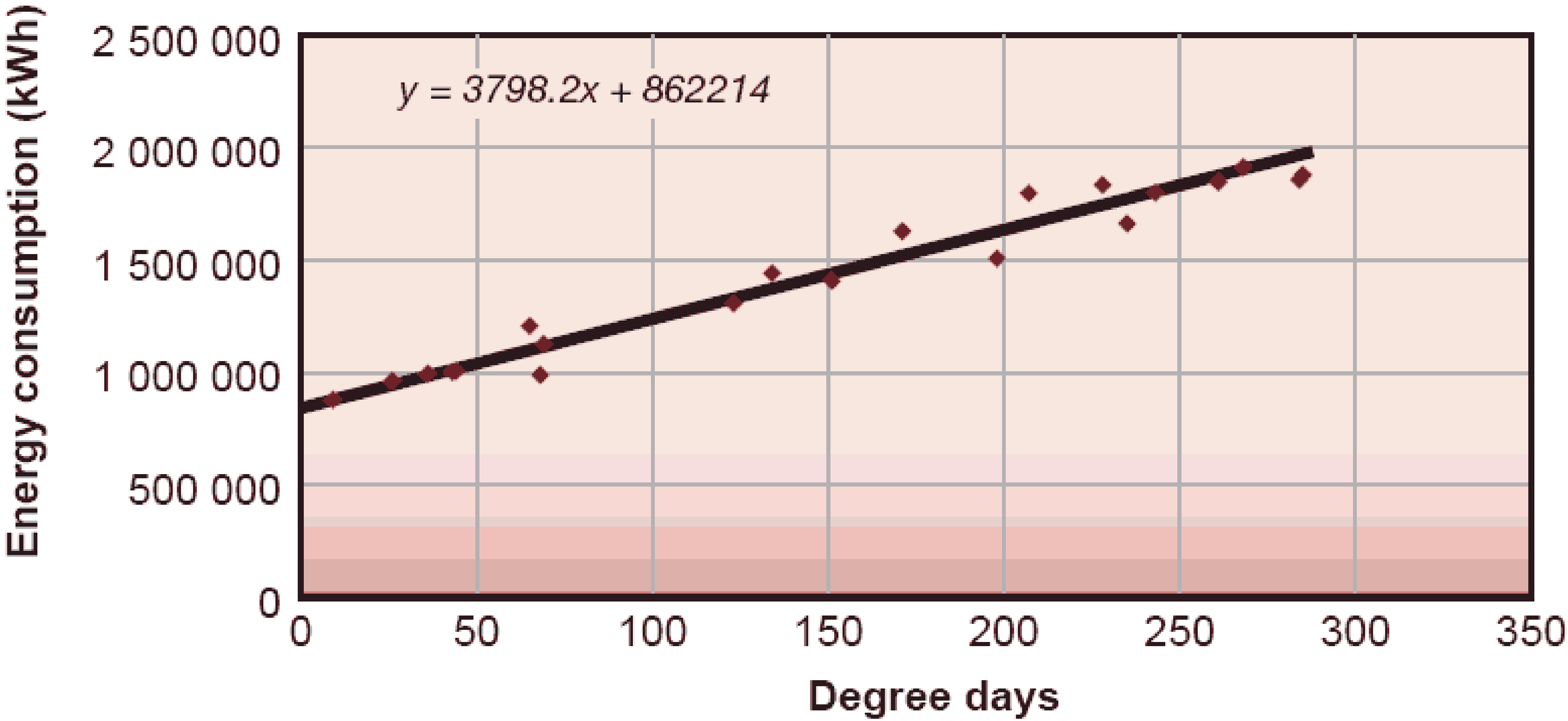
Outdoor Temperature (°C)

12	12	12	13	13	15	17	18	19	19	20	21	21	20	19	19	18	18	17	16	15	14	13	13	
6	6	6	5	5	3	1	0	0	0	0	0	0	0	0	0	0	0	1	2	3	4	5	5	Total 52

Temperature Difference Below 18°C Base Temperature (Degree-Hours)

$$Degree\ Days = \frac{Degree\ Hours}{24} = \frac{52}{24} = 2.2\ DegDay$$

Correlation between energy consumption and degree days



Energy Calculation Methods

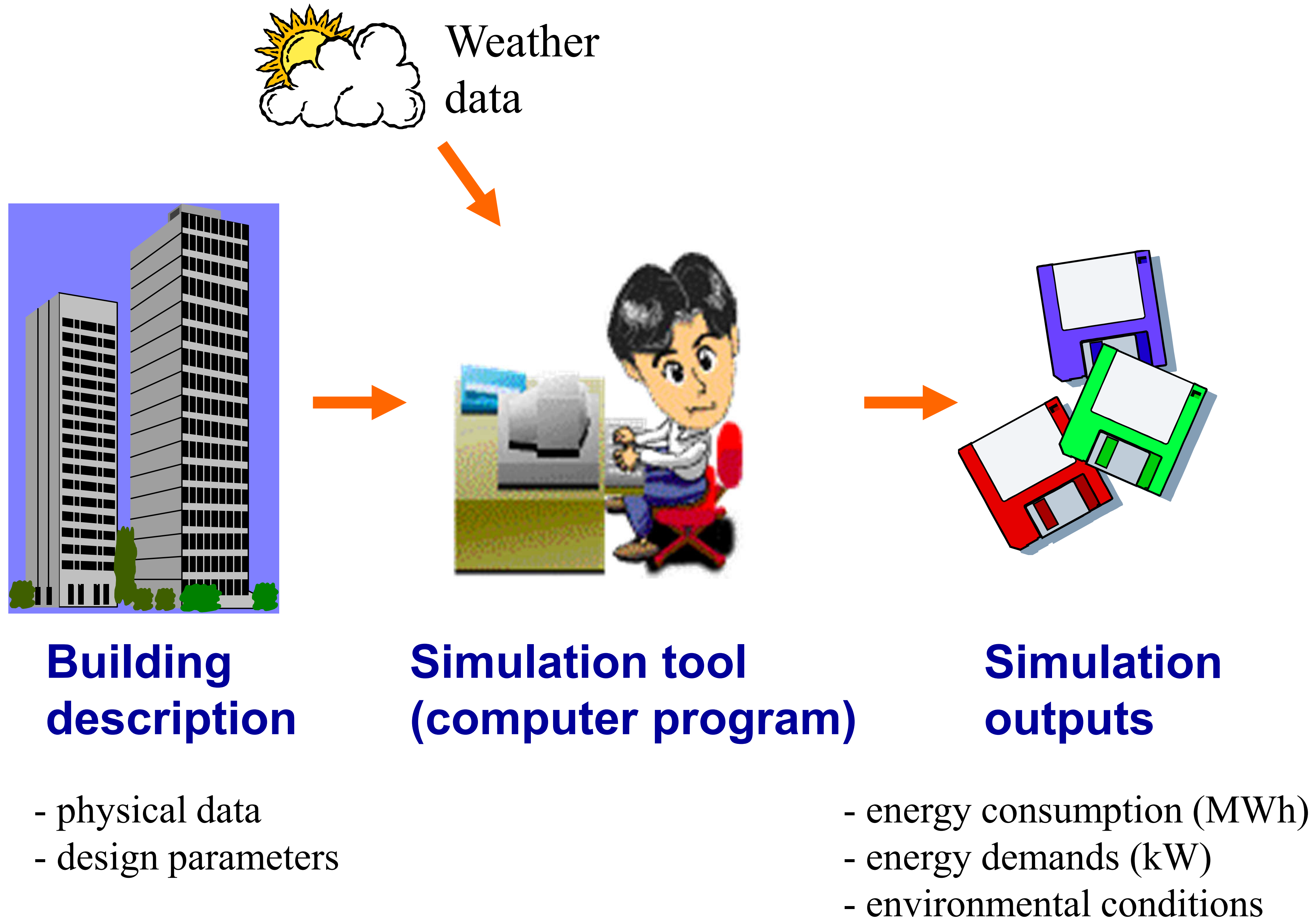
- Variable base degree-day (VBDD) method
  - Degree-day with variable reference temperatures
    - To account for different building conditions and variation between daytime and nighttime
    - First calculate the balance point temperature of a building and then the heating and cooling degree hours at 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

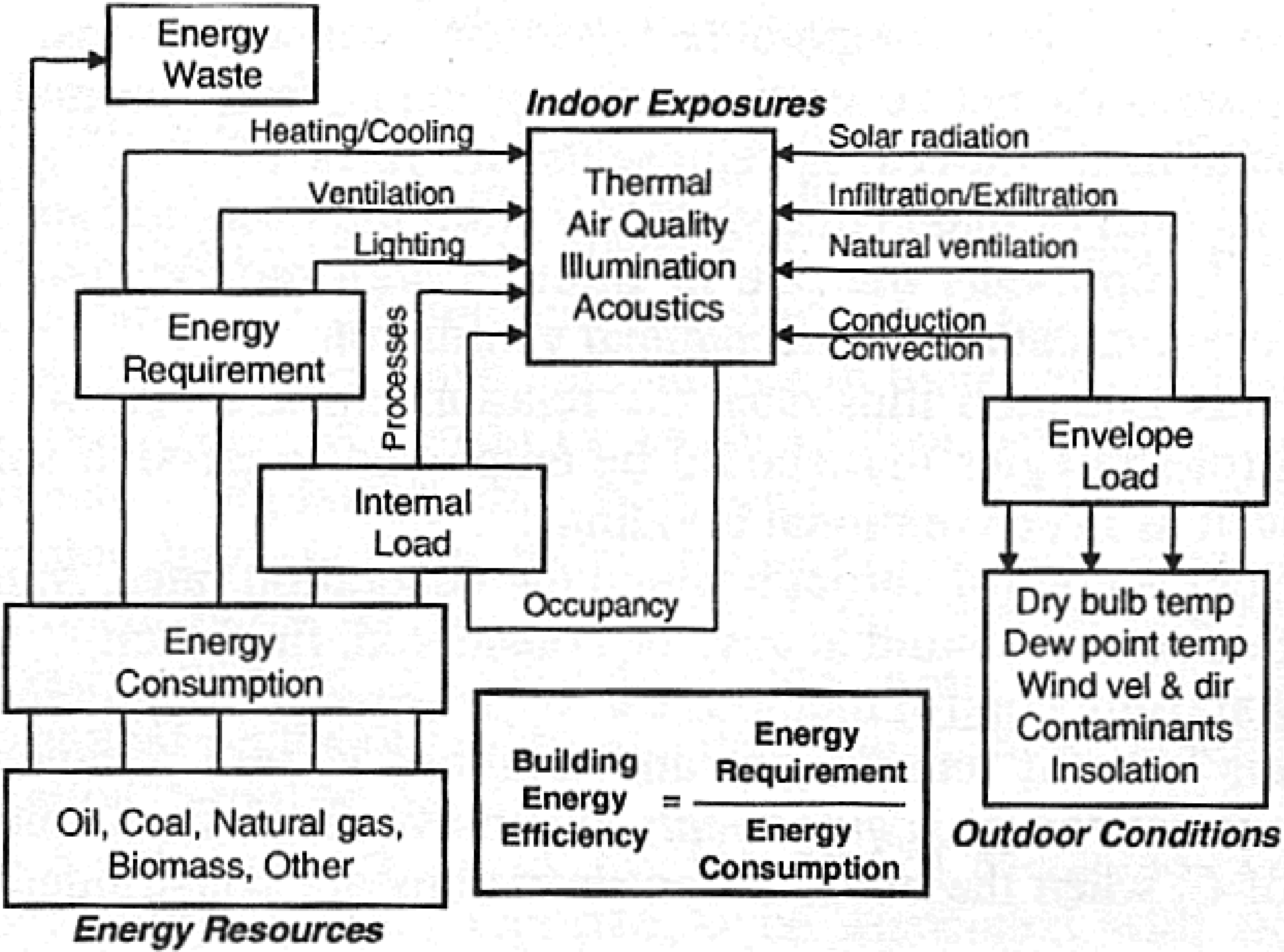
- Bin and modified bin methods
  - Evolve from VBDD method
  - Derive building annual heating/cooling loads by calculating its loads for a set of temperature "bins"
  - Multiplying the calculated loads by nos. of hours represented by each bin (e.g. 18-20, 20-22, 22-24 ^{o}C)
  - Totaling the sums to 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

