Building Energy Performance Using Sheap

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ABSTRACT

This paper describes a *Simplified Hourly Energy Analysis Package* (*SHEAP*) for the computation of annual energy consumption in non-residential buildings. The package, developed at the Mechanical Engineering Faculty, uses the *transmission matrix method* in calculating conduction heat gains through opaque building sections, and adopts the *weighting factor method* for the calculations of cooling loads, heat extraction rates and actual space air dry bulb temperatures. *Typical daily profiles* of measured hourly weather data are used to approximate the external climatic conditions over a one-year period. A preliminary validation study indicates that SHEAP produces, reasonably good estimates when compared to the predictions by BUNYIP, a commercial building energy analysis package.

INTRODUCTION

A great number of building energy analysis programs perform hour-by-hour calculations for a one-year period, using actual hourly weather data for a particular location. The calculations are normally divided into three major stages [3]: (1) *space load prediction*, (2) *air distribution system simulation*, and (3) *central plant simulation*.

Transient thermodynamic analysis is essential when calculating space thermal loads, because heat transfer through the often massive building elements are rarely in steady state. However, steady state assumptions can be used to simulate air distribution systems on an hourly basis, since energy storage capacity of the circulating air stream is very small in comparison to the energy being transferred to it by the mechanical system, and also due to the fast response of system controls (usually in minutes or seconds). Similar reasoning then allows for the steady state simulation of the central plant components.

The solution of the unsteady state heat conduction equation is central to the heat transfer problem in space load prediction, where practically all programs assume a one-dimensional heat transfer described by:

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T}{\partial \tau} \qquad \text{Eqn. 1}$$

where T is temperature, x is the space dimension normal to the conducting surface, τ is time, and α is the thermal diffusivity. Provided that this partial differential equation can be solved, then conductive, convective and radiative energy balance equations can be written at the interior and exterior surfaces. The *heat balance* equations must aslo include energy inputs from people, lights and equipment, and the space heating and cooling system. The internal surface temperatures are then computed, together with the space dry bulb temperature by solving simaltaneously the heat balance equations for the space, on an hourly basis. There are not many programs that use this "exact" method of load calculations because the procedure requires high speed digital computers with large memories being available. However, the *heat balance method* has been adopted by ASHRAE [10], and Mitalas and Stephenson [12].

A commonly accepted simplification to the "exact" method is to use the weighting factor (WF) method in determining the space thermal loads and air temperatures. The methodology is described in references [3] and [2]. In SHEAP, the WF method has been used as a basis for space load calculations. On the other hand, the transmission matrix method as described by Buffington [4] was used to calculate the conduction heat gains through multilayered, opaque building sections (e.g. walls, roofs, partitions, etc.).

The following sections will briefly describe the approaches to solving the *unsteady state* one-dimensional heat conduction equation (equation 1), the transmission matrix and WF methods, and their implementation in SHEAP. Results of a comparison study are then presented and discussed.

CONDUCTION HEAT GAINS THROUGH WALLS AND ROOFS

The methods for calculating the unsteady state conduction heat gains through walls and roofs can normally be classified into three categories [6] : (1) *response factor methods*, (2) *harmonic methods*, and (3) *numerical methods* .

At present, for conduction heat gains calculations, the response factor method is a mainstay. The method is desirable because it does not require the heat conduction boundary conditions to be periodic or linear. However, the determination of the response factors can be algorithmically and computationally complex (see [16], [13] and [11]).

The harmonic methods can be used to solve the heat conduction equation when the boundary conditions are represented as periodic functions. However, they require the building heat transfer parameters such as convection coefficients to be constant with time, and that the radiant heat transfer be linearized.

On the other hand, with the advent of digital computers, the heat conduction equation can be solved by *finite difference techniques*, where the space and time derivatives are represented by finite differences. Numerical techniques can be conceptually simple, and able to handle either linear or nonlinear boundary conditions. However, accuracy, cost, and model stability are dependent on the number of nodes, the time step used, and the solution method chosen.

Buffington [4] has shown that the transmission matrix method, which belongs to the harmonic method, is capable of producing almost identical results with those obtained using the Z-transfer functions (belongs to the response factor method), when the boundary conditions are *periodic* . Consequently, the transmission matrix method has been adopted by SHEAP, because it is simpler than the response factor methods, and also because it is more accurate than the numerical methods, when the boundary conditions are periodic.

