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# ENHANCING AND EXTENDING THE CAPABILITIES OF THE BUILDING HEAT BALANCE SIMULATION TECHNIQUE FOR USE IN ENERGYPLUS

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## ABSTRACT

With the advent of the computing age, heat balance based techniques for simulating thermal loads in buildings became a reality for architects and engineers. However, since the 1970s, the capabilities of most of the well-known heat balance based simulation programs have remained fairly stagnant. Much of the reason behind this trend lies with the complexity of the programming required to deal with the fundamental physics encountered in a building and the relative simplicity of the programming languages that were available. With the ever-increasing capabilities of the desktop personal computers and the improved features of the modern programming languages, it is now possible and prudent to revisit the basic heat balance formulation and investigate how its capabilities can be expanded. This paper discusses some of the technical details behind recent advances in heat balance based simulation capabilities achieved by the team of researchers developing the EnergyPlus program for the United States Department of Energy. The EnergyPlus project seeks to combine the best features of the DOE-2 program and the IBLAST program (research version of BLAST). This paper focuses on the marriage of the basic heat balance engine of BLAST with advanced simulation ideas from the IBLAST and DOE-2 programs. This complex task requires careful attention to algorithmic integrity as well as overall program construction and data management. This paper provides the theoretical background for several of the enhancements to the heat balance based simulation technique used in EnergyPlus.

## INTRODUCTION

The concept of applying the heat balance technique to buildings is certainly not a new approach in the field of building thermal simulations. This model was essentially defined in Energy Calculation 1 (ASHRAE 1976) and was implemented by Walton (1983) in the Thermal Analysis Research Program (TARP). Since this initial implementation, it has also appeared in other simulation programs such as BLAST (BSO 1995) and IBLAST as well as the HBFort program (Pedersen et al. 1997).

The application of the heat balance approach to building thermal physics requires that the First Law of Thermodynamics be enforced at each building element/air interface and on a control volume around the zone air mass. Thus, each building surface will have two separate heat balances associated with it: an outside face heat balance and an inside face heat balance. Different building surfaces are grouped together logically into thermal "zones". Therefore, a thermal zone with "n" surfaces will have a total of 2n+1 heat balances associated with it.

The outside face heat balance is obtained by drawing a control volume around a thin layer of the surface exposed to the external boundary conditions. These could include either the outdoor environment or another thermal zone depending on the location of the zone within the building. The inside face heat balance is likewise obtained by drawing the control volume around a thin layer of the surface exposed to the interior environment.

The interconnections between the various heat balance equations and the boundary conditions can be seen in Figure 1. In this diagram, it is assumed that the surface being analyzed is exposed to the outdoor environment. If the surface is exposed to another thermal zone, a heat balance similar to the inside face heat balance can be constructed.

The heat balance approach has the potential to be the most accurate method of solving for the heating and cooling loads in a building because it accounts for all energy flows in their most basic, fundamental form and does not impose any simplifications on the solution technique. This was critical to determining which load calculation method to use in EnergyPlus from the legacy programs.

In DOE-2, thermal loads are calculated by applying room weighting factors (ASHRAE 1997), calculated in a preprocessor, to hourly instantaneous heat gains from solar radiation, conduction, lights and people/equipment. However, because the weighting factor method assumes time-invariant room properties, its accuracy is limited compared to the heat balance method, which allows time-varying properties. Some of the resultant limitations of the weighting factor method are:

- It assumes a constant value for inside air film conductance, which can over- or under-estimate the rapidity with which heat stored in the thermal mass of a zone appears as a load. In contrast, the heat balance method allows this conductance to vary with time depending on surface-to-air temperature difference, direction of heat flow and supply air flow rate.
- It assumes constant thermo-physical material properties, whereas in the heat balance method these can be time varying. As a result the weighting factor method cannot model walls containing phase-change materials nor can it model walls whose conductance is temperature or moisture dependent.
- It assumes a constant distribution for solar radiation absorbed by inside surfaces. For the heat balance method, on the other hand, this can vary from time step to time step depending on sun position, sky condition and deployment of window shades.