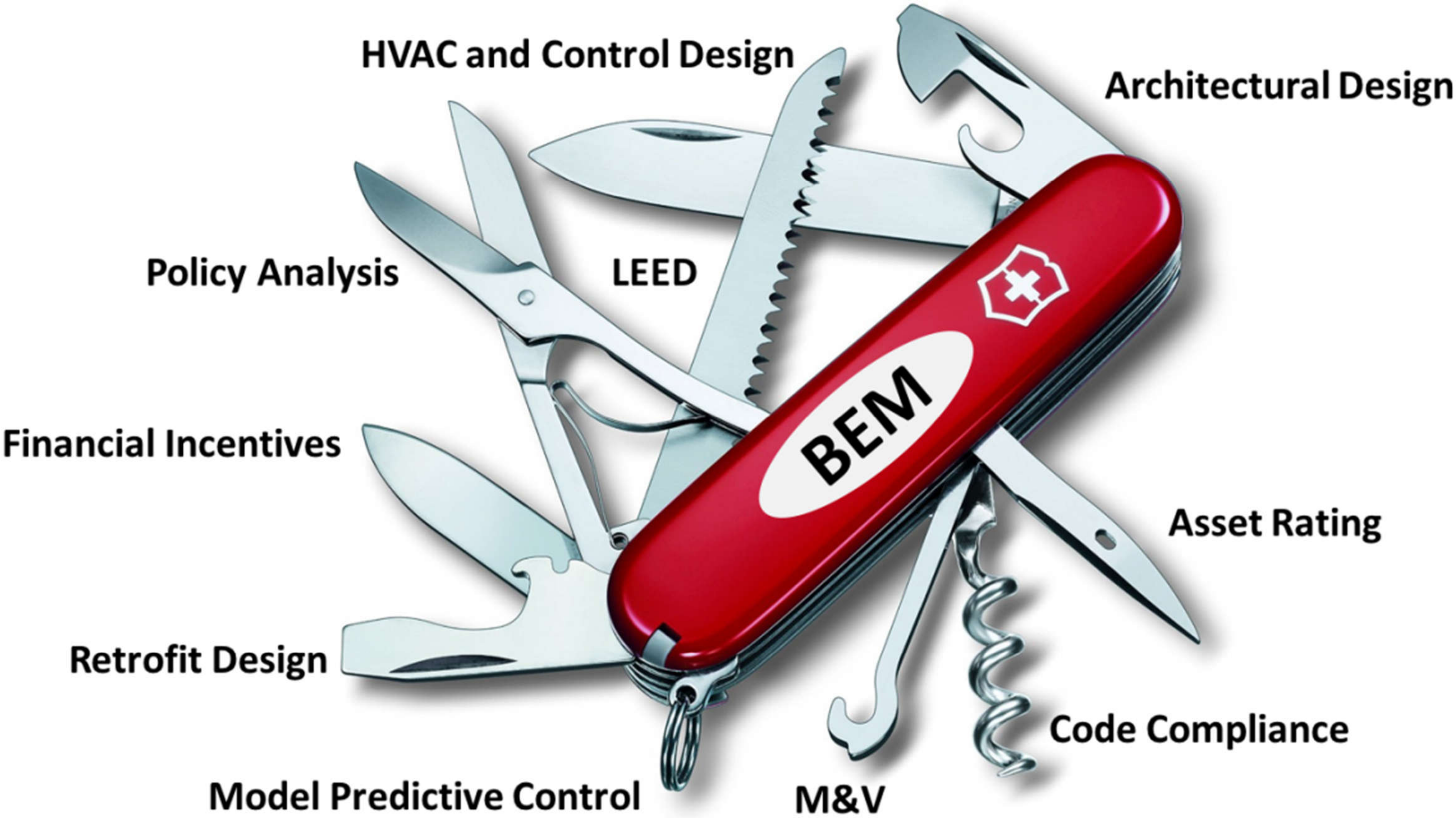
Energy flow and concept in buildings



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

Applications of building energy modelling (BEM)



(Source: https://www.energy.gov/eere/buildings/about-building-energy-modeling)

Building Energy Simulation

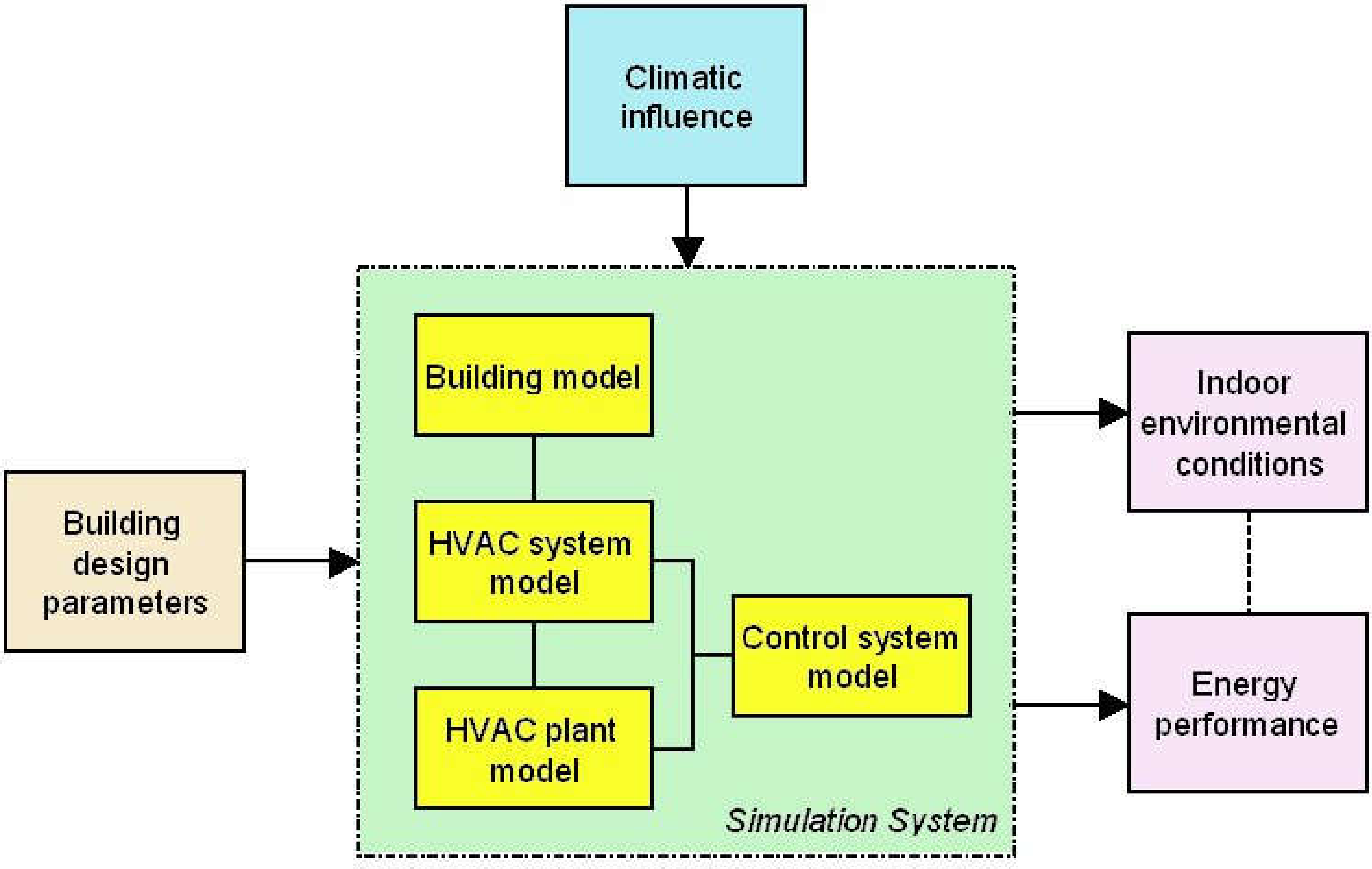
- Two approaches:
  - Forward (classical) modelling
    - Modelling for building & HVAC system design and associated design optimization [design performance modelling]
  - Data-driven (inverse) modelling
    - Modelling energy use of existing buildings for establishing baselines, calculating retrofit savings, and implementing model predictive control [building operation modelling]

(See also: ASHRAE Handbook Fundamentals 2017, Chapter 19 Energy Estimation and Modeling Methods)

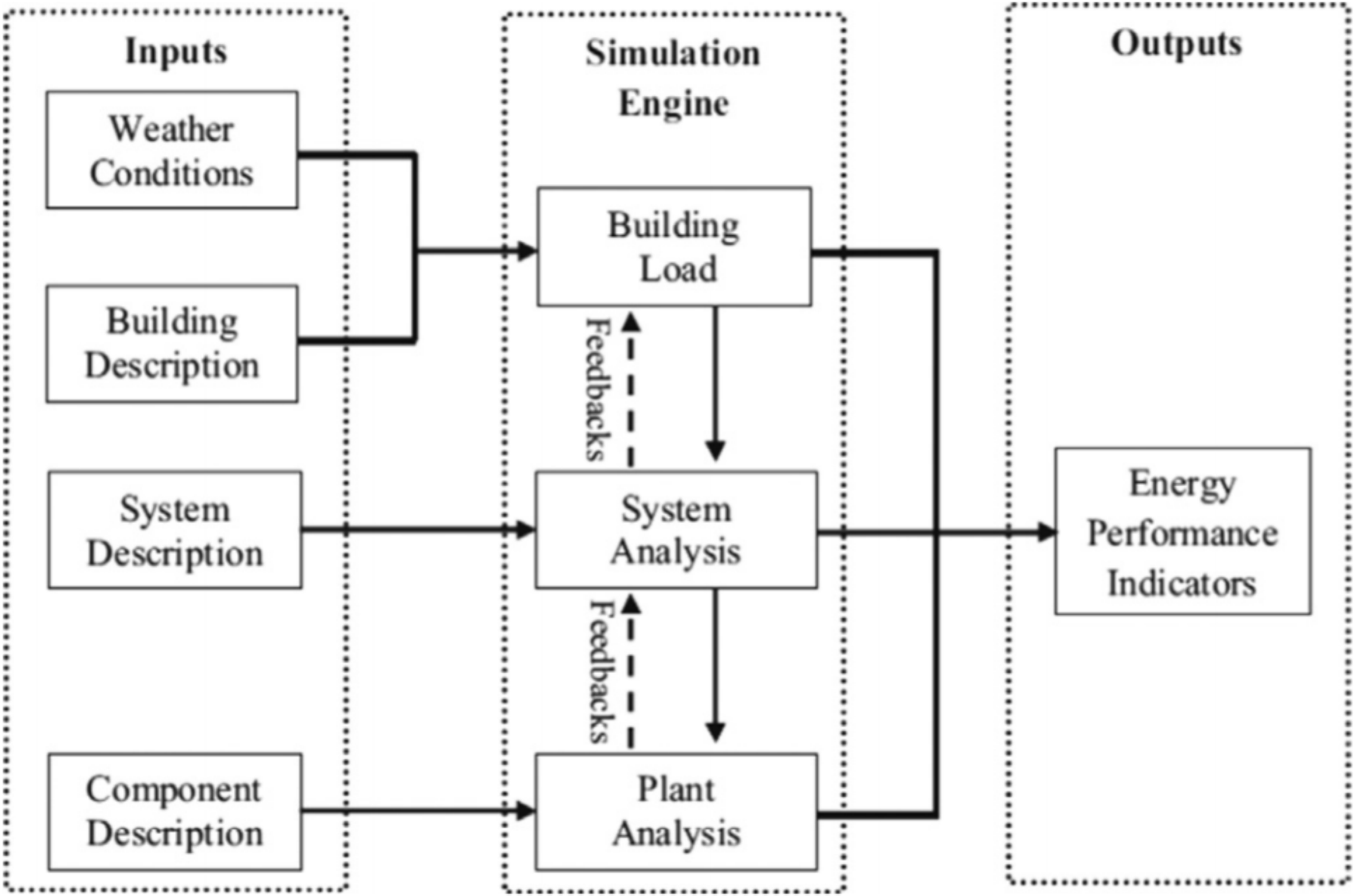
Building Energy Simulation

- Four major elements
  - Building (load) 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

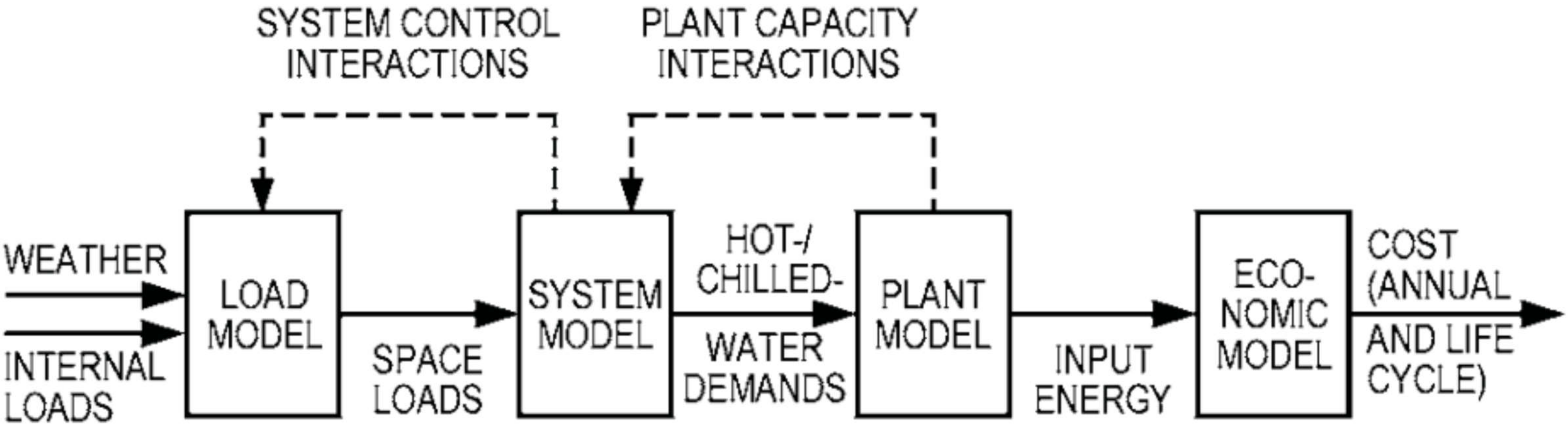


Data flow and main procedure of building energy simulation



(Image Source: Li X. & Wen J., 2014. Review of building energy modeling for control and operation, *Renewable and Sustainable Energy Reviews*, 37: 517–537.)

Overall modelling strategy



Solid lines represent data passed from one model to the next; dashed lines represent information, usually provided by the user, about one model passed to the preceding model. For example, the system information may consist of a piecewise-linear function of zone temperature that gives system capacity.

