

Development of an integrated Energy Simulation Tool for Buildings and MEP Systems, the
BEST (Part 16)
Simulation Method of HVAC systems

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This paper describes simulation methodologies of HVAC systems, which are to be implemented in the “BEST” program. To achieve extensibility and ease of maintenance, modular structure is introduced. Any appliance can be modeled as a module class that implements formatted common functions. Execution procedures, especially calculation order of modules and data structures of equipment performance are presented.

Introduction

This report describes a simulation method for HVAC systems. The ideal program structure for BEST, which gives emphasis on easy extension and maintenance, is described first. Then, the concept of a fundamental element module that expresses equipment, etc., is described. The solving methods for an entire HVAC system, particularly the calculation procedures for element modules and the principles for creating data on equipment performance, are also described.

1. Program structure and functionalities BEST should have

(1) Modularity of components

BEST is designed so that each equipment model can be expressed using modules, which comply with the unified format and each entire system can be expressed by connecting these modules with each other. This concept is the same as those of other similar overseas simulation tools developed previously (e.g., TRNSYS and EnergyPlus). Accordingly, BEST can accept various system configurations (i.e., various connection patterns of the modules) and accept module additions by users, ensuring the easy maintenance of BEST. BEST is developed using Java language and implemented common interface functions with a high level of abstractness. The details of each module are concealed from the outside because each

module is expressed as a class.

(2) Calculation for segmented systems

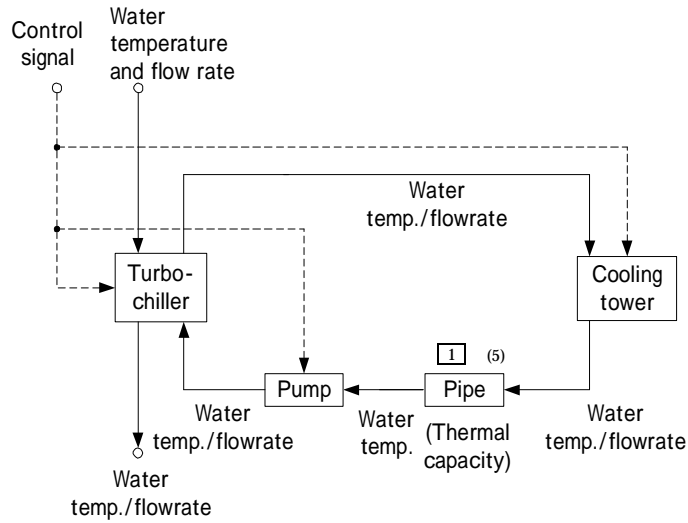
At least a space and heat source equipment is required to make up a complete HVAC system. In some cases, however, users may need to run simulations for a combination of only the heat source equipment and the condensing water circuit (hereinafter called a heat source group) (see Figure 1(a)). Considering such cases, BEST aims to accept the need to simulate not only the behavior of entire HVAC systems, but also those of the components of an HVAC system (hereinafter called a segmented system). In simulations for segmented systems, the “broken” input signals (the inlet water temperature, flow rate and control signal in Figure 1 (a)) will be replaced with other values, including fixed values, values prepared for case studies and time-series values obtained by BEMS (Building Energy Management System).