Since the BLAST and IBLAST programs are based on a heat balance approach, the main calculation module from these programs was selected to form the foundation for the EnergyPlus load calculation. As will be seen in the next section, recent developments in DOE-2 also play a major role in the simulation of the building thermal loads.

The "merger" of BLAST and DOE-2 capabilities showcases one of the key aspects of the EnergyPlus program: programming clarity and easy extensibility. These two critical characteristics were the driving forces behind the programming standards and modular concepts defined for the EnergyPlus project and the way that the EnergyPlus heat balance based load calculation algorithm was constructed.

EnergyPlus itself is a vast departure from the programs that preceded it. In the legacy programs, data, algorithms, and program logic were spread out in the code, reducing readability and at times causing complex and unintended interactions between simulation units. The EnergyPlus team sought to avoid the past problems through the use of modules. Figure 2 shows a high level picture of the EnergyPlus load calculation module.

Each of the modules shown has a direct and/or indirect impact on either the surface heat balances or the air heat balance. The next section provides some of the details and capabilities of the components that make up the terms in the heat balance equations.

## SIMULATION METHODOLOGY

### Transient Conduction Modeling

One of the most important components in the heat balance approach is transient heat conduction. This directly affects the way the inside and outside face heat balances interact with each other and the way that other more complex building characteristics such as radiant systems, combined heat and mass balance, and ground heat transfer are integrated into the overall zone model. The EnergyPlus program uses a time series solution commonly referred to as conduction transfer functions (CTFs) to solve for transient heat conduction through building elements. The basic equation for calculating transient conduction with CTFs is shown below:

$$q_{i,t} = \sum_{m=1}^{M} X_{k,m} T_{i,t-m+1} - \sum_{m=1}^{M} Y_{k,m} T_{o,t-m+1} + \sum_{m=1}^{k} F_m q_{i,t-m}$$

where $q_{i,t}$ represents the heat flux at the interior surface of a building element at the simulation time step t; $T_{i,t-m+1}$ represents the temperature at the inside surface at time step t and a fixed number of previous time steps; $T_{o,t-m+1}$ represents the temperature at the outside surface at time step t and a fixed number of previous time steps; $q_{i,t-m}$ represents the heat flux at the interior surface of a building element at a fixed number of previous time steps. $X_{k,m}$, $Y_{k,m}$ and $F_m$ are the conduction transfer functions which are constant for a particular building element over the entire simulation.

As can be seen by this equation, the heat flux due to conduction at either side of a building element can be characterized by the current temperatures at both sides of the element as well as a limited number of temperature histories and flux histories. Thus, the response of the building element to temperature changes on either side can be described by a single, linear equation. In addition, the time step used to generate the transfer functions can be a computationally reasonable amount of time such as an hour, if necessary. In EnergyPlus, time steps of less than one hour may be used.

EnergyPlus uses a state space method for calculating CTFs. This method (Ceylan and Myers 1980; Seem 1987; Ouyang and Haghighat 1991) is derived from state variable theory and has recently received increased attention. The mathematical form of a state variable problem is given by the following equations:

$$\frac{d[x]}{dt} = [A][x] + [B][u]$$

$$[y] = [C][x] + [D][u]$$

where x is a vector of state variables, u is a vector of inputs, y is the output vector, t is time, and A, B, C, and D are coefficient matrices. This formulation is used to solve the transient heat conduction equation by enforcing a finite difference grid over the various layers in the building element being analyzed. In this case, the state variables are the nodal temperatures, the interior and exterior temperatures are the inputs, and the resulting heat fluxes at both surfaces are the outputs. Thus, the state space representation of the finite difference equations would take the following general form:

$$\frac{d\begin{bmatrix} T_1 \\ \vdots \\ T_n \end{bmatrix}}{dt} = [A]\begin{bmatrix} T_1 \\ \vdots \\ T_n \end{bmatrix} + [B]\begin{bmatrix} T_i \\ T_o \end{bmatrix}$$

$$\begin{bmatrix} q_i \\ q_o \end{bmatrix} = [C]\begin{bmatrix} T_1 \\ \vdots \\ T_1 \end{bmatrix} + [D]\begin{bmatrix} T_i \\ T_o \end{bmatrix}$$

where matrices A, B, C, and D are defined by the nodal equations. It should be noted that the finite difference grid applied to the building element does not have to be restricted to the simply one-dimensional case. Two- and three-dimensional problems can be solved using this analysis with the definition of additional nodes.