(Image Source: ASHRAE Handbook Fundamentals 2017, Chapter 19 Energy Estimation and Modeling Methods)

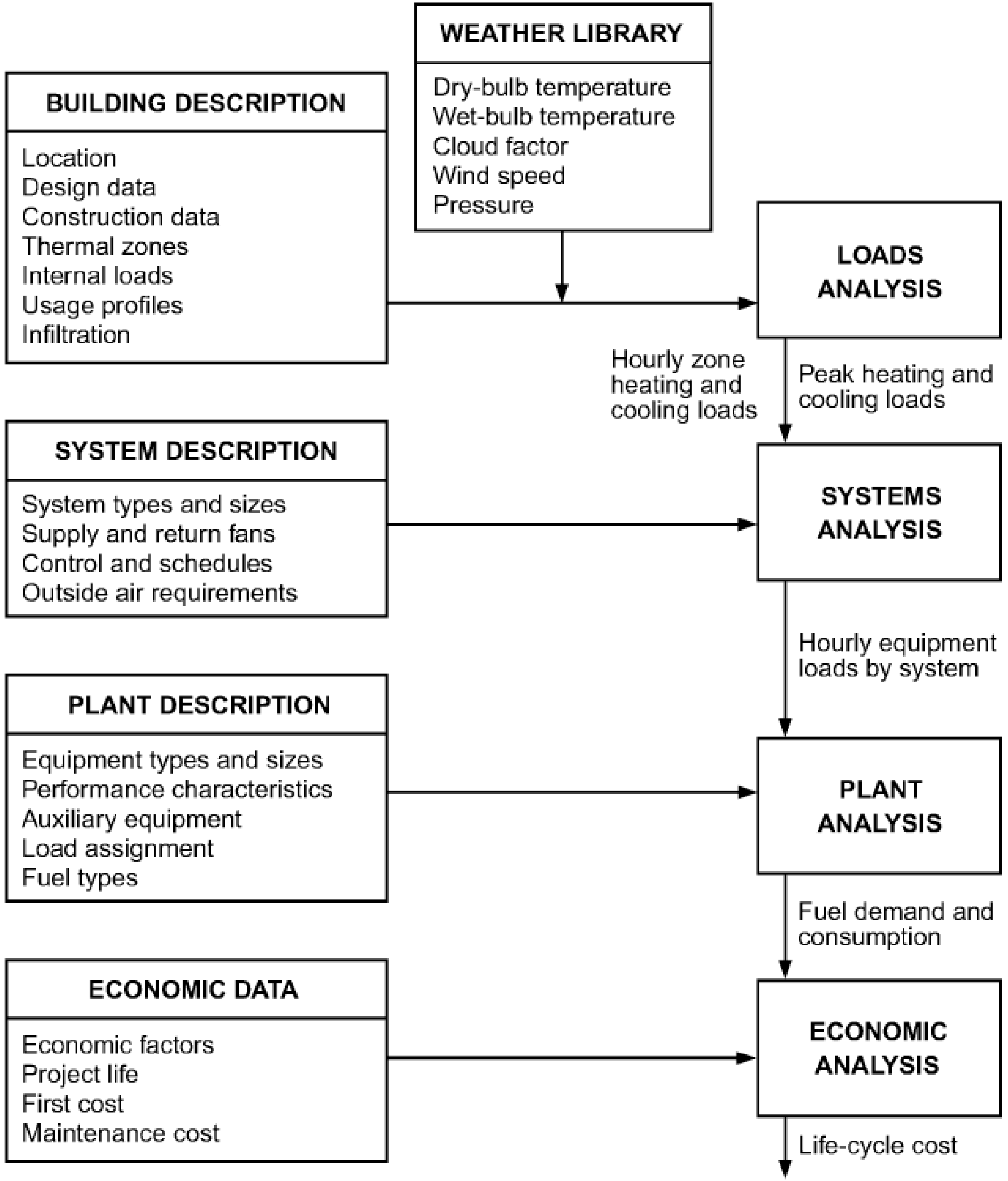
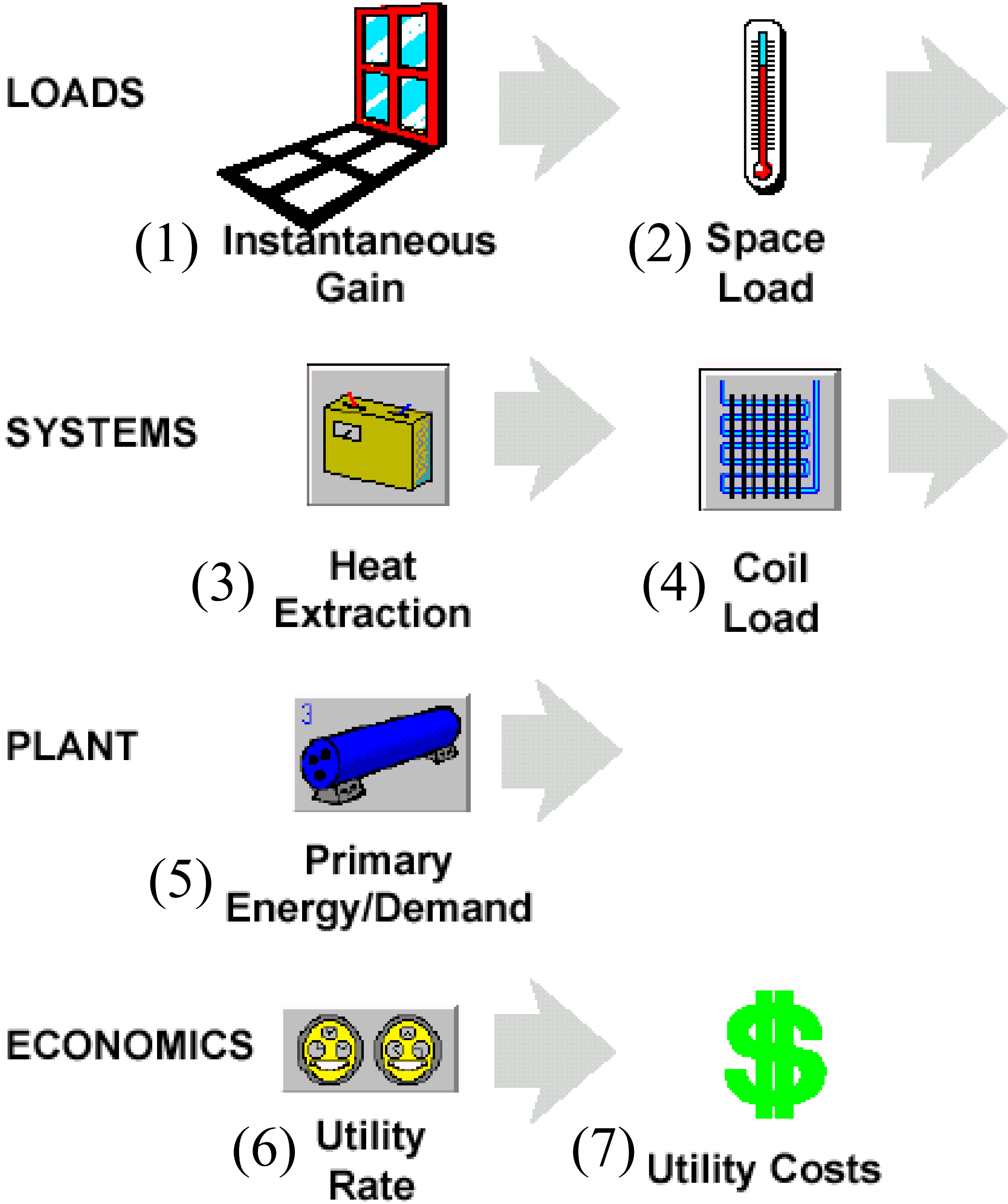


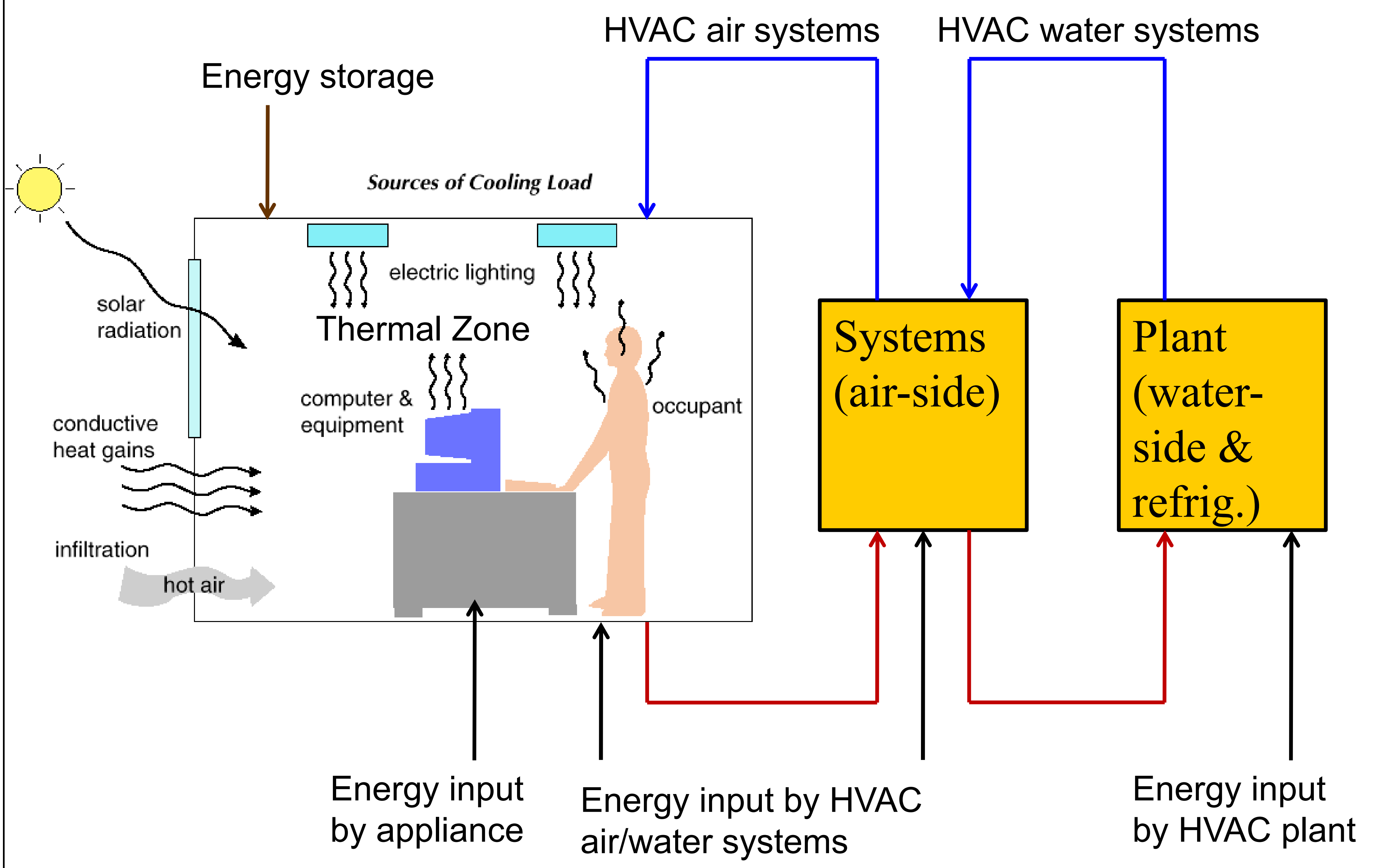
Fig. 1 Flow Chart for Building Energy Simulation Program

(Source: ASHRAE Handbook Fundamentals 2005)