(3) Registration of segmented system as a macro class

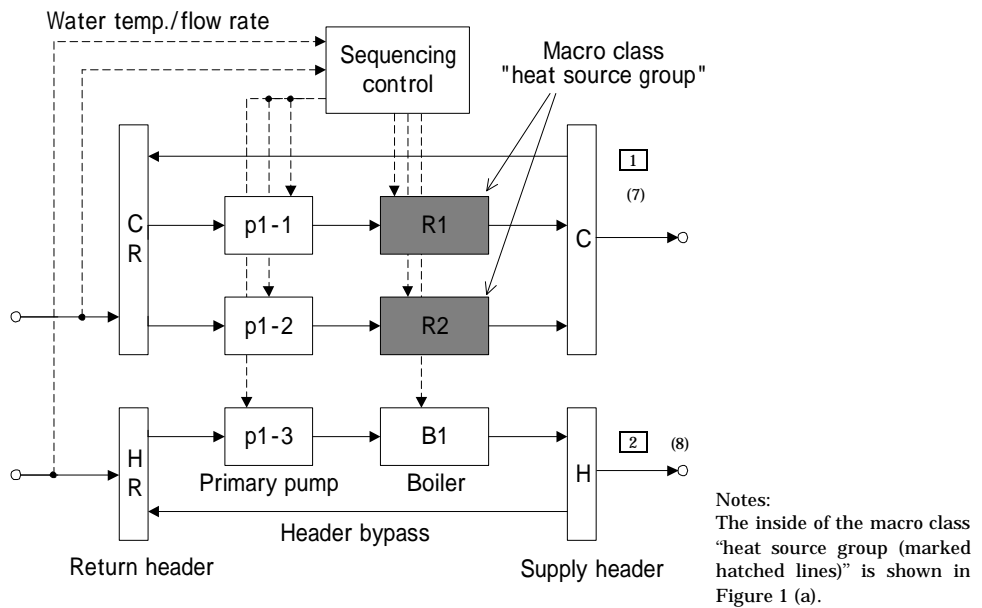
HVAC systems are often made up of several sets of the same “segmented system.” Figure 1(b) is an example of a primary plant containing 2 sets of the segmented system “heat source group.” It is ideal for simulation tools to be equipped with the functionality to register the segmented systems that are made up of the same module configuration and used at several places in one system. The registered segmented systems are dealt with as macro classes and used just like the equipment element modules (hereinafter called the atomic classes). It is planned to implement common interface functions into these 2 classes.

(4) Correspondence to calculations for dynamic systems

In many conventional simulation tools, only a space and the thermal storage tank of the system were considered to be the dynamic components of the system. This is insufficient, however, if the effects of the controllability quality on the indoor environment or energy consumption must be examined. In this case, the dynamic performance of other equipment must be incorporated into the simulation model along with the space and the thermal storage tank. In BEST, one common function (hereinafter called the methods), “derivative,” is planned to be implemented into the atomic and macro classes in order to make a numerical integration calculation to describe the dynamic performance (see Table-1).



(a) Example of segmented system "heat source group" (turbo-chiller)



(b) Example of macro class "primary plant" (under cooling operation)

Figure 1: Segmented system and macro classes (for explanatory notes, see Figure 3)

(5) Correspondence to discontinuous nonlinear element module model

One possibility is to restrict the expression of each module model to a linear equation or differential algebraic equation to solve the entire system effectively. However, most general equipment shows nonlinear behavior. For example, after changing to a certain state, most equipment discreetly transits to

another mode. Accordingly, BEST is designed to accept the differentiation of conditions in the equipment models (by using “if” statements) and associated discontinuous modeling (e.g., mode exchange) and the differentiation of the input and output based on the physical process.

2. Fundamental element module

Figure 2 shows a proposed fundamental element module (in the atomic and macro classes). Table-1 is a list of the proposed methods to be implemented. The principle of each module is to calculate the output condition (y) by using the input condition (u), which varies from hour to hour, along physical currents such as water or air. The parameter (p) is the characteristic value of the equipment, therefore constant during the calculation. The parameter is set to a variable of the module by the “initialize” method before the hour loop starts. The state (x) is required only by the dynamic modules, such as a room module that cannot ignore the building thermal capacity and a coil module for which dynamic performance is also expressed. It is planned that the information will be stored as private variables in each object. This concept is different from those of TRNSYS and Simulink⁽¹⁾ where the characteristic variables are prepared as state variables. The derivative value of the state variable is passed to the integration solver by the “derivative” method and the state variable is renewed before the next step.

Once the heat carrier class, which flows in and out of other modules, is received by the “input” method, the heat carrier state changed by other modules is always reflected in the heat carrier objects in this module (because call by reference is used). Similarly, the heat carrier state renewed by the “update” method is also reflected in other modules that call the heat carrier class.

The control algorithm can be also expressed by element modules. In this case, the input (u) and the output (y) are control signals, including the start/stop signals, measurement values and control outputs. This information, excluding the heat carrier state, is exchanged between its own class and the upper-level classes (e.g., macro classes) as arguments of the “input” and “update” methods or as the return value of the “output” method.