Through matrix algebra, the state variables can be eliminated from the system of equations, and the output can be related directly to the inputs and time histories of the inputs and outputs. The state space method results in an equation for heat flux as shown above with the same number of history terms for both the temperatures and the fluxes.

The state space solution for CTFs is an important part of the EnergyPlus heat balance because it allows the extension of CTFs to model other phenomena besides simple one-dimensional transient conduction. For example, radiant heating and cooling systems essentially utilize a building surface as a heating or cooling element within the thermal zone. This is accomplished by applying a heat source or sink at some location within the building element. It can be shown (Strand and Pedersen 1994, Strand 1995) that the matrix equations resulting from this additional input to the system are:

$$\frac{d\begin{bmatrix} T_1 \\ \vdots \\ T_n \end{bmatrix}}{dt} = [A]\begin{bmatrix} T_1 \\ \vdots \\ T_n \end{bmatrix} + [B]\begin{bmatrix} T_i \\ T_o \\ q_{source} \end{bmatrix}$$

$$\begin{bmatrix} q_i \\ q_o \end{bmatrix} = [C]\begin{bmatrix} T_1 \\ \vdots \\ T_1 \end{bmatrix} + [D]\begin{bmatrix} T_i \\ T_o \\ q_{source} \end{bmatrix}$$

The resulting CTF equation for transient heat conduction through the wall is very similar to the one given above. It simply has an additional series term with constant coefficients multiplied by histories of the heat source or sink.

$$q_{i,t} = \sum_{m=1}^{M} X_{k,m} T_{i,t-m+1} - \sum_{m=1}^{M} Y_{k,m} T_{o,t-m+1} + \sum_{m=1}^{k} F_m q_{i,t-m} + \sum_{m=1}^{M} W_m q_{source,t-m+1}$$

In this equation, $W_m$ are the heat source transfer functions that are analogous to the CTF, and $q_{source,t-m+1}$ is the history of heat sources/sinks. Such enhancements in the IBLAST program have already been shown effective in modeling radiant systems (Strand and Pedersen 1997) and will expand the capabilities of the EnergyPlus program.

Another feature of the IBLAST program that is planned for EnergyPlus is the modeling of combined heat and mass transfer through building surfaces. Based on the Evaporation-Condensation theory and the application of the fundamental heat and mass transfer equations to building elements, Liesen (1994) showed that such analysis was possible using a response factor formulation similar to CTFs. As implemented in the IBLAST program, the modeling technique takes into account vapor adsorption/desorption and diffusion in composite building elements. Vapor adsorption is one of the primary parameters that couples the mass and energy equations and is crucial for interactions between the mass and heat equations. The moisture transfer function (MTF) model is capable of analyzing the entire building (not just one building element) for moisture effects.

The analysis begins by transforming the governing equations for mass and heat transport:

$$\frac{\partial \rho_v}{\partial t} + \frac{(1-\varepsilon)}{\varepsilon}\rho_s \frac{\partial U}{\partial t} = \nabla \bullet (\tau_o D_A \nabla \rho_v)$$

$$\rho' c_p \frac{\partial T}{\partial t} = \nabla \bullet (k_T \nabla T) + \frac{\lambda \rho'}{(1-\varepsilon)}\frac{\partial U}{\partial t}$$

where:

- $\varepsilon$ Porosity or the void fraction of the material
- $\rho'$ Density of the solid per unit volume of the whole
- $\rho_S$ Density of solid skeleton
- $\rho_V$ Density of water vapor, vapor concentration
- U Moisture (liquid + vapor) content dry basis
- $\tau_O$ Tortuosity; factor taking into account the difficulty of the diffusion path
- $D_A$ Molecular diffusion of water vapor in air
- T Temperature of the material
- $c_p$ Specific heat of the solid skeleton
- $k_T$ effective (overall) thermal conductivity
- $\lambda$ Heat of adsorption/desorption
- t time

into a new solution space where equations for the normal coordinates are given by:

$$G_1 = \rho_v + s_1 T$$

$$G_2 = r_2 \rho_v + T$$

These transformations result in two state space systems that can be solved separately for $G_1$ and $G_2$. The equations for $G_1$ and $G_2$ are similar in form to those shown for $q_{i,t}$ above. These solutions are then transformed back into the parameters of interest: temperature and vapor density. Details of this solution procedure are provided in the literature (Liesen 1994).

Another area of concern being addressed by current development work in EnergyPlus is ground heat transfer. Two models are being reengineered for use with EnergyPlus (Bahnfleth 1989, Krarti et al. 1988). These include both a three-dimensional finite difference model and an analytical method of estimating temperature profiles. Both of these will greatly improve the predictions of heat transfer between the building being modeled and the ground over the current approximations used in legacy programs.

## Windows and Daylighting Modeling

### Window Calculation

EnergyPlus uses algorithms from WINDOW 4 (Arasteh 1989) to calculate conduction and solar gain through windows. Windows are described layer by layer as solid panes (glass, plastic film, etc.) separated by gaps containing a gas fill (air, argon, krypton, etc.). Using Fresnel equations and taking inter-reflections between panes into account, the solar absorptance of each pane vs. angle of incidence and the solar and visible transmittance of the glazing system vs. angle of incidence are calculated in a preprocessor and fit to polynomials. In the time step loop a heat balance is done on the effective inside and outside layers of the window as part of the overall heat balance calculation for the zone. The program accounts for the temperature dependence of the conductance of the gas fills, edge of glass effects, the presence of framing elements, and direct and diffuse solar shading by overhangs and other exterior obstructions. In a feature carried over from BLAST, EnergyPlus also tracks where solar radiation transmitted by the windows falls on the inside surfaces of the zone.

The program models sun control with an interior pull-down shade or switchable glazing (such as electrochromic glazing in which an applied voltage darkens the glass). Sun control is initiated when a trigger exceeds a user-defined set point. Trigger choices include solar incident on the window and zone temperature.

### Daylighting Calculation

The EnergyPlus daylighting calculation has been carried over from DOE-2 (Winkelmann 1985). The first release of EnergyPlus will be limited to simple room and fenestration geometries. Later, a radiosity method for internal reflections will be added to allow simulation of complex geometries (L-shaped rooms, roof monitors, etc.), and a bi-directional distribution function method will be added to handle light transmission through complex fenestration systems (blinds, light shelves, etc.).

The daylighting calculation has three main stages:

*Daylight factor preprocessor*: By integrating transmitted luminous flux over the area of each window, interior illuminance at two user-selected room locations is calculated for clear skies for the hourly position of the sun on fourteen representative sun paths spanning the year. This calculation is also done for a typical overcast sky. Dividing the interior illuminance by the corresponding exterior illuminance gives illuminance "daylight factors" that are stored for later use in the time step loop. Analogous factors for discomfort glare are also calculated. Accounted for are the luminance distribution of the sky for each sun position; window dimensions, slope and azimuth; window transmittance vs. angle of incidence; reflection from inside surfaces; diffusing of light by pull-down shades; and blocking of light by overhangs, neighboring buildings and other obstructions.

*Time-step illuminance and glare calculation*: The interior illuminance and glare contribution from each window are found by interpolating the stored daylight factors for the current time step's sun position and cloud cover, then multiplying by the current time step's exterior horizontal illuminance. The exterior illuminance is determined by applying luminous efficacy factors (Perez 1990) to solar radiation from the weather file. If the glare-control option has been specified, the program automatically deploys window shading to decrease glare below a pre-defined comfort level.

