# TECHNIQUES FOR SIMULTANEOUS SIMULATION OF BUILDINGS AND MECHANICAL SYSTEMS IN HEAT BALANCE BASED ENERGY ANALYSIS PROGRAMS

by

Michael J. Witte, Research Engineer
C. O. Pedersen, Professor
J. D. Spitler, Research Engineer
Department of Mechanical and Industrial Engineering
University of Illinois at Urbana-Champaign
1206 West Green Street
Urbana, Illinois 61801

## ABSTRACT

The current generation of building simulation software is based upon separate building and mechanical system simulations. While separate simulations are adequate for some buildings, there are many configurations which require a simultaneous simulation to completely model the interactions between the building and mechanical systems. Work is underway to develop a new version of the Building Loads Analysis and System Thermodynamics (BLAST) [1] energy analysis program which will simulate buildings and mechanical systems simultaneously. Several possible techniques for combining the simulations have been explored.

BLAST currently uses a linear univariate control profile to describe the heating and cooling provided by the fan system as a function of room temperature. Control profiles for each thermal zone are used to model the system response during the building simulation. This model of the fan system works very well for systems that provide amounts of heating or cooling that are dependent only on zone temperature.

When the output of the fan system is affected by outdoor temperature or by conditions in other zones, the present control profile model is no longer adequate. The conditions in the zones must be known in order to calculate the system output, but the system output must be known in order to calculate the conditions in the zones. So a more sophisticated representation of the mechanical systems is needed.

Three options have been considered as possible solutions:

- Generating multivariate control profiles by pre calculating the mechanical system response.
- Simulating the mechanical system in full during each iteration of the building simulation.
- Adding thermal capacitance to the zone air, using a time step much less than one hour, and calculating system and building conditions without iterating by using information from the previous time step.

Each of these approaches has some potential to improve the simulation capabilities of BLAST and other heat balance based energy analysis programs. This paper presents some results of experimenting with these techniques.

## 1. INTRODUCTION

The current state of the art in building energy analysis software consists of hourly simulation tools which are capable of simulating a building and its mechanical systems for an entire year. The current hourly programs use either a heat balance method or a weighting factor method to model the thermal response of the building. The Building Loads Analysis and System Thermodynamics (BLAST) program uses the heat balance method and is used as the basis for the discussion here, although the principles may be applied to any program based on the heat balance method. In current software, the building and the mechanical systems are simulated sequentially. First the building is simulated using some simplified representation of the fan systems, and then the fan systems are simulated to match what was determined in the building simulation. This technique works well for cases where the system response is well-defined, but it loses accuracy in situations where the system response is heavily dependent on the building load and the outside conditions or where the space temperatures are allowed to float drastically. In order to model today's energy-efficient designs, it is necessary to simulate the building and mechanical systems simultaneously. This paper discusses several approaches to combining the BLAST building and fan system simulations. These approaches have been evaluated in terms of their effect on computation time, accuracy, and simulation flexibility.

## 2. CURRENT STRUCTURE OF BLAST

BLAST is currently divided into three main simulations: building, fan systems, and central plants. The building simulation models the basic heat transfer in each zone including the building surfaces, internal loads, and a contribution from the fan system. The fan system simulation models the air handling systems which serve the zones, and the central plant simulation models the chillers, boilers, etc., which serve the fan systems. Each of the three simulations are done sequentially with information passed from building to system to plant, but no information is passed back in the other direction.

### 2.1. Overview of Separate Simulation Procedure

Figure 1 illustrates the current flow of the BLAST simulation. The user describes the building, fan systems, and central plants in three distinct blocks of input along with some preliminary input which applies to all three simulations. The building is simulated using information from the building description without any knowledge of the contents of the fan system and central plant descriptions. A simple linear model is used to represent the amount of heating or cooling provided by the fan system as a function of room temperature. This linear model is called the "control profile" and is discussed in detail in the next section. The main purpose of the building simulation is to calculate the following information for each hour: zone temperatures, zone sensible loads (the amount of sensible heating or cooling provided by the fan system), and zone latent loads (the amount of moisture being added to the zone). The fan system simulation takes this information and determines the coil outputs necessary to meet the zone loads calculated by the building simulation. The fan system simulation generates hot water, steam, chilled water, electricity, and gas demands which are then met by the central plant equipment and utilities.