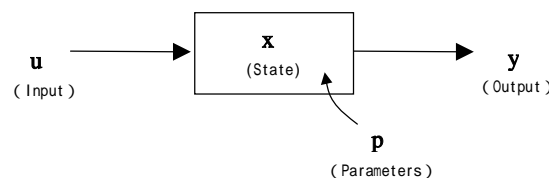


Figure 2: Fundamental element module

Table 1: List of proposed interface functions (or methods) to be implemented in element modules

Method	Definition
initialize	For setting a fixed value (e.g., rated value of equipment) For making a necessary initialization (e.g., creation of variables to maintain result)
input	For receiving an operational schedule For receiving a heat carrier class that flows in and out
output	For receiving a class that controls its own class For returning a simulation result (e.g., power consumption)
update	For receiving the indication, etc., necessary for condition differentiation For updating a heat carrier class of the output side to return it
derivative	For returning a derivative value of a state variable to be applied to a numerical integration
setParameter	For updating an internal state from outside
getState	For returning a current internal state
start	For writing a process necessary for start
terminate	For writing a process necessary for end

3. Processing procedure for segmented systems and entire systems

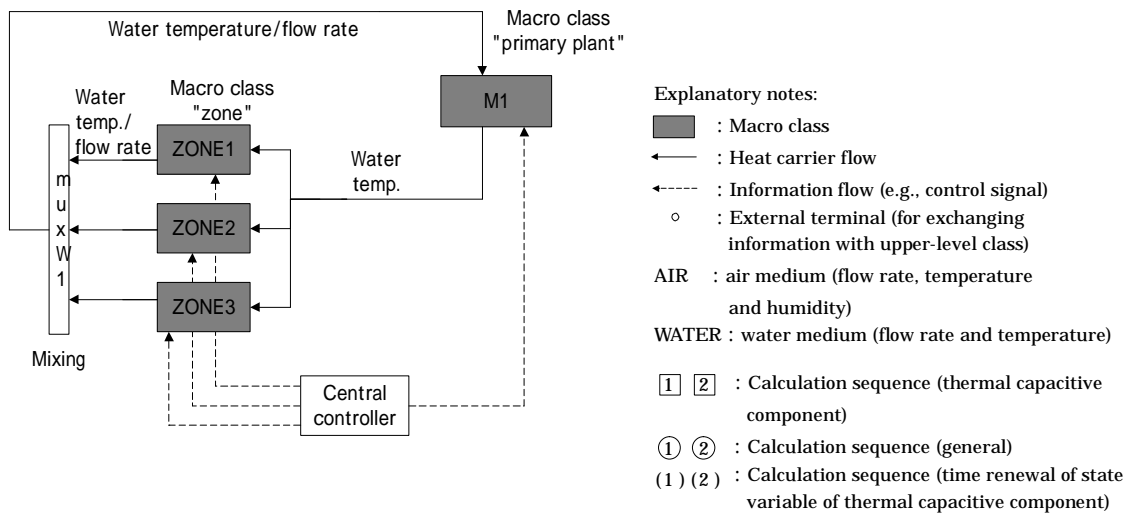
3.1 Outline of solving method

Existing simulation tools used for HVAC system studies can be divided into 2 categories: (i) generic simulators (e.g., Simulink¹⁾) and (ii) simulation programs specializing in HVAC systems. From the viewpoint of the calculation efficiency, the latter is superior. BEST, however, aims to become the former as much as possible. Accordingly, the characteristics of each HVAC system can be expressed only by the algorithms of the element modules and by the connection relationship among the modules. Users can add equipment without understanding the algorithm of the solver to solve the entire HVAC system.