*Electric lighting control*: Stepped and continuously dimming lighting control systems are simulated to determine the overhead electric lighting power needed to make up the difference, if any, between the daylighting illuminance level and the design illuminance. The lighting electrical requirements are then passed to the thermal calculation.

### Advances in Air Flow Modeling

As shown in Figure 2, the air heat balance for each thermal zone will be linked to a COMIS module. COMIS (Feustel et al. 1989) is a stand-alone program that is being incorporated into the EnergyPlus program to allow for better modeling of infiltration and interzone air flows. Further details on its inclusion in the EnergyPlus program can be found in a separate paper by Huang et al. (1999).

## CONCLUSIONS

One of the main advantages of the heat balance approach is that it does not have any built-in assumptions as is typical of many of the simplified methods for building thermal load calculations. As a result, it allows interaction with a variety of complex "component" modules that model specific physical phenomena such as heat and mass transfer or daylighting without requiring a total rewrite of the load calculation procedure. In implementing and reengineering a well-established heat balance based thermal load calculation procedure, the EnergyPlus program will have the advantages such a procedure brings as well as significant improvements in code clarity and modularity, making it much easier to link existing and new models to the program. Benefits from these advances are already being seen as modules such as daylighting and WINDOW 4 are added to EnergyPlus from DOE-2 and radiant systems and combined heat and mass transfer are added from IBLAST. In addition, EnergyPlus will benefit from research being conducted at the University of Illinois at Urbana-Champaign on the ASHRAE Loads Toolkit. The synergistic effect of these two projects working in tandem will result in general improvements to both projects. Finally, the integration of the EnergyPlus heat balance with the HVAC simulation described in a separate paper (Fisher et al. 1999) will permit better simulation of a building's response to its heating and cooling system by allowing feedback between these two main simulation components.