TRANSMISSION MATRIX METHOD

A model for computer simulation of heat flow by conduction through walls and roofs based on the *transmission matrix method* has been described by Buffington [4]. The method relates the periodic temperature and heat flow on one side of a homogeneous layer to the *periodic* temperature and heat flux on the other side by means of a *transmission matrix as* in the following [4]:

$$\begin{bmatrix} t_o \\ q_o \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} t_i \\ q_i \end{bmatrix} \qquad \text{Eqn. 2}$$

where,

t_i = inside surface temperature of the layer, F
t_o = outside surface temperature of the layer, F
q_i = inside surface heat flux, Btu/h/square-foot
q_o = outside surface heat flux, Btu/h/square-foot

The complex matrix elements, A, B, C dan D are calculated based on the thermal properties of the layer as follows:

$A = \cosh(FL + FLj)$
$B = \sinh(FL + FLj) / (kF + kFj)$
$C = (kF + kFj) \sinh(FL + FLj)$
$D = A$

where,

F $= (\omega/2\alpha)^{0.5}$
ω = harmonic frequency, radians/h
α = thermal diffusivity, ft^2/h
L = slab thickness, ft
k = thermal conductivity, Btu/h/ft/F
j = complex operator

To use equation (2), the temperatures should be expressed in the form of a Fourier series. As a result, the resultant heat fluxes will also be in the form of a Fourier series expressions.

The overall transmission matrix for a multi-layer building section can be obtained by chain multiplying the individual matrices in the other the materials appear in the composite layer from the outside to the inside of the space.

The transmission matrix elements for a resistance air film are given by :

$$A = D = 1, \; C = 0 \text{ and } B = 1/h$$

where h is the surface heat transfer coefficient in $Btu/h/ft^2/F$.

In the calculations, the periodic outside and inside air temperatures are expressed in the *complex* form of a *Fourier series* expression, the details of which are described by Buffington [4].

Assuming that the transmission matrix shown in equation 2 to be the *overall transmisson matrix* for a composite building section, and that the outside and inside air temperatures are known, q_i, the *transient* heat flux on the inside of the building is given simply as follows, for a single harmonic k :

$$q_{i,k} = t_o/B - (A/B)t_i \quad Btu/h/ft^2 \qquad \text{Eqn. 3}$$

In the simulation, the *transient* inside and outside air temperatures are expressed in the complex form of a Fourier series expression with 6 harmonics.

The total inside heat flux at a given time is calculated by summing the steady state portion of the heat flux and the transient portion of the heat flux calculated from equation (3). In other words, the *superposition principle* is used, that is q_i is calculated for each harmonic and the sum of the individual q_i gives the resulting inside heat flux. Thus,

$$q_i' = \frac{\Delta t}{R} + \sum_{k=1}^{n} q_{i,k} \quad \text{Btu/h/square} - \text{foot} \qquad \text{Eqn. 4}$$

where,

q_i' = total instantaneous heat flux at inside surface per unit area of the surface
Δt = average temperature differential across the composite layer, F
R = thermal resistance of the composite layer, $(h.ft^2F/Btu)$
n = number of harmonics of Fouries series expression

The required heat flux at the inside surface is then obtained by extracting the real part of the complex form of equation (4).

THE WEIGHTING FACTOR METHOD

The WF method of calculating *instantaneous space sensible load* (*cooling load*), *heat extraction rate, and space air temperature* has been introduced by Mitalas and Stephenson [12,15]. The instantaneous space sensible load or cooling load is defined as the rate at which sensible heat must be extracted from the space to maintain the air temperature at a constant value. On the other hand, heat extraction rate refers to the rate at which heat is actually removed from the space.

There are two general assumptions in the WF method [3]. First, the processes modelled are linear. This assumption is necessary because the *superposition principle* is employed, whereby heat gains from various sources are calculated independently and summed to obtain the overall result. Thus, nonlinear processes, such as radiation or natural convection, must be approximated linearly. However, it is not a significant limitation because these processes can be linearly approximated for most calculations. The second assumption is that system properties influencing the weighting factors are constant, that is, they are not time dependent. It is necessary to use this assumption because only one set of weighting factors is used during the entire simulation period. This assumption can limit the use of weighting factors in instances where important space properties vary during the calculation. Two examples, are the distribution of solar radiation incident on the interior walls of a space, and the inside surface heat transfer coefficient that can vary hourly. A detailed account on the assumptions in the WF method and their implications on load calculations have been presented by Kerrisk et al. [8].

The WF method involves a two-step process to determine the air temperature and heat extraction rate of a building space for a given set of conditions [3]. Firstly, the space's air temperature is assumed to be fixed at some reference value; normally chosen as the average air temperature expected for the space over the simulation period. Instantaneous heat gains are then computed based on the reference temperature. The types of heat gains considered include: solar energy entering through windows; energy from lighting, people and equipment; conduction through opaque envelope elements, and infiltration gains. However, conduction and infiltration heat gains are directly dependent on the reference temperature and corrections must be made when the air temperature deviates from the reference value. In order to account for this deviation, Cumali [5] has presented an analytical technique for incorporation into detailed hourly programs. such as DOE-2 that uses the *response factor* method of determining conduction gains. However, a different approach will be utilised in SHEAP, where the use of transmission matrix method readily allows for the calculation of transient heat gain when both the outside, *sol-air* and inside air temperatures vary periodically. In SHEAP, solar heat gain calculations follow the ASHRAE procedure described in reference [2], whereas heat gains from lighting, people, equipment and infiltration air are computed using the input schedules and intensity levels.