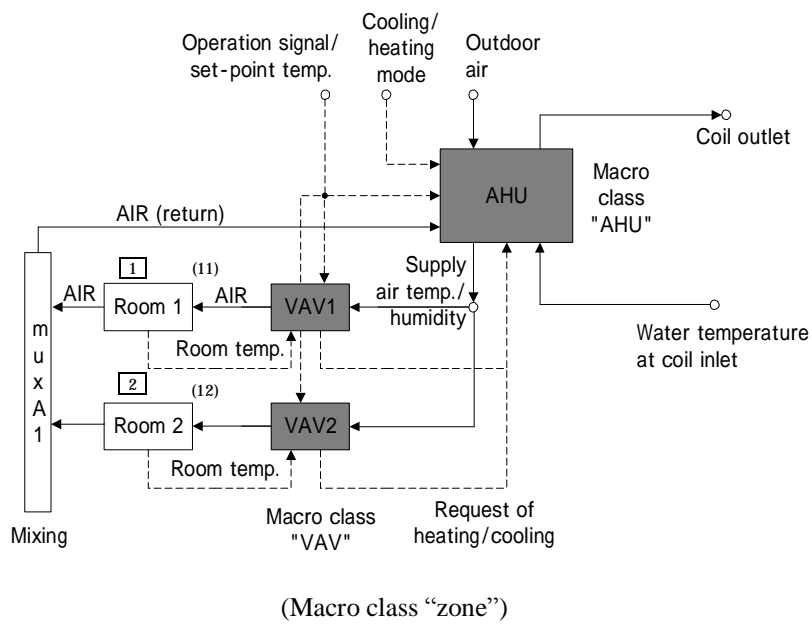
There are 2 solving methods for module-based simulation programs. One is the method to solve nonlinear equations expressing an entire HVAC system based on Newton's method, etc. The other is the method to simply calculate modules successively. BEST applies the latter method and short calculation time intervals to calculate the dynamic variations with time (hereinafter called the forward method). Accordingly, BEST does not aim to solve the equations based on convergent calculations.

3.2 Calculation sequence and processing procedures ¹⁾

If the forward method is applied to solve an entire system, the key is the calculation sequence. Sometimes, there is input from modules that can affect output, either of that module itself or other simultaneous modules (this input is referred to as a direct-feedthrough port ¹⁾; hereinafter referred to as d.p.f). If a d.p.f exists, other modules connected to the d.p.f must be calculated first. An example of an entire system configuration is given in Figure 3. First, the output that is not affected by the d.p.f must be calculated in each macro class (indicated by the numbers in the square in Figure 3). Then, every module is successively calculated along the flow of the signal in order of the numbers in the circle. In this case, these “calculations” correspond to the procedures defined in the methods such as “update” and “getState” (see the Table-1). Finally, the state value at the next time step is calculated by a numerical integration using the “derivative” method (indicated by numbers in parentheses).



(Entire system)



(Macro class "zone")

Figure 3: Example of system hierarchy structure and calculation sequence (Part 1)
 (For inside of the macro class "primary plant", see Figure 1(b))