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FIGURES

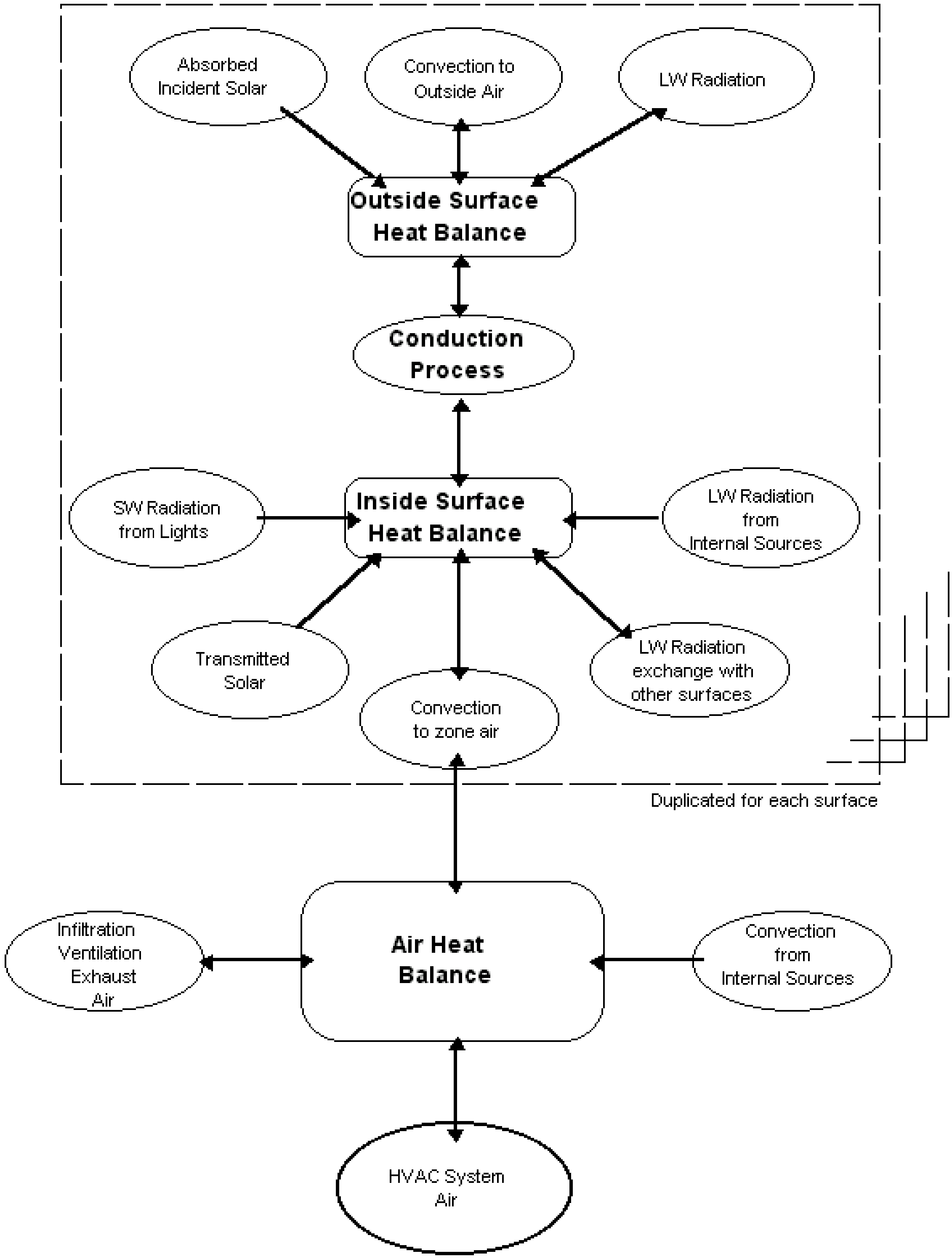


**Figure 1.** Schematic of the Energy Balance Processes in a Zone (Pedersen 1997).

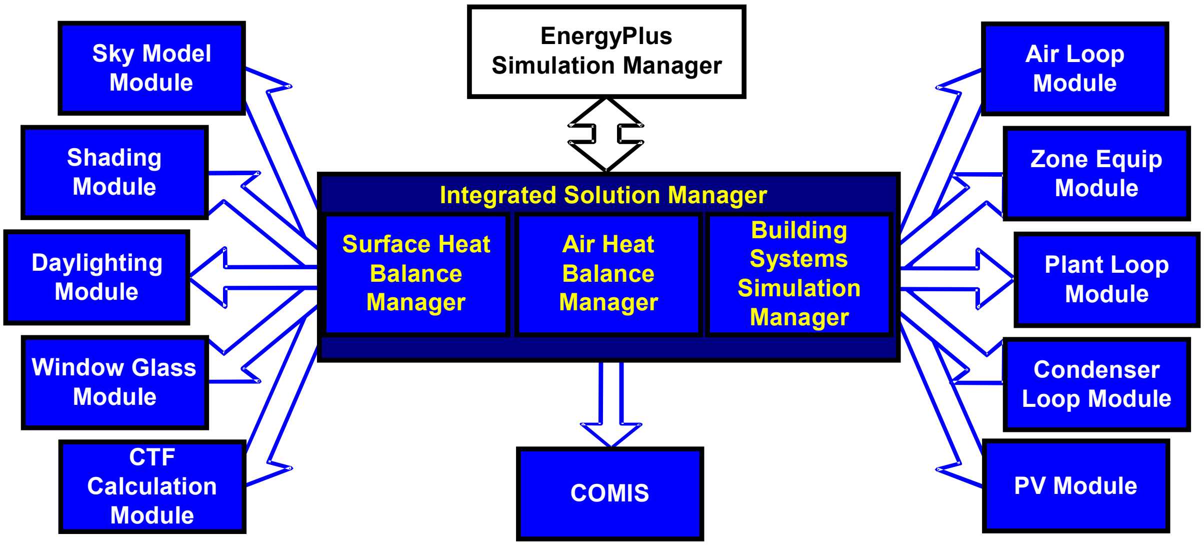


**Figure 2.** Integrated EnergyPlus Solution Manager Featuring the Heat Balance Modules.