### 2.2. The Building Simulation

The building simulation uses a successive substitution heat balance technique which is based on conduction transfer functions to model the transient heat transfer in the building surfaces. Fig. 2 illustrates the heart of the iterative loop in the building simulation. The solid lines indicate the default solution technique, and the dashed lines indicate optional solution paths. The basic flow of the building simulation is to perform heat balances on the outside of each surface, the inside of each surface, and the air in each zone. The default simulation path solves the outside surface balance only once each hour, and then iterates between the insides surface balance and the zone air balance until the solution converges. The more detailed options include the outside surface balance inside the iteration loop. This increases accuracy, but it also increases execution time.

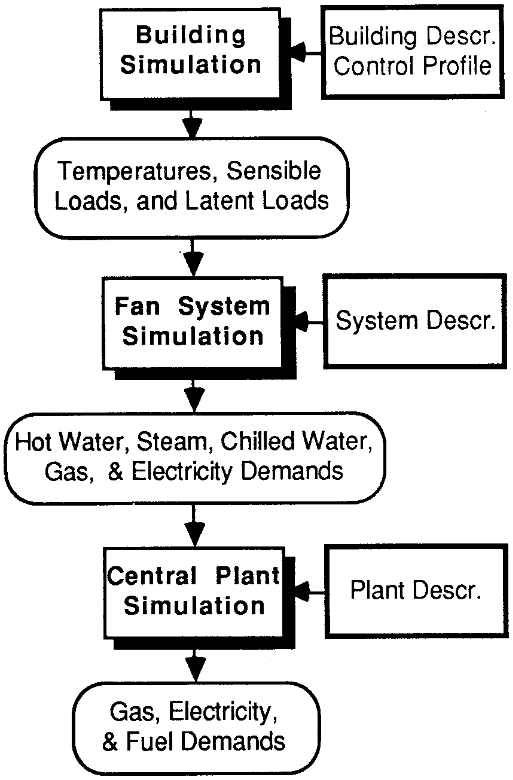

Figure 1. Basic flow of separate simulations in BLAST.

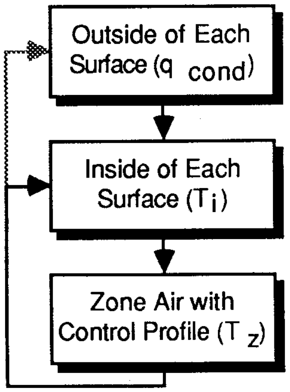

Figure 2. Iteration loop in BLAST building simulation.

### 2.3. Zone Heat Balances

The basic processes which must be described in a room or zone heat balance are:

- Radiation exchange among all the surfaces in the zone, including equipment and people.

- Convection exchange between each surface and the air in the zone.
- Conduction heat transfer to/from the back of each surface in the zone.
- Mixing of air in the space, and any air introduced into the space.
- Disposition of solar radiation which enters the space.

Several assumptions must be made to develop reasonable models yet keep the models in line with reasonable descriptions of the processes.

- Assume that there is a reasonable minimum size which can be used to define surfaces such that they are isothermal. In BLAST this is assumed to be each wall surface or subsurface (window, door, etc.)
- Assume that the radiation exchange process can be described in two wavelength bands, that is, short wavelength visible radiation and long wavelength thermal radiation.
- Assume that the radiation exchange processes are diffuse, and that the surface size in assumption 1 is small enough to provide uniform irradiation. Also assume that the air does not participate in the radiative exchange
- Assume that the convection exchange process can be described using a heat transfer coefficient and the difference between the surface temperature and some suitable air temperature.

This is accomplished in BLAST by assuming the zone air has negligible capacitance, and is well-stirred. Thus there is a uniform temperature throughout the zone. This means that the air exiting the zone is at the zone air temperature; incoming air is mixed immediately.