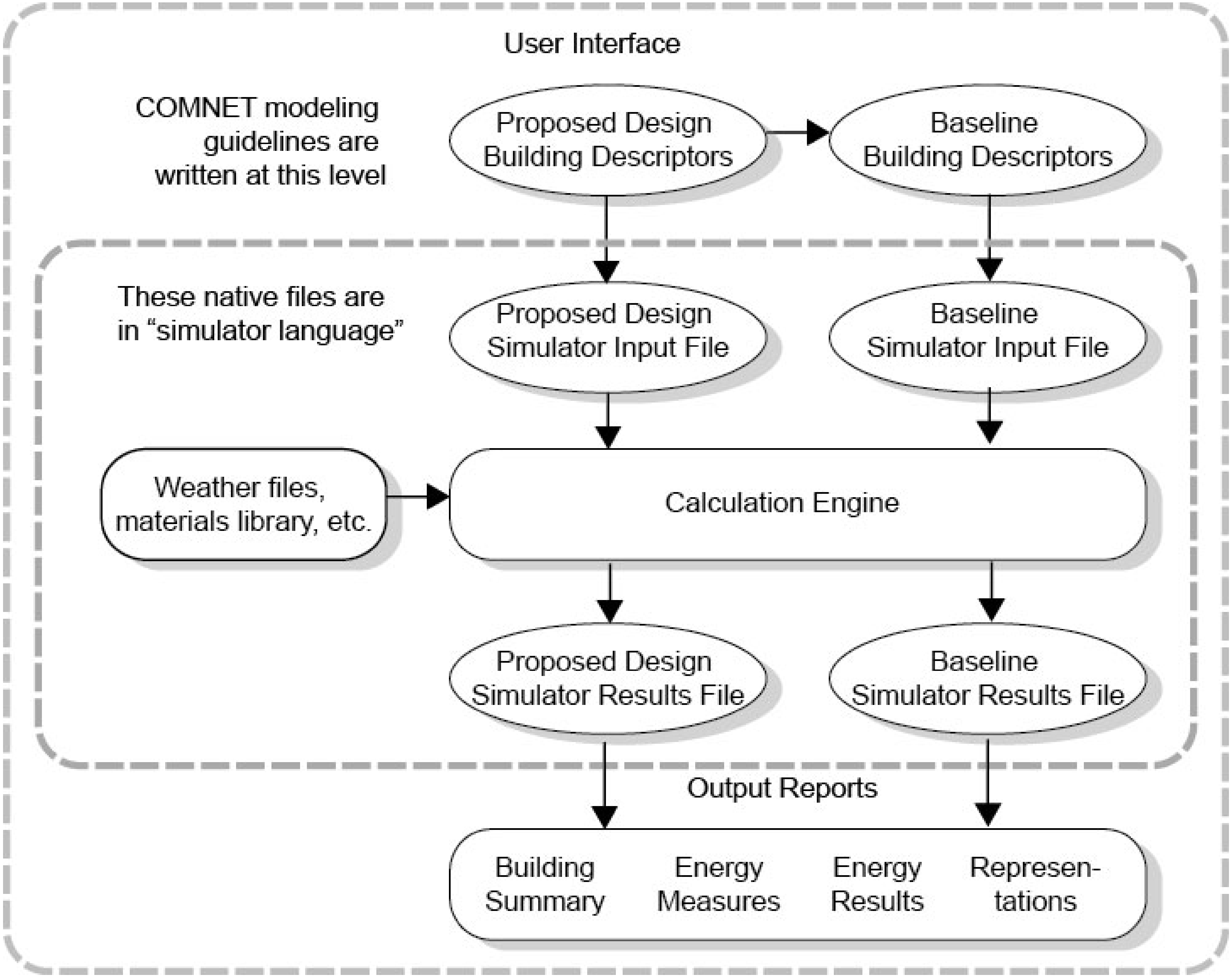
"Seven steps" of simulation output



Building energy simulation process

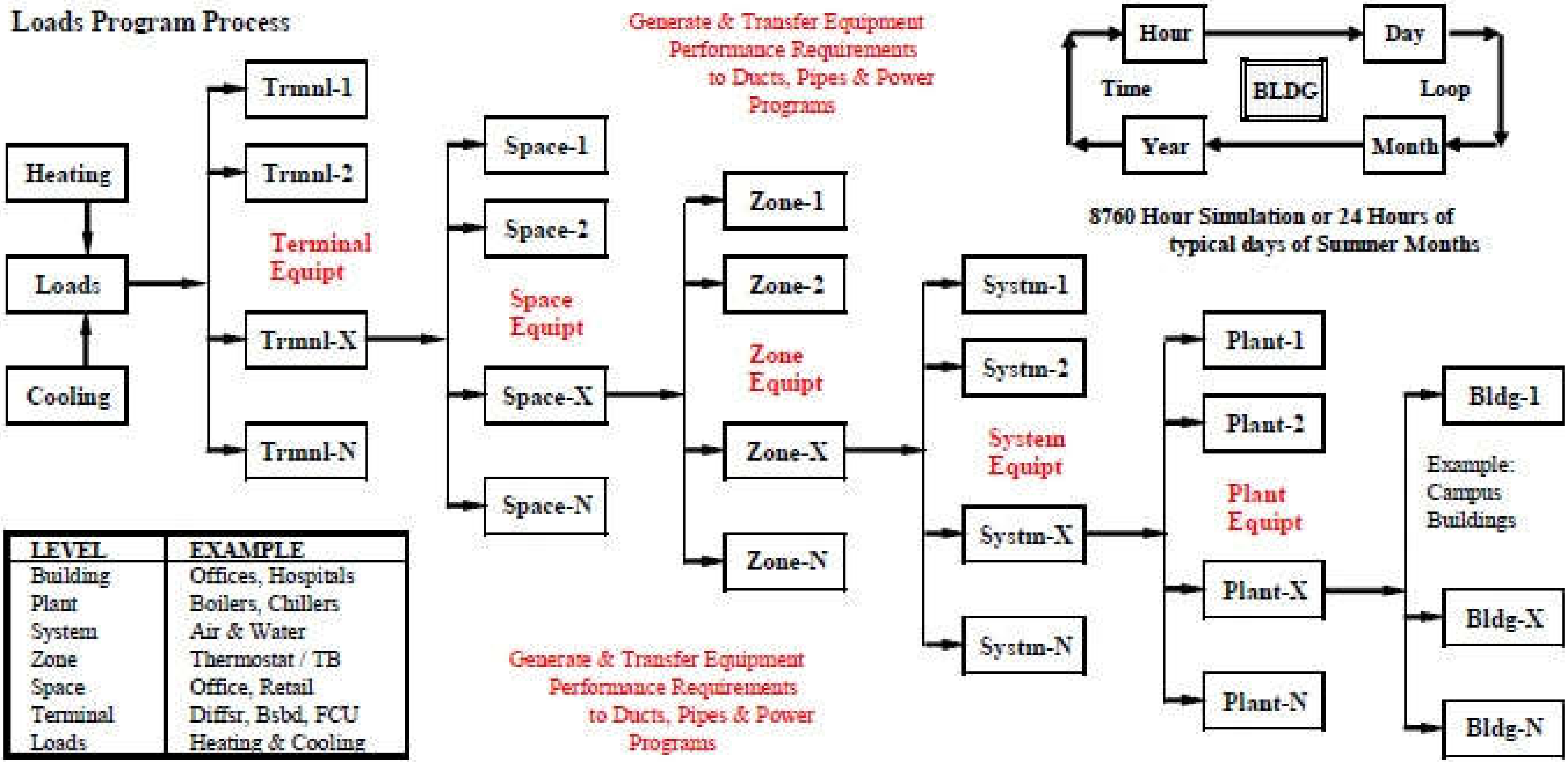


Information flow for building energy simulation & modelling



(Source: https://www.comnet.org/index.php/21-general-requirements-data-user)

Example of software structure for building energy simulation (DOE-2)



LEVEL	EXAMPLE
Building	Offices, Hospitals
Plant	Boilers, Chillers
System	Air & Water
Zone	Thermostat / TB
Space	Office, Retail
Terminal	Diffsr, Bsbd, FCU
Loads	Heating & Cooling

(Source: http://energy-models.com/energy-usage-analysis-buildings)

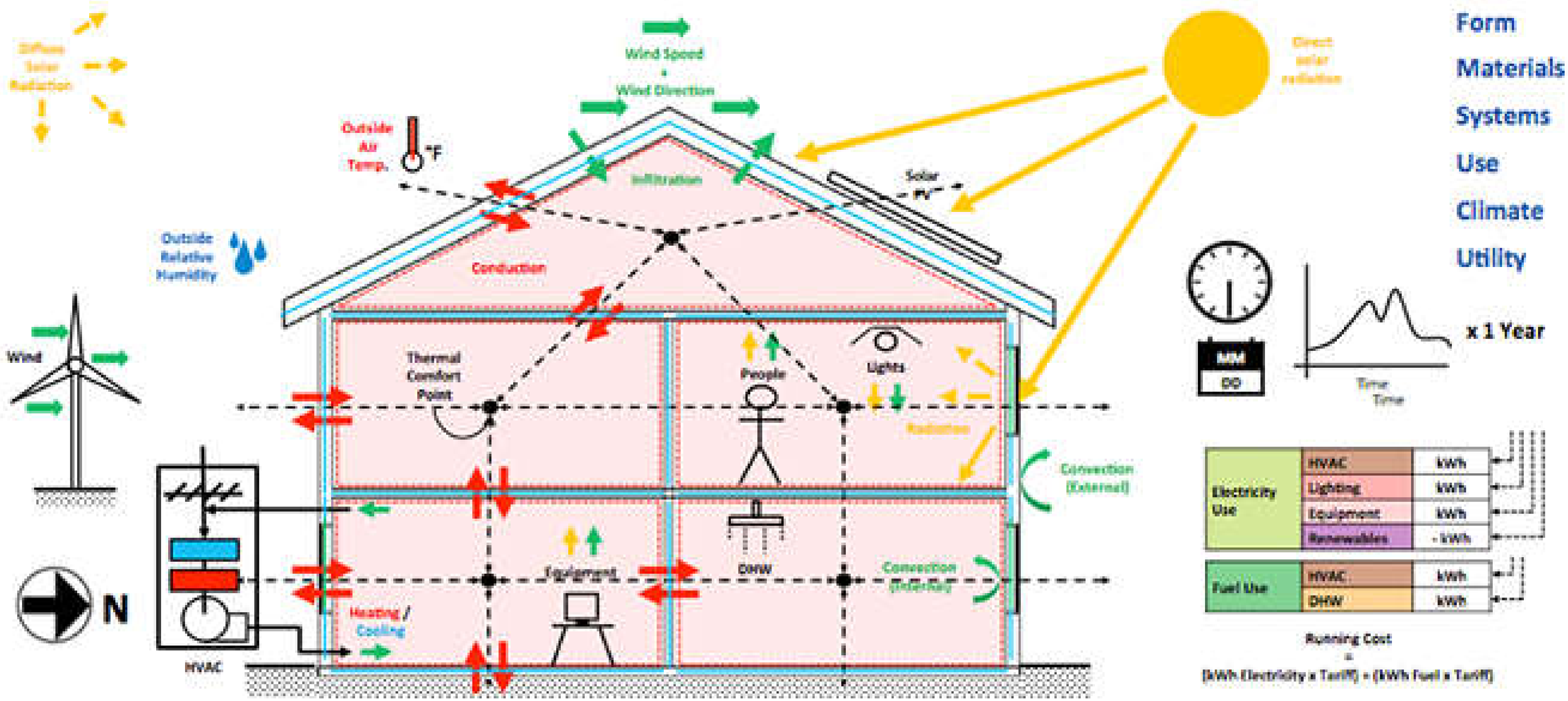
Building Energy Simulation

- HVAC component modelling
  - Modelling strategies
    - Empirical (regression-based) models
    - First-principles models
  - Typical components
    - Terminal units & controls
    - Secondary system components (fan, pumps & distribution systems)
    - Primary system components (boilers, chillers, cooling towers, heat pumps)

Building Energy Simulation

- Low-energy system modelling
  - Natural & hybrid ventilation
    - Computational fluid dynamics (CFD) or network airflow models may also be used
  - Daylighting
    - Daylighting & lighting simulation tools may be used
  - Passive cooling & heating and passive solar design
    - Solar energy simulation models may also be used
  - Renewable energy systems
    - Such as solar photovoltaics (PV), solar thermal, wind

Modelling of low-energy systems for green buildings



(Source: https://gbs.autodesk.com/GBS/)

Simulation Software Tools

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

- Building Energy Software Tools Directory
  - https://www.buildingenergysoftwaretools.com/

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

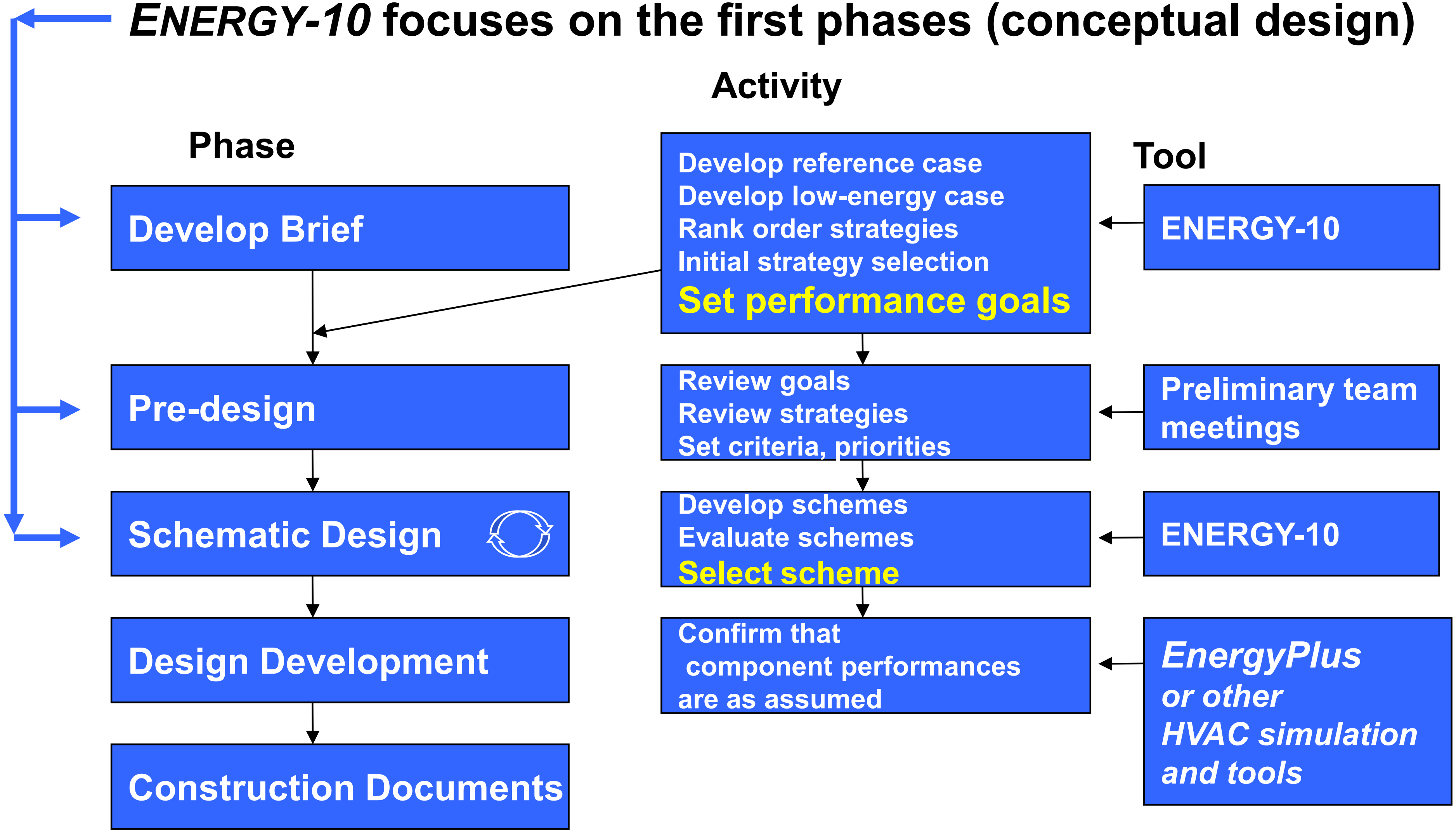
Tas

Simulation Software Tools

- Selected software tools:*
  - Energy-10 (version 1.8)
    - http://arizonaenergy.org/Analysis/Builders/energy10.htm
    - 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)
  - VisualDOE (version 4.1)
    - A powerful tool based on DOE-2.1e simulation engine to evaluate energy savings of building design options

(* These software tools are no longer updated and available for purchase of license.)