A space sensible cooling load is then computed for each type of instantaneous heat gain. In general, the cooling load differs from the instantaneous heat gain because some of the energy (the radiative portion) from the heat gain can be absorbed by walls or furniture and stored for later release to the air. An accepted way of relating a heat gain component to a corresponding cooling load component is to use a *transfer function*, which depends on the nature of heat and the heat storage characteristics of the space [2].

The cooling load at time τ can be related to the current value of heat gain and the preceding values of cooling load and heat gain by [2]:

$$Q_\tau = ((v_0 q_\tau + v_1 q_{\tau-\Delta} + ..) - w_1 Q_{\tau-\Delta} - w_2 Q_{\tau-2\Delta}..) \qquad \text{Eqn. 5}$$

where,

Δ = time interval (taken as an hour)
q_τ = heat gain at time τ, Btu/h
Q_τ = cooling load at time τ, Btu/h

The terms v_0, v_1..., w_1, w_2..., are coefficients of the z-transfer function [4]:

$$K(z) = \frac{v_0 + v_1 z^{-1} + v_2 z^{-2} + ...}{1 + w_1 z^{-1} + w_2 z^{-2} + ...} \qquad \text{Eqn. 6}$$

which relates the corresponding parts of the cooling load and heat gain. The procedure to obtain the coefficients has been described by Kerrisk et al. [8].

However, precalculated set of transfer function coefficients (also called coefficients of room transfer functions), which are tabulated in reference [2] have been used in SHEAP.

In the second step, the heat extraction rate, ER, and space air temperature t_r are calculated using the *room air transfer function* [2] :

$$\sum_{i=0}^{1} p_i(ER_{\tau-i\Delta} - Q'_{\tau-i\Delta}) = \sum_{i=0}^{2} g_i(trc - t_{r,\tau-i\Delta}) \qquad \text{Eqn. 7}$$

where g and p are the coefficients of the room air transfer function, Q_{τ}' is the total cooling load for the space at time τ. In SHEAP, trc, the daily average zone air dry bulb temperature is calculated for each space depending on the 24 hourly temperature profiles calculated at the last step of iteration – see "iteration loop" in Figure 2, Appendix B.

The pre-calculated values of p_0, p_1, g_0, g_1 and g_2 can be obtained from reference [2]. Equation 7 can be solved simaltaneously with the equation describing the characteristics of a simple proportional thermostat to give ER_{τ} and $t_{r,\tau}$ (see reference [2] for details).

However, when a space thermostat is not present (for Constant Air Volume system without reheat), equation 7 must be solved simaltaneously with the following equation :

$$ER_{\tau} = 1.1 \text{ cfmzd } (t_{r,\tau} - TSA) \quad \text{Btu/h} \qquad \text{Eqn. 8}$$

where "cfmzd" is the design supply air flow rate (cubic feet per minute) to the space, and TSA is the temperature of the conditioned air entering the space (deg. F).

When the cooling unit is not operating, ER is set to zero. For a VAV cooling only system, the following equation must be solved with equation 7 to obtain ER_{τ} and $t_{r,\tau}$ when the space air temperature moves outside of the lower limit (dependent on the imposed minimum supply air flow rate) of the thermostat throttling range, during the period the cooling unit is operating:

$$ER_{\tau} = 1.1 \text{ cfmmin } (t_{r,\tau} - TSA) \quad \text{Btu/h} \qquad \text{Eqn. 9}$$

where cfmmin is the minimum allowable supply air flow rate to the space. Equations 7 and 8 can be used to calculate ER_{τ} and tr,τ when the space temperature exceeds the upper limit of the thermostat throttling range, for either a VAV or DD/MZ system.

OVERALL SIMULATION METHODOLOGY

Figure 2, Appendix B, shows the simplified flow chart for building energy calculations in SHEAP. The inputs required include building data, 24 hourly schedules for lighting, occupancy, infiltration air and equipment usage, and their respective intensity levels; weather data; system and plant data.

It is intended that SHEAP uses *twelve typical days*; one day per month (some programs call it characteristic days) of weather data to represent a one year period. The 24 hourly weather data for each typical day consists of *direct* and *diffuse* radiation on a horizontal plane, outside air dry bulb temperature, and mean coincident humidity ratio.