With these assumptions it is possible to formulate the zone heat balance mathematically as follows:

A heat balance on the air produces:

$$\sum_i h_i A_i (T_i - T_z) + q_c + \dot{C}_{infil}(T_o - T_z) + q_{system} = 0 \qquad (1)$$

where the summation is over all surfaces in the enclosure, and $q_c$ refers to the convective parts of heat input from people, equipment, and lights, and $\dot{C}$ is mass flow times specific heat.

At each surface, i, a heat balance produces:

$$A_i h_{c,i}(T_z - T_i) + \sum_i A_i F_{ij}(E_j - E_i) + q_{r,i} + q_{cond,i} + q_{solar,i} = 0 \qquad (2)$$

where $q_{r,i}$ refers to the radiative component of heat transfer from equipment, people and lights incident on surface i.

Equation 2 must be applied to each surface in the zone.

In the current version of BLAST the radiation exchange is simplified. The summation over all surfaces in the zone is replaced with radiation from a single fictitious surface which is at a mean radiant temperature, (MRT) [2]. This surface has different characteristics for each surface, i, in the zone, but most of these characteristics can be calculated once and used throughout the simulation.

## 2.4. The Control Profile

The zone air heat balance given by equation (1) has traditionally been used in BLAST by solving for $T_z$ :

$$T_z = \frac{\sum_i h_i A_i T_i + q_c + \dot{C}_{infil} T_o + q_{system}}{\sum_i h_i A_i + \dot{C}_{infil}} \qquad (3)$$

Equation (3) solves explicitly for the zone temperature which would result in a heat balance for a zone. If an air system is simulated,

$$q_{system} = \dot{C}_{sys}(T_{su} - T_z) \qquad (4)$$

Either the system flow, $\dot{C}_{sys}$ , or the supply temperature, $T_{su}$, would have to be adjusted to maintain $T_z$ at the required setpoint.

The current separated loads and systems scheme in BLAST does not make use of the air system simulation to provide the heating/cooling energy. Instead, the relationship between zone temperature and amount of heating/cooling supplied to the zone is specified by a control profile in the form:

$$q_{system} = f(T_z) \qquad (5)$$

In BLAST, the functional relationship is represented by a piecewise linear function. Appropriate logic is included to select the correct segment, so that the system energy is always specified as:

$$q_{system} = mT_z + b \qquad (6)$$

where m is the slope of the linear segment in the control profile, and b is the value of $q_{system}$ at the segment endpoint. With this, equation (3) becomes:

$$T_Z = \frac{\sum_i h_i A_i T_i + q_c + \dot{C}_{infil} T_O + b}{\sum_i h_i A_i + \dot{C}_{infil} - m} \qquad (7)$$

Note that m is always negative in control profiles, and in cases where the default capacities are used, it is a very large negative number.

The current scheme in BLAST iterates on equation 7 until the resulting zone temperature agrees with the desired zone temperature. It is interesting to note that the major change which can be made to affect the iteration is to change to a new segment of the control profile which will give a new m and b. If the surface heat balance is recalculated within the iteration for $T_Z$, then the $T_i$ can change as well (see figure 2).

## 3. IMPLICATIONS OF COMBINED SIMULATION

The simultaneous simulation of of the building and fan system offers improvements in accuracy and capabilities. However, there are also trade-offs to this new simulation structure.

### 3.1. Current Limitations

The current separated structure introduces several limitations which make the simulations less than ideal. The main limitations which can be corrected by combined simulation are:

- The absence of feedback from the systems simulation to the loads calculation prevents proper correction for system capacity which is not able to satisfy the zone load. These situations are currently reported as "unmet loads" in the output.
- If the system introduces outside ventilation air into the air circuit, it will affect the effective capacity of the system. It is cumbersome to account for this in the loads simulation.
- Variations in indoor and outdoor temperatures which affect the system are not accommodated.
- Large intermediate files containing information on zone loads and temperatures have to be accommodated.
- The specification of control actions in the loads segment is somewhat artificial and complicated if done correctly.