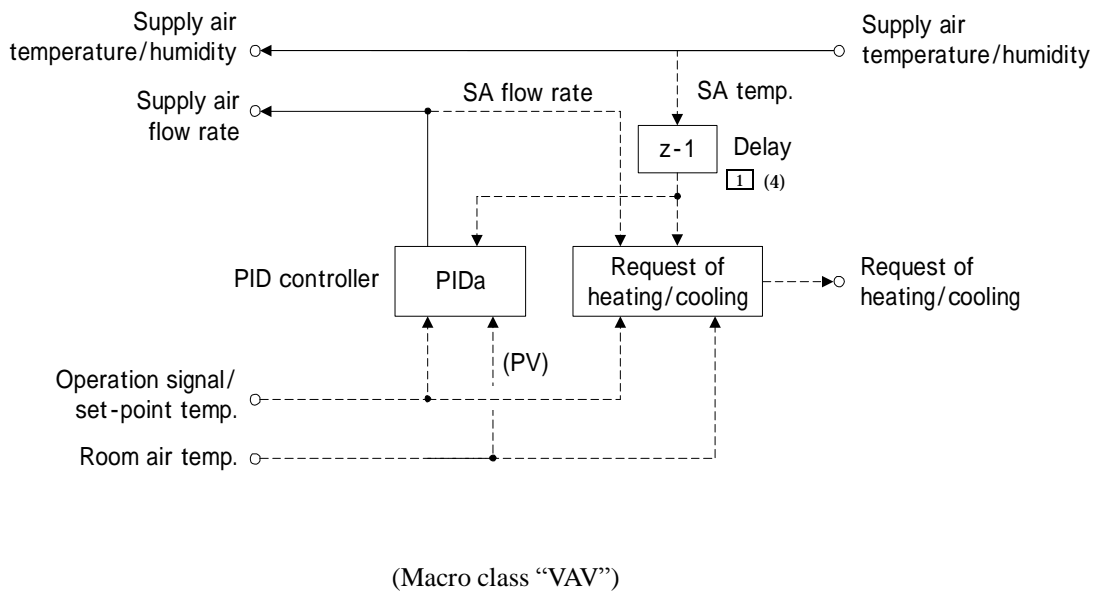
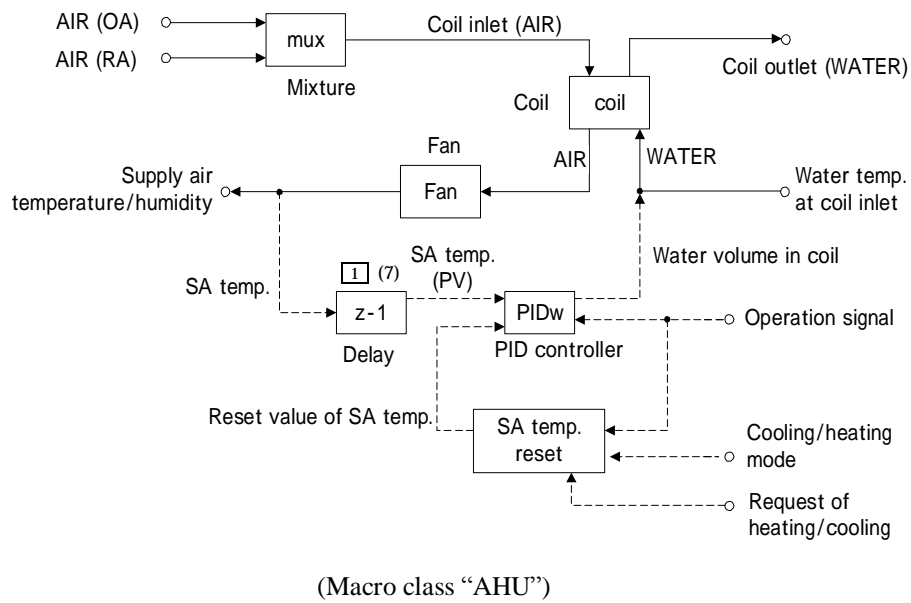


Figure 3: Example of system hierarchy structure and calculation sequence (Part 2)

In the forward method, the appropriate solution cannot be obtained if only modules with d.p.f are connected in a loop. BEST has several restrictions in place in order to avoid the occurrence of algebraic loops, and these restrictions are applied to ducts or pipes even when they are looped physically. For example, (i) if the ducts make a loop, the space thermal capacity must be provided; (ii) if the pipes make a loop, a thermal capacitive component must be provided to pack the thermal capacities of pipes and headers; and (iii) the flow rate cannot make a loop. In Figure 3, the restriction (iii) breaks the loop so that the water flow from the heat source equipment cannot be delivered to the coil and the air supply from the air-handling unit (AHU) cannot be delivered to the VAV unit under the assumption that the flow rate calculations start from the output of the PID controller.

4. Equipment performance in BEST

4.1 Concept

In BEST, equipment performance data is basically created from data on the steady-state performance of the equipment. Performance data on major equipment has been independently obtained by using questionnaires as part of the BEST development project to create a model for data creation and collection. Data on the dynamic performance of equipment is often unavailable from manufacturers. To handle such cases, it is planned to establish alternative approaches, such as replacement of unavailable data with both dead time and a thermal capacity.

BEST is an object-oriented program. Accordingly, the equipment performance to be stored in the object can be expressed freely. If data is stored in an object based on the relationship between input and the variables affecting the output, the object can be used by BEST.