Example: Energy-10



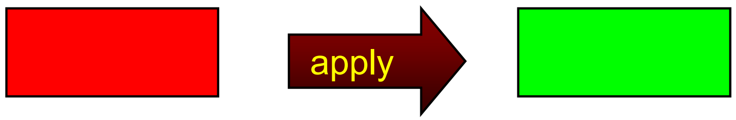
Example: Energy-10

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

- **Location**
- **Building Use**
- **Floor area**
- **Number of stories**
- **HVAC system**

Gets you started quickly.

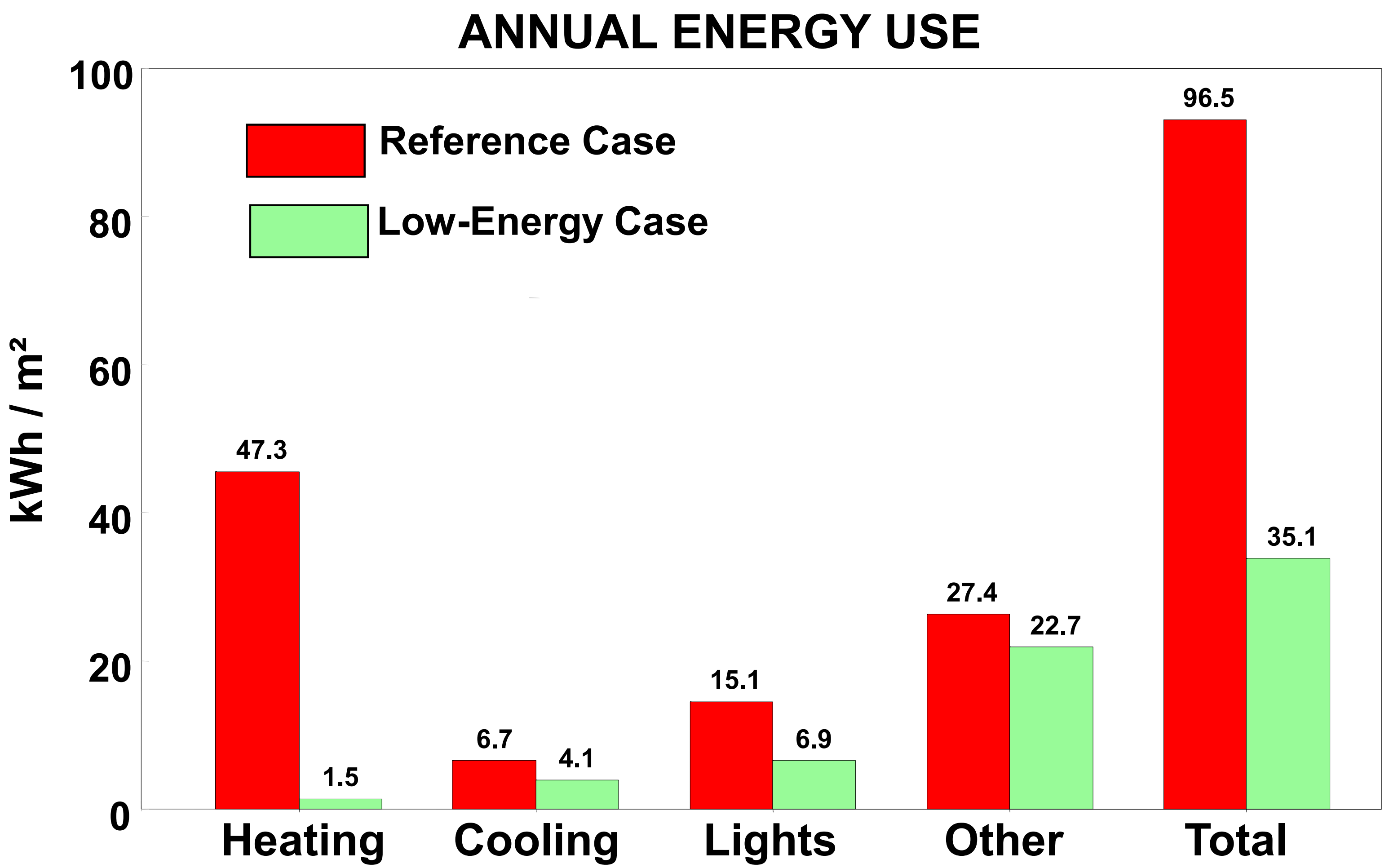
For example:



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

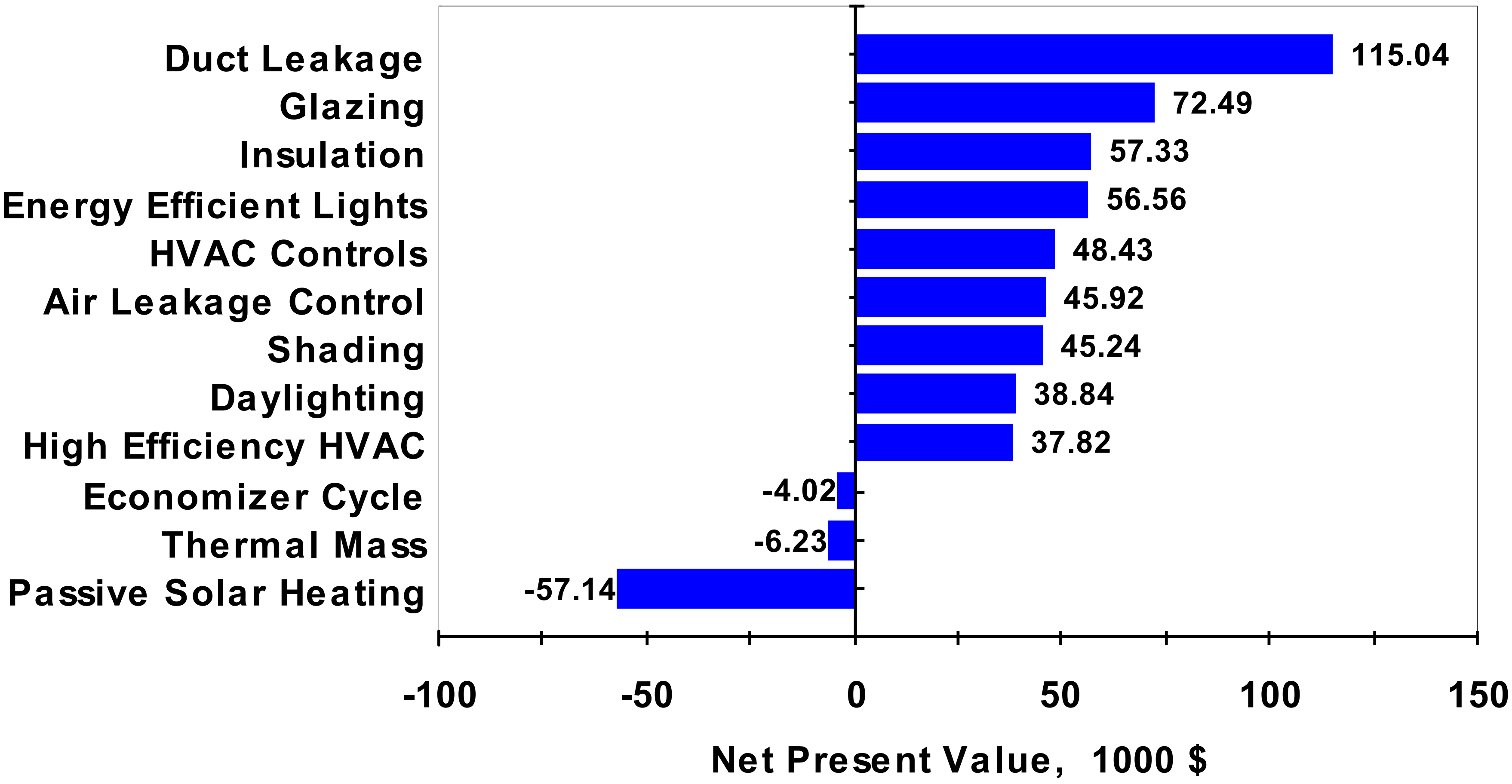
Example: Energy-10

2,000 m² office building

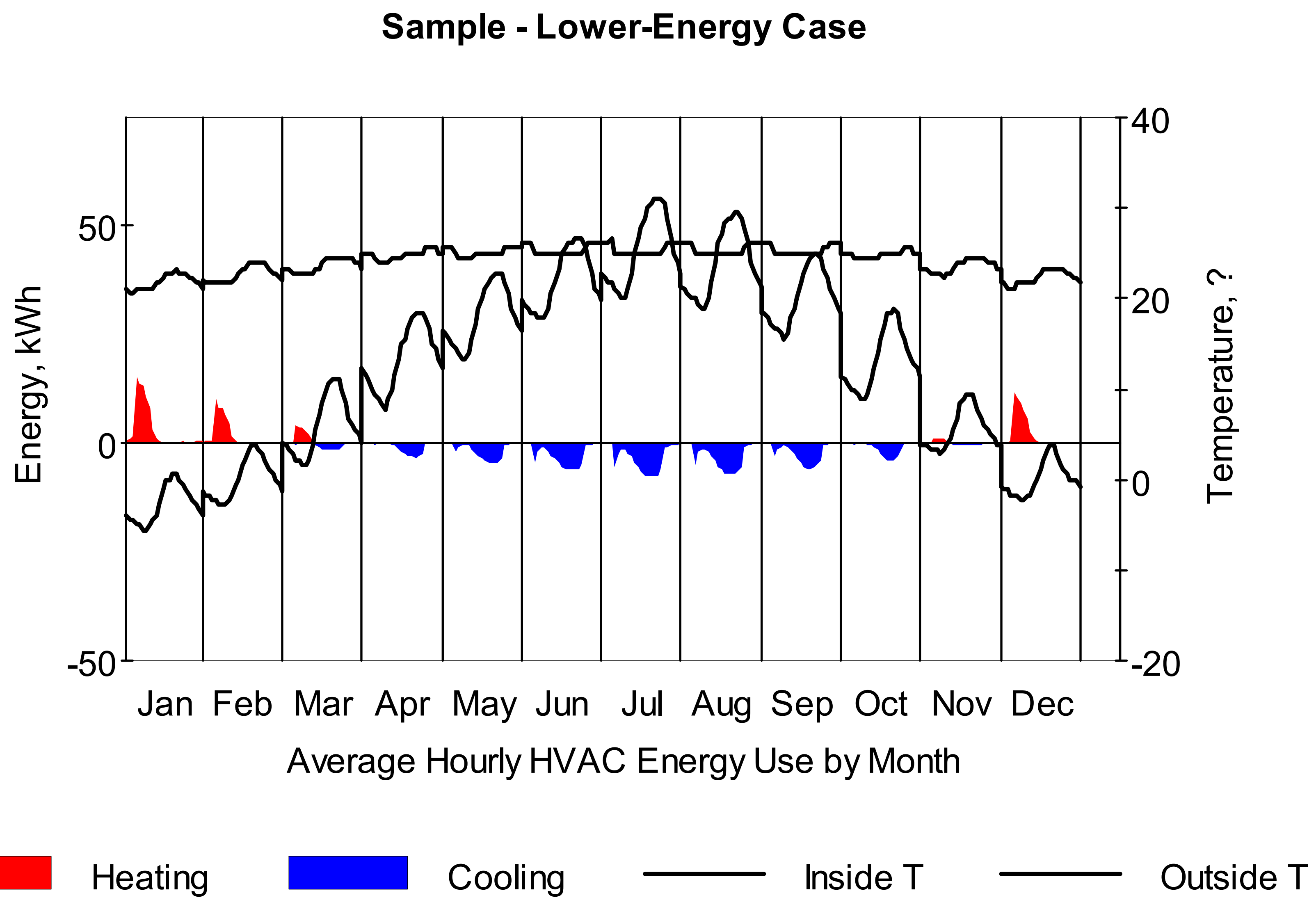


Example: Energy-10

RANKING OF ENERGY-EFFICIENT STRATEGIES

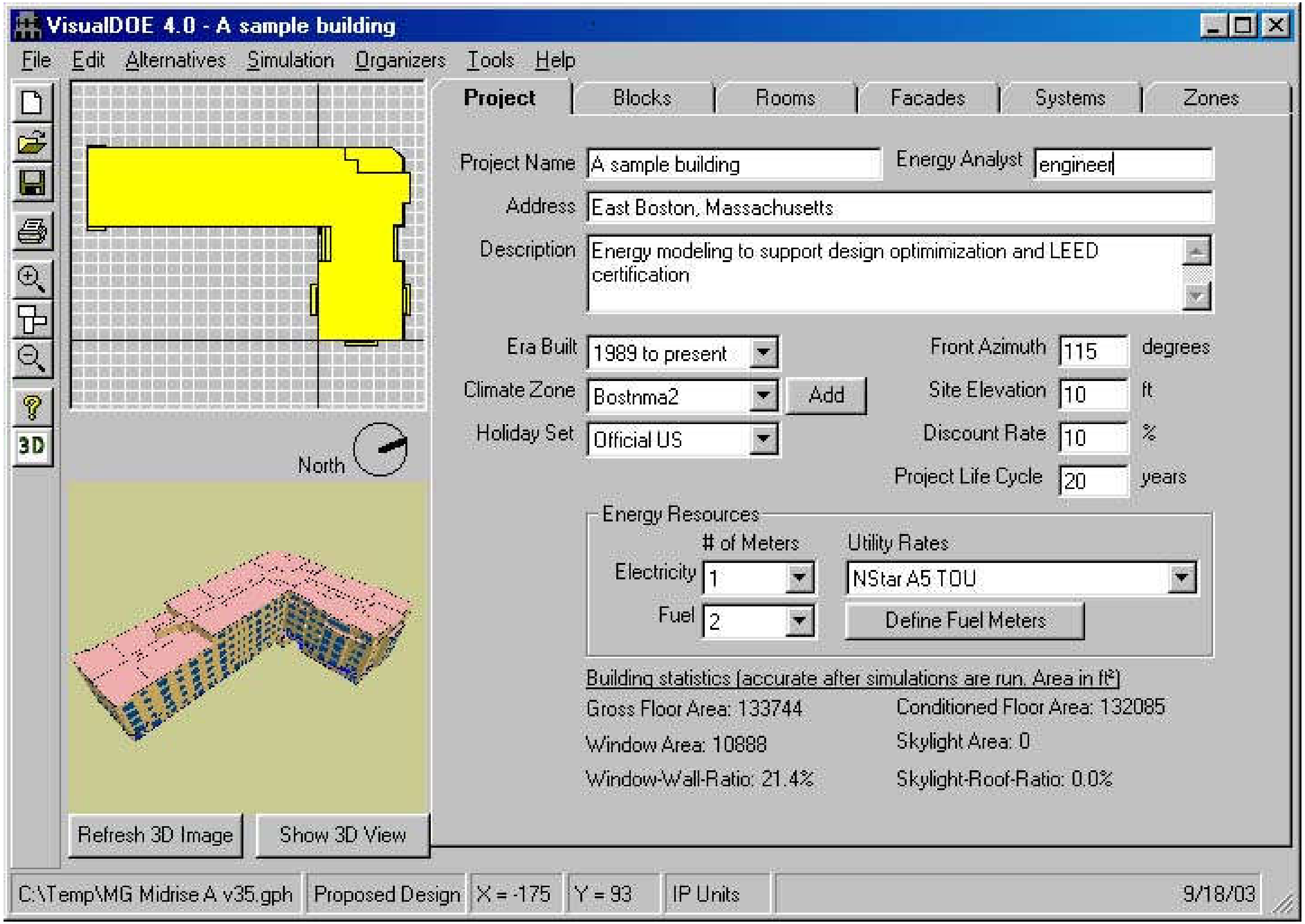


Example: Energy-10



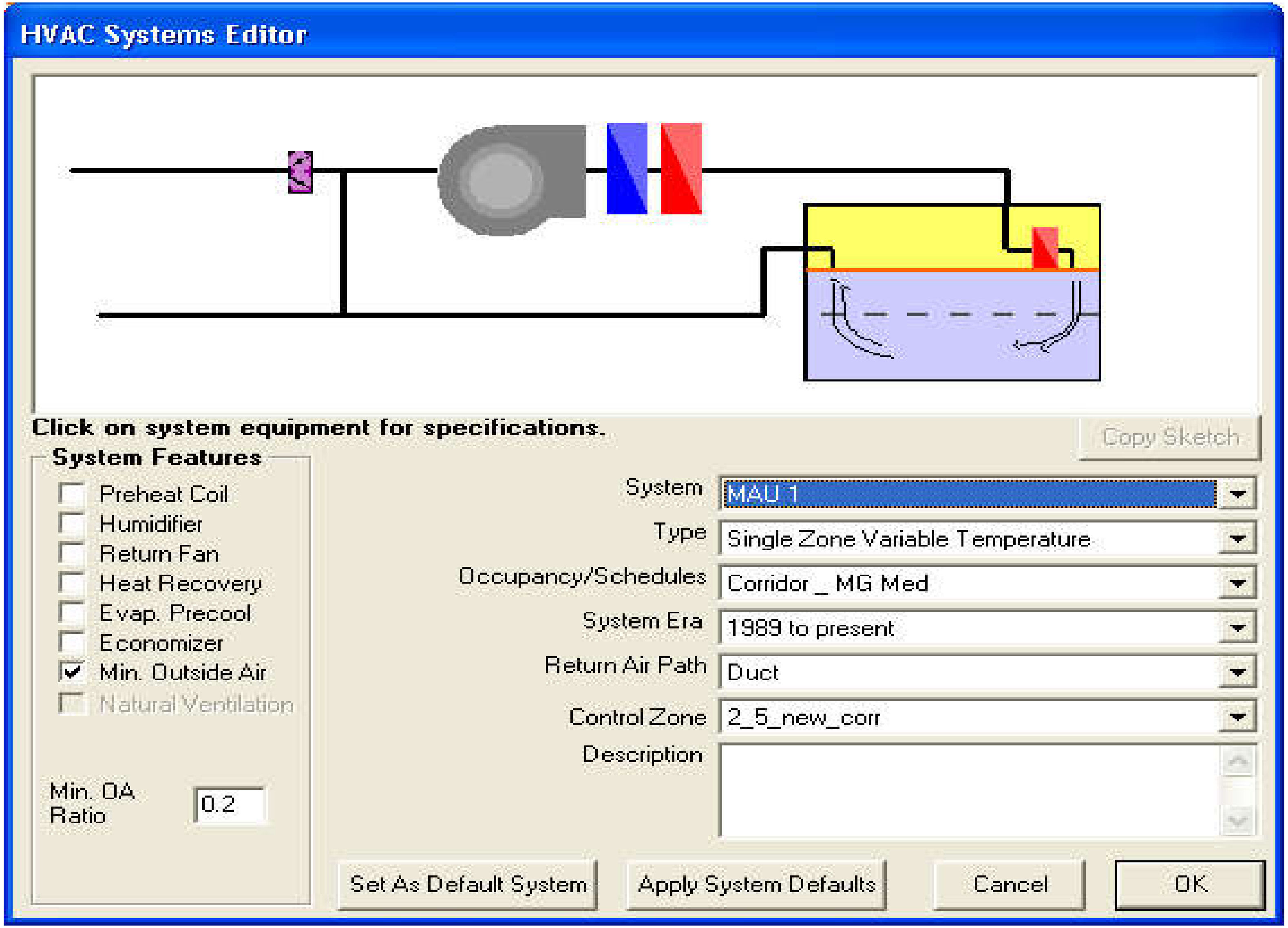
Example: VisualDOE

DOE-2



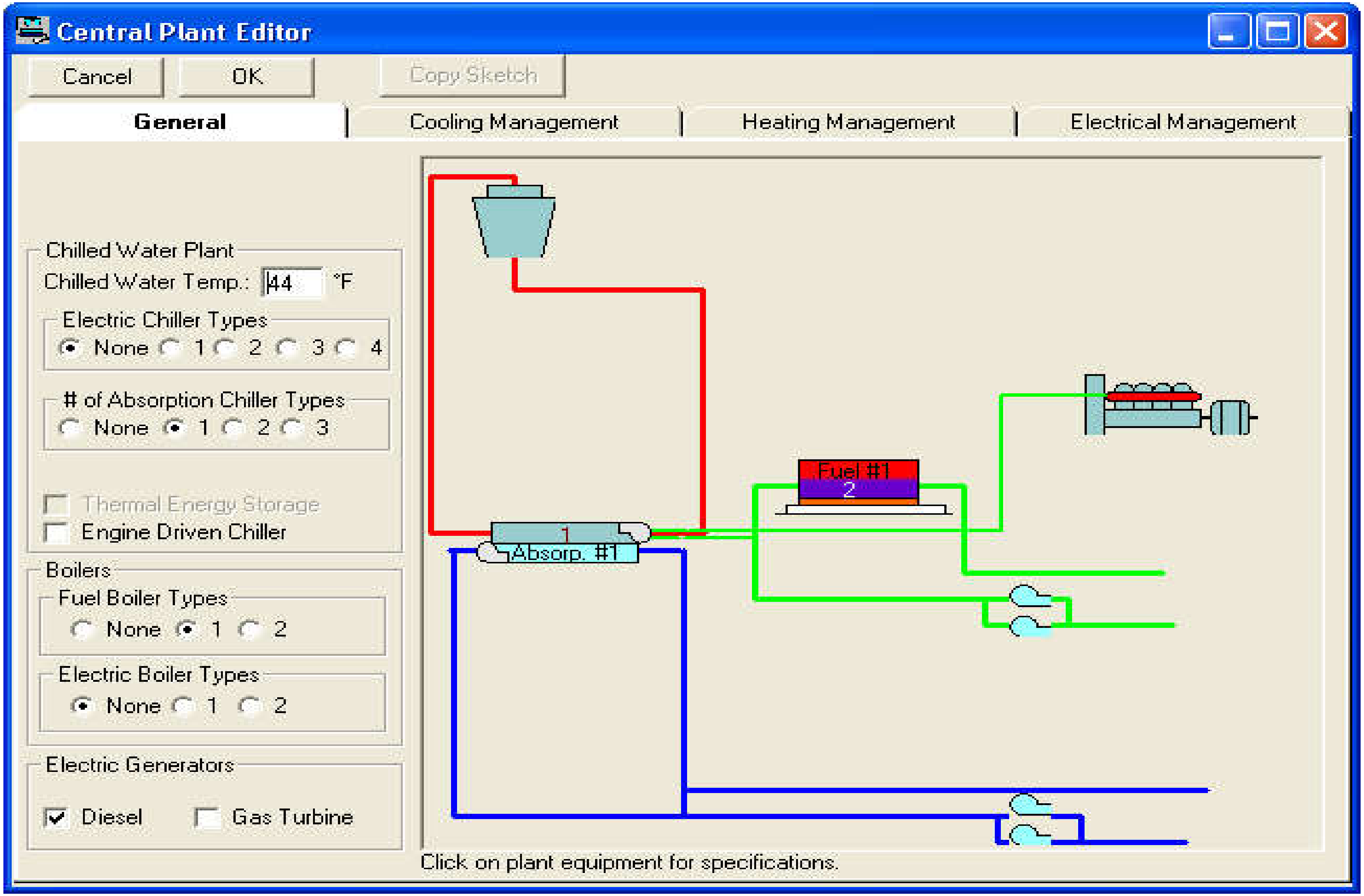
Example: VisualDOE

DOE-2



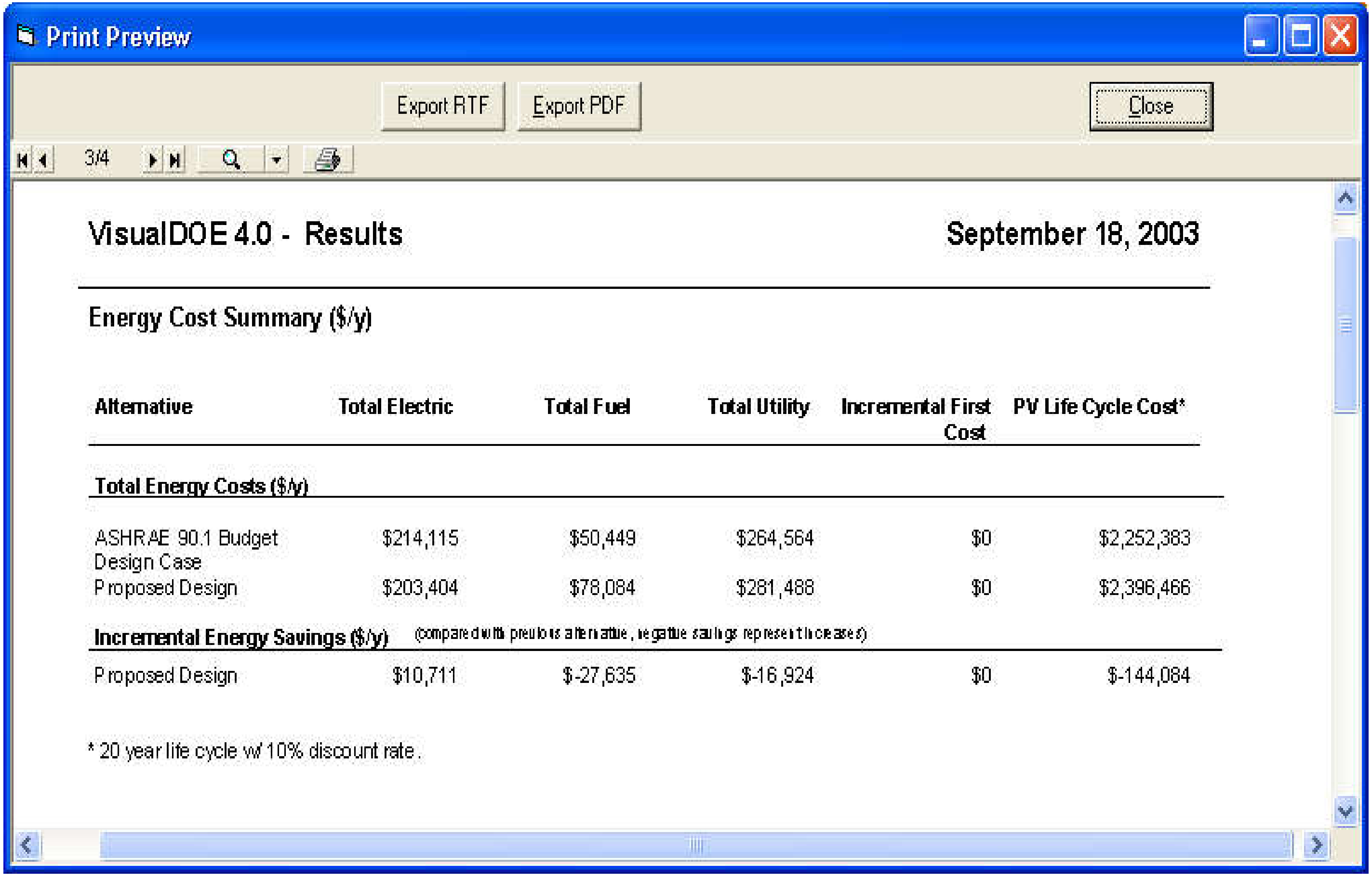
Example: VisualDOE

DOE-2



Example: VisualDOE

DOE-2



VisualDOE 4.0 - Results

September 18, 2003

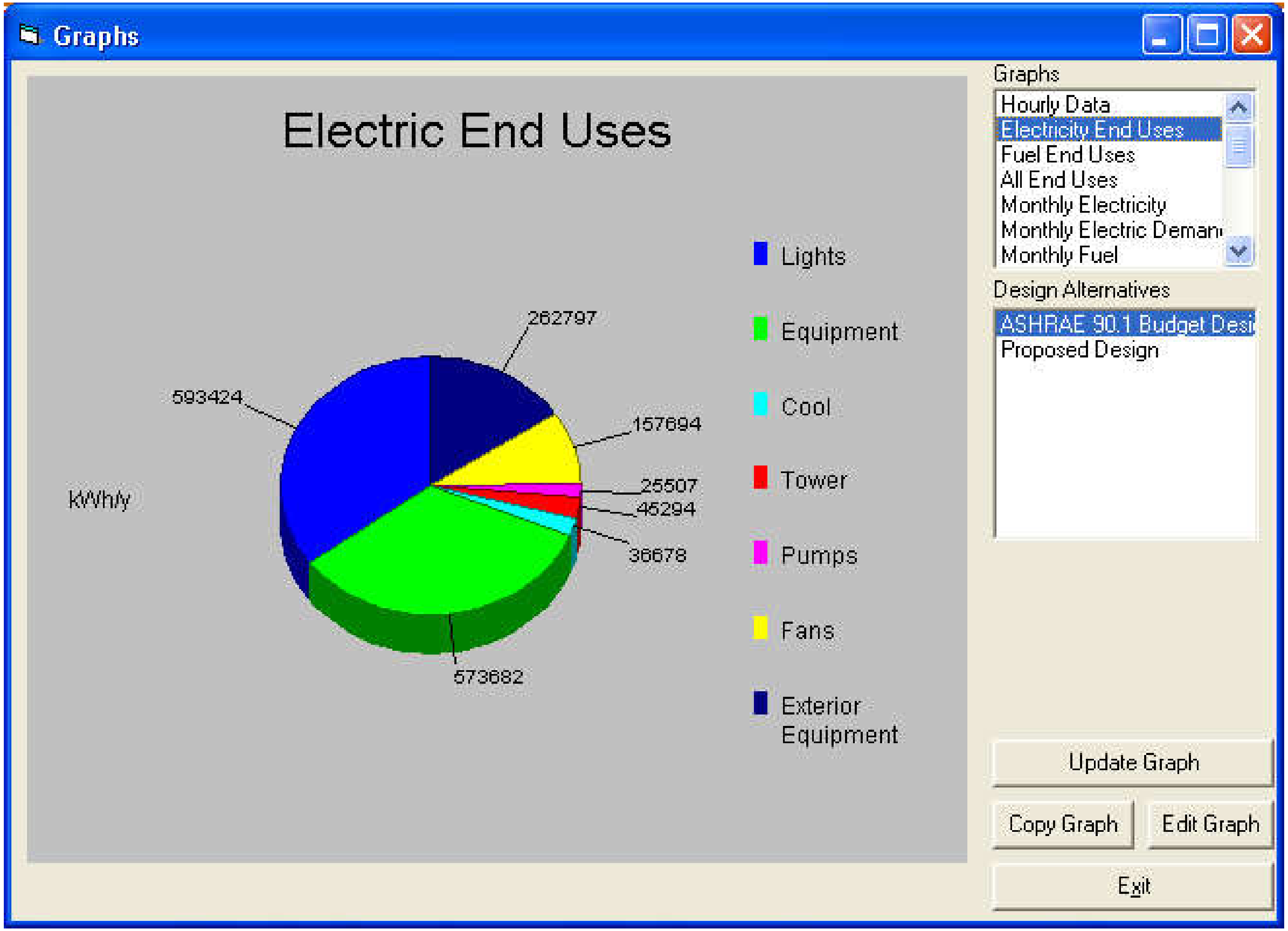
Energy Cost Summary ($/y)