### 3.2. Problems Introduced

The combined simulation can eliminate the problems discussed in the previous section, but has the potential for introducing some new problems as well. They are:

- The concept of setpoints and throttling ranges has to be included in more detail, and the control system has to be simulated.
- Different convergence problems may be introduced.
- The resulting combined computer code may still be large for many of the current target machines.
- Current users will have to be retrained.

## 4. EVALUATION OF OPTIONS FOR COMBINED SIMULATION

### 4.1. Multivariate Control Profiles

In most cases, the piecewise linear control profile represented by Eq. (6) is a completely adequate model. In order for this model to be accurate, deck temperatures must remain constant with varying outdoor conditions and varying system loads.

The user specifies a control schedule for each zone in the building. The control schedule consists of a set of control profiles, and an hourly schedule that assigns a profile for each hour of the week.

An improvement to the current BLAST model is to account for the effects of outdoor temperature on the system's delivery of heating or cooling. Note that this is not the same as accounting for the effects of outdoor temperature on system energy consumption. Any system that can provide a constant deck temperature with varying outdoor temperatures can already be accurately modeled by BLAST. However, there are systems that are operated in such a manner that the outdoor temperature affects the temperature of the air supplied to the zones. Examples include three deck multizone systems, multizone systems operated with one of the coils turned off and unit ventilator systems that provide ventilation air during the cooling season.

This improvement could be implemented as a direct extension to the current method. Instead of the user providing a single control profile for any given hour, the user specifies a table of control profiles for different outdoor temperatures. Essentially, this means that Eq. (5) is replaced by a new function:

$$q_{system} = f(T_Z, T_O) \qquad (8)$$

Then for any given hour, the outdoor temperature is known from weather data, and a control profile is determined by interpolating between specified control profiles.

The bivariate control profile has been implemented into a special version of BLAST. This new model has been tested with several simple buildings.

An example of a system that can be modeled better with a bivariate control profile is the single zone unit ventilator system, which is in common use at Army installations. A typical application would be to provide heating as necessary during the winter, with a certain fraction of outdoor air introduced for ventilation purposes. During the remainder of the year, the system is used for ventilation only; brings in a 100% outdoor air; and is only operated when the zone is occupied. During this operational mode, the "deck temperature" is the outdoor temperature, and thus the amount of cooling (or heating) provided varies hourly. Some aspects of this can be simulated with BLAST currently, using the FORCED VENTILATION model. However, as the simulation works now, ventilation will not occur when the outdoor temperature is higher than the zone temperature, even though the system may be operated in that manner. Also, the user has to choose changeover dates when the system changes from a unit ventilator system to a ventilation system.

To illustrate the difference between the bivariate and univariate control profiles, a simple building with a unit ventilator system was simulated with various types of weather conditions. The results of the first simulation are shown in Fig. 3. The simulation using the univariate control profile and the BLAST ventilation model tracks the simulation using the bivariate control profile fairly well.from 6 p.m. to 11 a.m.. During these hours, the outdoor air temperature is cooler than the zone air temperature and therefore both simulations model the outdoor air entering the zone. However, between 11 a.m. and 6 p.m., the simulation results diverge. The simulation using the univariate control profile does not bring in outdoor air; therefore the zone air temperature remains lower. In the real building, however, outdoor air is brought in and the zone air temperature is higher, as shown by the bivariate control profile.

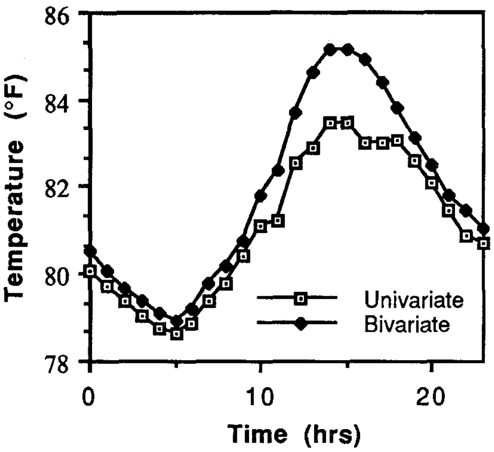

Fig. 3. Zone air temperatures for summer design day using univariate and bivariate control profiles.