4.2 Steady-state performance

In order to calculate the energy consumption and capacity, etc., of equipment using the load ratio, inlet temperature and water flow rate (airflow rate), etc., as arguments, approximation formulas are established. Considering future maintenance after BEST is completely developed, these approximation formulas can be commonly used in each equipment model. Additionally, it is planned to avoid using the individual approximation formula provided by each manufacturer or provided for each equipment capacity as much as possible. For example, the approximation formula for the heat transfer coefficient (Kf) of a coil in an HVAC system, which can be predicted physically, can be written as follows;

$$K_f(U_f, V_w) = 1 / (a * \exp(b * U_f) + c * \exp(d * V_w))$$

where

Kf: heat transfer coefficient;

Uf: airflow velocity;

Vw: water velocity inside the coil; and

a, b, c and d: coefficients.

Steady-state performance of equipment with complex physical expressions (e.g., chilling unit) is expressed by multiplying by the influence functions that are approximated by polynomial equations. For example, the power consumption (Pe) of a turbo freezer can be approximated by the following formula;

$$P_e(X_u, G_{cd}, T_{cdi}, G_c, T_{ci}) = P_{e0} * C_{Xu}(X_u) * C_{Gcd}(G_{cd}) * C_{Tcdi}(T_{cdi}) * C_{Gc}(G_c) * C_{Tci}(T_{ci})$$

where

Pe: power consumption;

Pe0: rated power consumption;

Xu: load factor;

Gcd: cooling water flow rate ratio;

Tcdi: temperature at cooling water inlet;

Gc: chilled water flow rate ratio;

Tci: temperature at chilled water inlet;

CXu: influence function of load factor;

CGcd: influence function of cooling water flow rate ratio;

CTcdi: influence function of temperature at cooling water inlet;

CGc: influence function of chilled water flow rate ratio; and

CTci: influence function of temperature at chilled water inlet.

Each of the influence functions C*** can be approximated by using 1st-order or 2nd-order polynomial equations.

If equipment is beyond the adaptive range of the approximation formula, users can select any of the following 4 alternative methods in each equipment data file. That is, (i) extrapolation based on the

approximation formula; (ii) replacement with the upper or the lower limit value; (iii) dealing with it as operation impossible; or (iv) use of a line that connects the origin and the lower limit value. In addition, users may arbitrarily change the upper and the lower limit values.

4.3 Dynamic performance

Just like HVACSIM²⁾, the dynamic performance of equipment should be generally examined based on the physical models that take the operation sequence and each element equipment control into account. Considering the need to cover nearly every equipment model sold in Japan, these physical models will become significantly complex. In addition, it may be impractical to update these models individually whenever a new model is released.

In BEST, the steady-state performance of equipment is expressed by using approximation formulas as described in Section 4.2. Accordingly, the delay dynamics during start, stop and reboot operations are sufficient for the dynamic performance of the equipment, without considering dynamic performance during operation. If the dynamic performance during start, stop and reboot operations are provided in each equipment model, it is possible to express dynamic performance using common functions. It is planned to use a function that uses an independent variable for the time elapsed from start, stop and reboot.

Equipment for which dynamic performance must be considered is that with a large thermal load (e.g., freezers, boilers and cooling towers). As for other equipment, only the steady-state performance may be sufficient because the calculation time intervals are on a minute basis.

There is also no problem in ignoring the time delay under these minute intervals even though the dynamic performance shows complex behavior, affecting the energy consumption in the boot sequence.

4.4 Database

The rated values of various models of equipment are planned to be listed in a data table in the database. These data tables are intended to be displayed on the input screen for selecting equipment models and rated values. If the equipment model is not specifically decided at the design phase, the user can select the rated value of the corresponding equipment from the Design Standards³⁾ by the Ministry of Land, Infrastructure and Transport of Japan. Equipment that must be listed by its rated value in the data table includes freezers (turbo-chiller), water/air cooled chillers, air-source heat pumps, direct-fired absorption water heater chillers and steam-driven and hot-water-driven absorption chillers. As for other equipment, an approximation formula is established based on theoretical formulas to determine the performance beyond the rated value and equipment model.

5. Conclusion

This report describes the basic program construction and solving methods in BEST, regarding the simulation method for HVAC systems. It is necessary to continuously study the reasonableness of the forward method, which does not require convergent calculations. In addition, the module calculation-sequence and automatic calculation-time-interval setting method will also be studied further.

Acknowledgement

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