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.

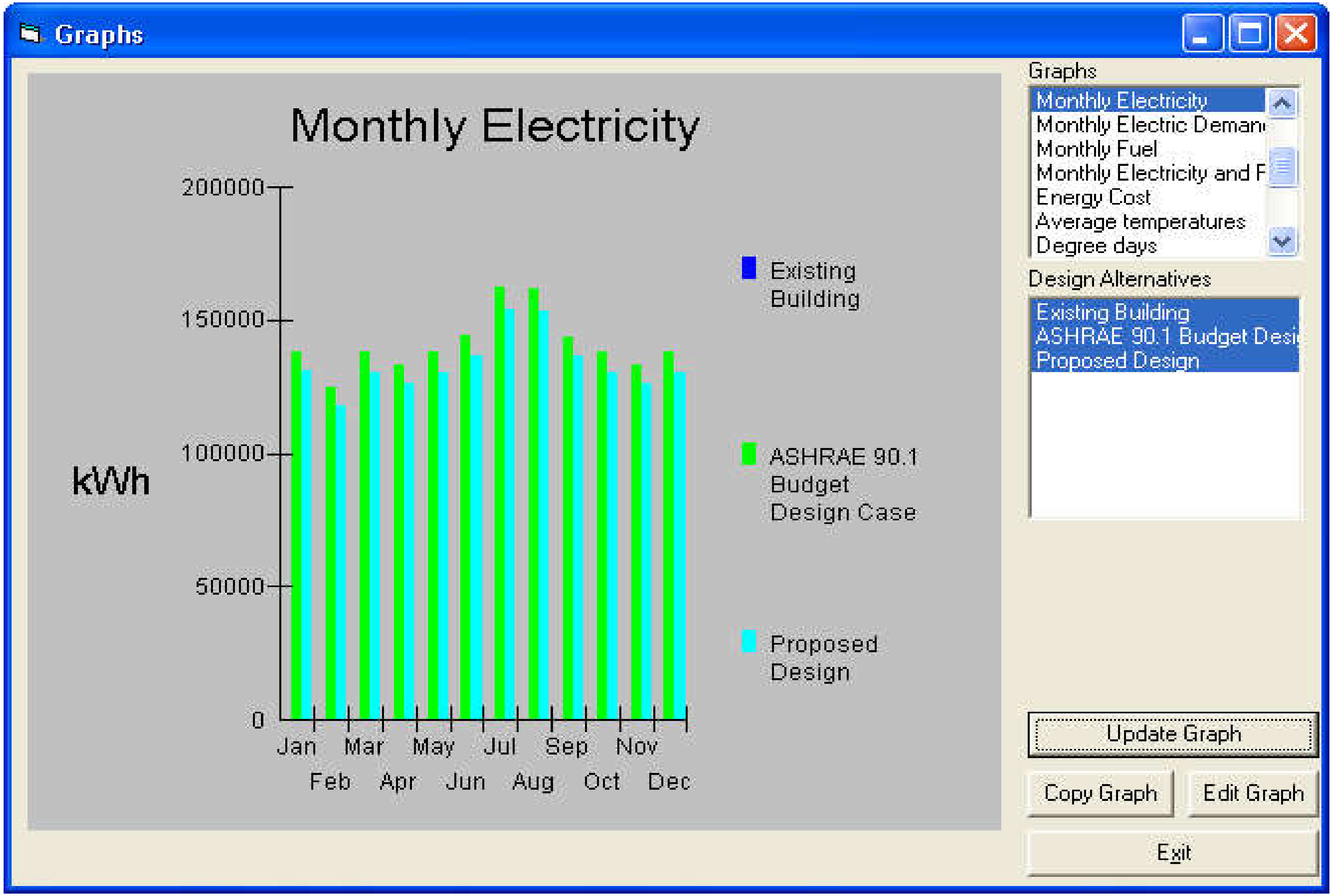
Example: VisualDOE

DOE-2



Example: VisualDOE

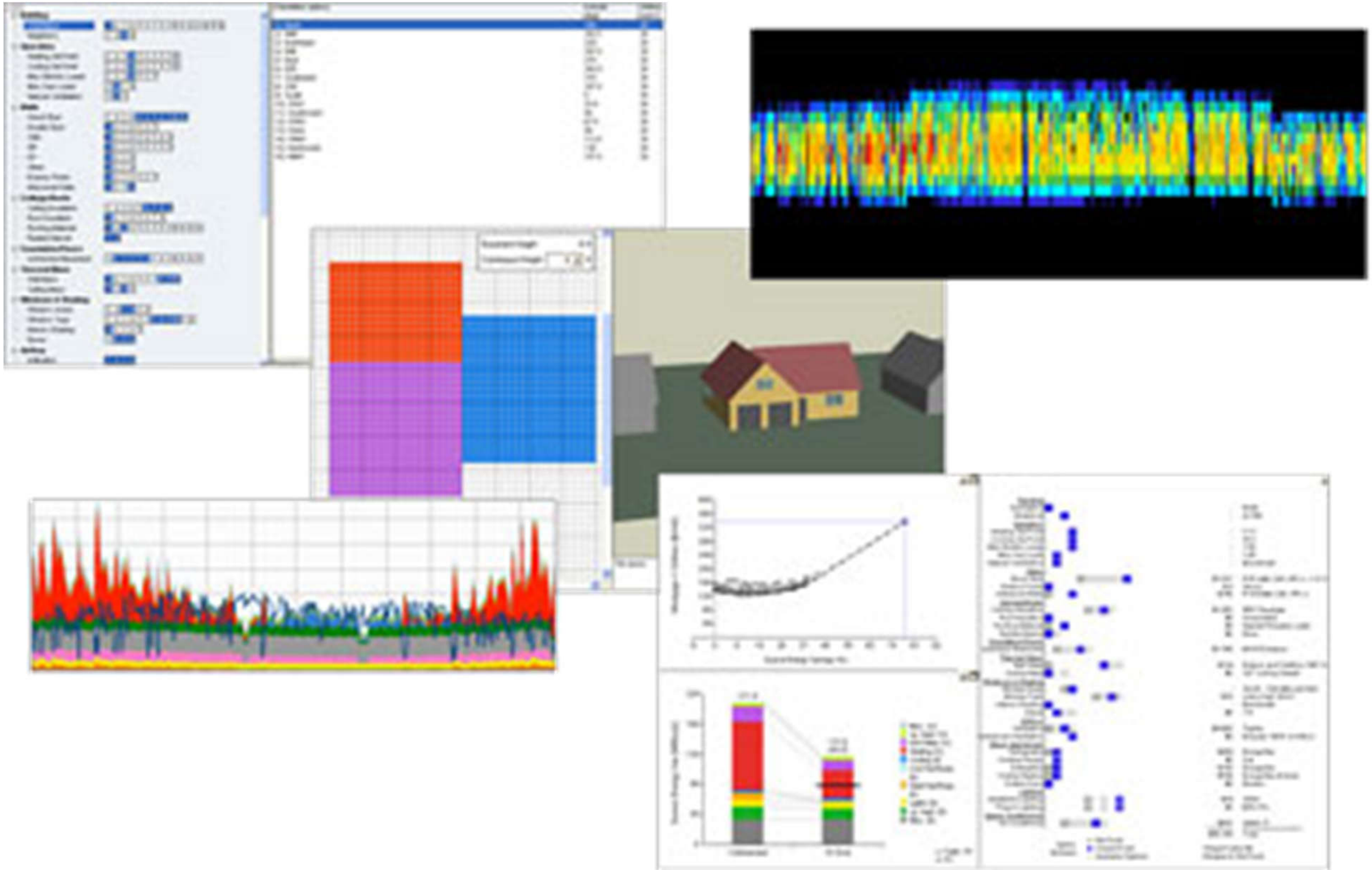
DOE-2



Simulation Software Tools

- Other software tools: (available for trial runs)
  - BEopt: Building Energy Optimization Tool https://beopt.nrel.gov/
    - Residential building energy modelling tool developed by National Renewable Energy Lab (NREL)
  - EnergyPlus https://energyplus.net/
    - A whole building energy simulation program developed by US Department of Energy (US-DOE)
  - MIT Design Advisor http://designadvisor.mit.edu/
    - Online simulation tool developed by Massachusetts Institute of Technology (MIT)