### 4.2. Simulation of Full System in Building Model

Rather than use Eq. (5) to determine $q_{system}$, the system could be simulated in full to determine the heating or cooling provided to each zone. Thus the complete fan system simulation would replace the control profile. There are three different ways of formulating this option:

1. Use the system simulation to calculate $q_{system}$ for each zone in the form of Eq. (3) directly. Use successive substitution.
2. Use the system simulation to calculate the system mass flow and supply air temperature for each zone and use the form of Eq. (4). Use successive substitution.
3. Define the zone heat balance so that the sum of the fluxes should equal zero and use a Newton-Raphson technique to determine the zone temperature.

This technique has been tested, but it is not a very good solution. With the successive substitution, the system is very sensitive and can easily become unstable to the point where the system oscillates between full heating and full cooling on each iteration. By using a large amount of damping (underrelaxation), the successive substitution solution will converge, however, the number of iterations is much greater than with the separate simulations. Even the Newton-Raphson method requires a high number of iterations to reach a solution. Table 1 shows that the best option for this technique is the damped successive substitution using the system mass flow and supply air temperature (Eqs. 3 and 4).

Table 1. Number of Iterations for System in Building Simulation Options.

| Option | Iterations |
|---|---|
| Standard BLAST | 184 |
| Not Damped | ∞ |
| Damped/Heat Flux | 627 |
| Damped/Temp, Mass Flow | 448 |
| Newton-Raphson | 1695 |

### 4.3. Alternating Solutions of System and Building with Shorter Time Step

Another option is to alternate between the building simulation and the system simulation. The system is simulated based on the building conditions at the end of the previous hour. This determines the system output for the current hour. Then the building is simulated using this system output. This technique causes the system to lag the building by one time step. The system cannot respond to changes in the zone temperatures until the next time step. With a one hour time step, this can lead to a system which is unstable as shown in Fig. 4. The effect of this lag can be minimized by using a shorter time step. However, a shorter time step means longer computation times. It would also mean major restructuring to compute new conduction transfer functions and to handle hourly events in a time step which is shorter than an hour. Further work is necessary to determine the optimum range of time step, although it is anticipated that ten to fifteen minutes should give adequate resolution.

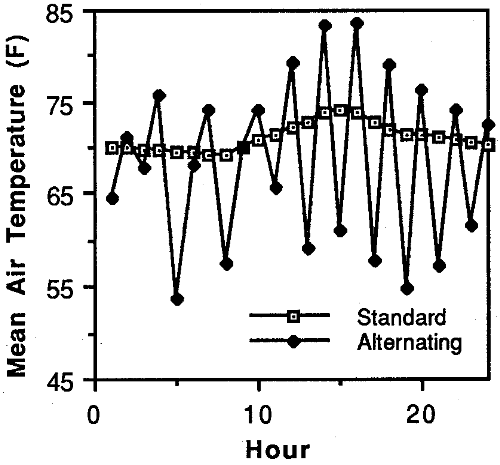

Fig. 4. Mean air temperature profiles using standard BLAST simulation and alternating system and building simulations.

### 4.4. Linked System of Equations with Air Capacitance and Short Time Step

An additional method for combining the segments of an energy analysis program is to combine the building and system models into a combined state space formulation. This formulation departs considerably from the current structure, and is not considered viable at the present time. Experience with models of this type for parts of systems has shown that the computational time required is not compatible with the goal of migrating BLAST to personal computers while retaining the detailed hourly (at least) heat balance formulation.

## 5. CONCLUSIONS

Preliminary tests of various methods of combining loads and system simulations described in this paper have shown that several schemes will work, but not all are viable.

The most satisfactory scheme is a damped successive substitution scheme which includes the actual air system simulation in the load calculation.

It appears to be possible to realize some of the potential advantages of the combination while minimizing the disadvantages.

## REFERENCES

1. BLAST 3.0 User's Manual, BLAST Support Office, University of Illinois at Urbana-Champaign, 1986.

2. Walton, G.N., "A New Algorithm for Radiant Interchange in Room Loads Calculations," ASHRAE Trans., Vol. 86, Pt. 2, 1980.