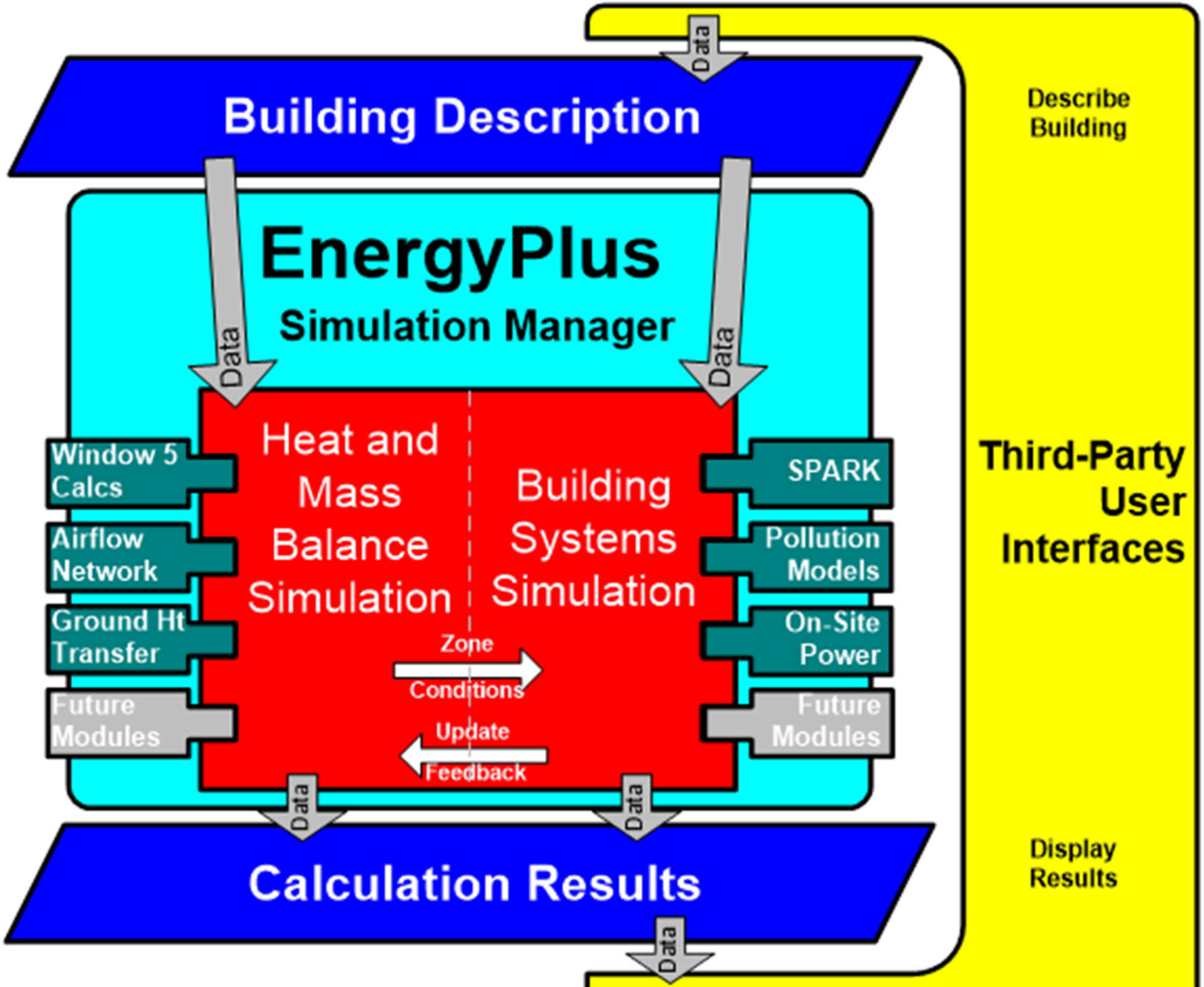
BEopt: Residential Building Energy Modeling Tool



BEopt (Building Energy Optimization Tool) can evaluate residential building designs and identify cost-optimal efficiency packages at various levels of whole-house energy savings along the path to zero net energy.

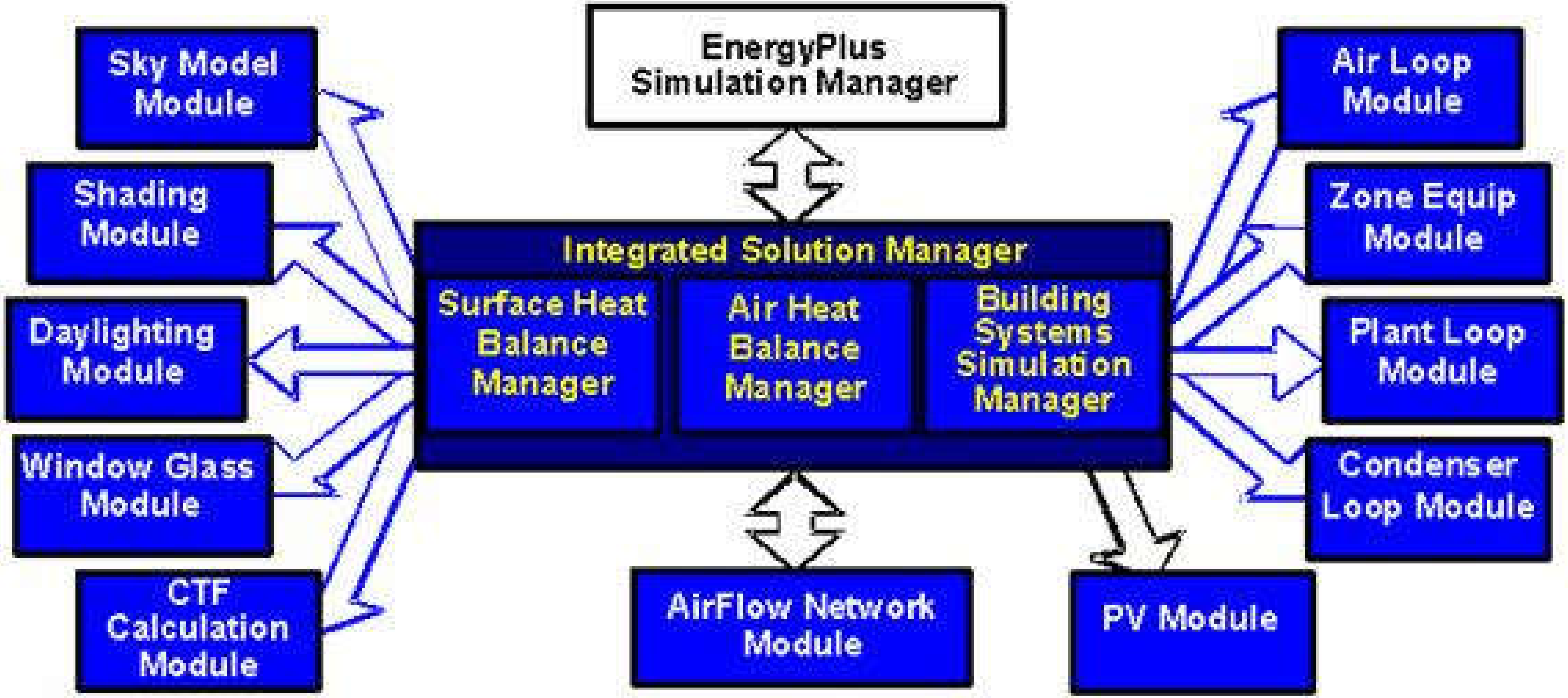
(Source: https://beopt.nrel.gov/)

Basic structure of EnergyPlus



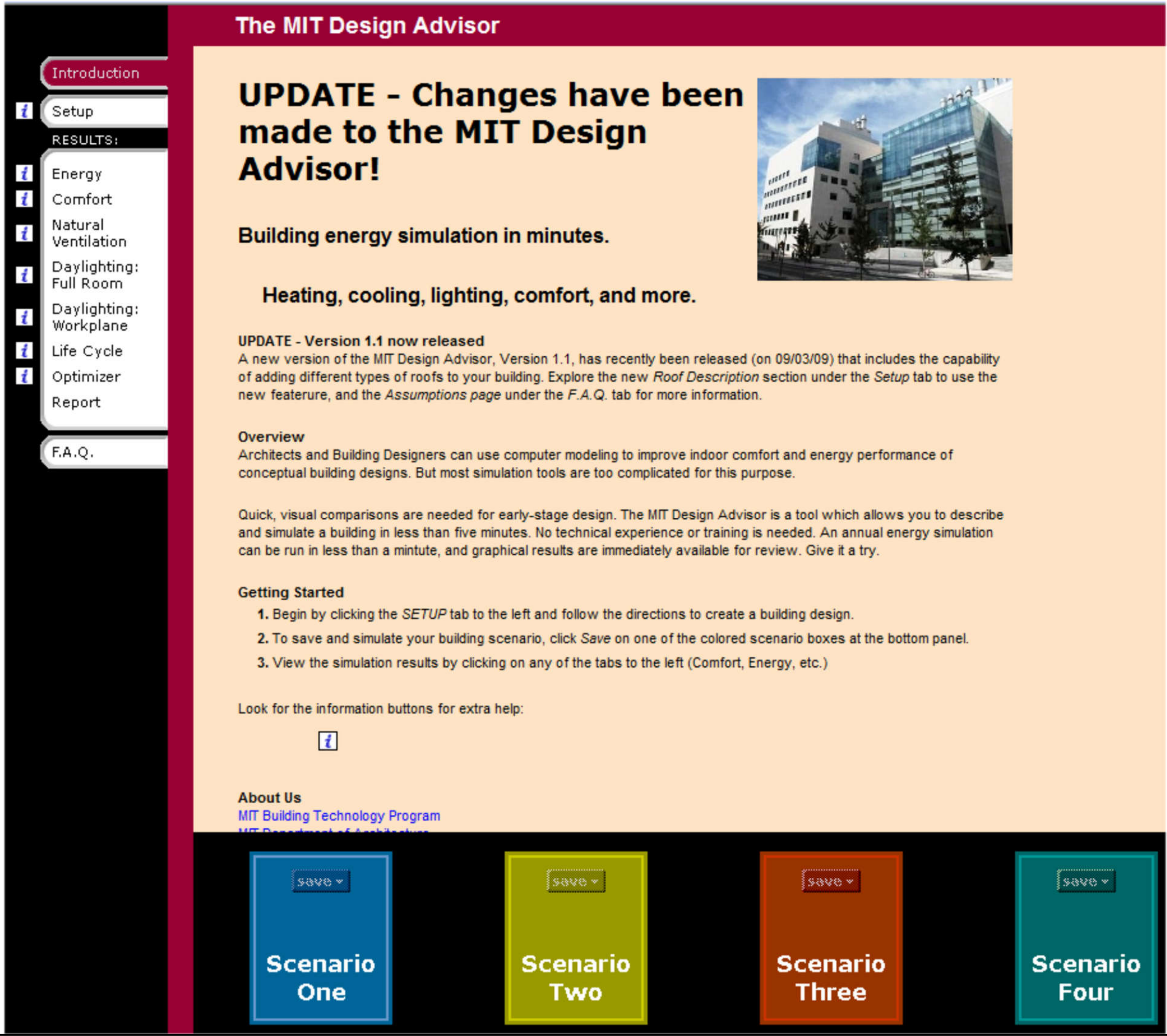
(Source: https://www.energyplus.net/sites/default/files/docs/site_v8.3.0/GettingStarted/GettingStarted/index.html)

Internal elements of EnergyPlus



(Source: https://www.energyplus.net/sites/default/files/docs/site_v8.3.0/GettingStarted/GettingStarted/index.html)

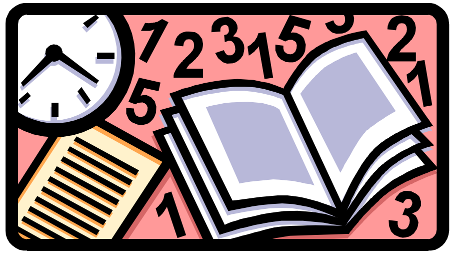
MIT Design Advisor, http://designadvisor.mit.edu/design/



Further Reading

- Building performance simulation - Wikipedia
  - https://en.wikipedia.org/wiki/Building_performance_simulation
- Energy Usage Analysis of Buildings http://energy-models.com/energy-usage-analysis-buildings
- What is Energy Modeling & Building Simulation
  - http://energy-models.com/what-is-energy-modeling-building-simulation
- Hui, S. C. M., 1998. Simulation based design tools for energy efficient buildings in Hong Kong, *Hong Kong Papers in Design and Development*, Vol. 1, 1998, pp. 40-46, Department of Architecture, University of Hong Kong. [http://ibse.hk/cmhui/hkpdd/hkpdd-v1.htm]

References



- ASHRAE, 2017. *ASHRAE Handbook Fundamentals 2017*, American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc., Atlanta, GA. [ASHRAE Catalog: 697 A82 T4]
  - Chapter 19 Energy Estimation and Modeling Methods
- Kreider, J. F, (ed.), 2001. *Handbook of Heating, Ventilation, and Air Conditioning*, Chapter 6: HVAC Design Calculations, CRC Press, Boca Raton, FL. [ebook via ENGnetBASE]
- Waltz, J. P., 2000. *Computerized Building Energy Simulation Handbook*, Fairmont Press, Lilburn, GA. [658.2 W241 c] [EBSCOhost]