In the calculations, it is assumed that a typical day is periodic in nature (i.e. it repeats for several days with a 24 hour period). This assumption is necessary because typical daily profiles of weather data are being used, in order to reduce computer execution times. In addition, the use of transmission matrix method also requires the *sol-air* and space air temperatures to be periodic. Thus, the calculated heat gains, cooling loads, heat extraction rates and space air temperatures will also be periodic.

Figure 2, shows an "interation loop" where the calculations for a space are repeated several times such that the calculated heat extraction rates and space air temperatures reach steady periodic states.

When heat extraction rates and space air temperatures have been determined for all spaces, system simulation is performed to determine the load at the cooling and dehumidifying coil. Latent load calculations are performed at the system level within SHEAP (see also [12]). A simplified procedure of determining coil performance as described by Knebel [9] has been utilised in SHEAP. Steady state simulation of air distribution systems parallel those described by Knebel [9], and a detail discussion will not be presented in this paper.

Finally, plant simulation is performed to determine the electrical energy consumption of plant components. The components than can be simulated include water-cooled chillers and direct expansion, air-cooled condensing units. Empirical part-load performance curves have been used to decribe the part-load operating conditions of the components. In addition, the energy consumption of chiller and condenser pumps, and cooling tower fan are also computed. Details on steady state plant simulation can be obtained from references [3], [9], [1] and [7].

The calculations are then repeated for the remaining typical days. A report on seasonal and annual energy consumption, and coil loads are then produced together with some simple graphs.

RESULTS OF A COMPARISON STUDY

In order to have a general idea on the accuracy of SHEAP, energy calculations for an office building model have been made, and the results are compared with the predictions from BUNYIP [14], which is a commercial building energy analysis package. BUNYIP uses finite difference tecnhiques to solve the heat conduction equation. It uses *characteristic days* of weather data [14], where on average there are four to six typical days representing a seasonal (bimonthly) weather data. However, SHEAP has used only one *typical day* per season, where the BUNYIP characteristic days for each season have been *compressed* into a typical day; one for each season.

A summary of input data is given in Appendix A, where the building has been divided into four perimeter zones (space and zone are synonomous) and one interior zone.

In all cases, the annual electrical energy usage by lights, equipment and supply air fan (for CAV and DD/MZ system only) estimated by SHEAP are within +/– 0.6% of BUNYIP's results.

Figure 3 shows the seasonal estimates of cooling coil loads by SHEAP and BUNYIP for a Constant Air Volume (CAV) system, where the agreement is extremely good. The maximum deviation occurs in the Jan/Feb season, with a percentage difference of –1.2% (BUNYIP is used as the reference). The annual difference is only –0.5%. Moreover, comparison in seasonal cooling energy (sum of compressor, cooling tower fan, and chiller and condenser pumps electrical energy usage) also indicate excellent agreement as shown in Figure 4, where a maximum deviation of –0.9% occurs in the Jan/Feb season. The annual difference is lower at –0.2%.

When comparison in seasonal coil load of a Dual Duct/Multizone (DD/MZ) system is made, the agreement between SHEAP and BUNYIP is still very good as shown in Figure 5. A maximum seasonal deviation of 3.5% occurs in the Jul/Aug season and the annual difference is only 2.1%. SHEAP also estimated the seasonal cooling energy close to BUNYIP predictions as shown in Figure 6, where a maximum deviation of 4.5% occurs in the Jul/Aug season. However, the annual difference is significantly lower at 1.9%.

On the other hand, for a Variable Air Volume (VAV) cooling-only system, the differences in seasonal estimates between the programs are reasonable. Figure 7 shows comparison in seasonal coil load estimates. A maximum difference of 4.3% occurs in the Jul/Aug season, whereas the annual difference is marginally lower at 3.5%. However, for cooling energy estimates, shown in Figure 8, a maximum deviation of 5.2% also occurs in the same season, with an annual difference of 4.2%. When comparison of the seasonal VAV supply air fan electrical energy consumption was made, a maximum difference of 0.9% occurs in the Jul/Aug season. However, the annual difference is lower at 0.4%. Although the agreements are good for the VAV system (i.e. within 5.2%), it is also important to note that the *trends* in the predictions obtained from SHEAP are almost identical to those from BUNYIP in all cases.

In the simulations, BUNYIP execution times were on a average 8 minutes (with co-processor), while execution times for SHEAP averaged at 9 minutes (without co-processor).

CONCLUSIONS

It has been demonstrated, in a limited comparison study, that the estimates given by a newly developed, simplified building energy analysis package, SHEAP, compared favourably with the results obtained from BUNYIP, for the CAV, DD/MZ and VAV systems. The agreements were extremely good for the CAV system.

The use of the transmission matrix method readily allows for inter-zone coupling to be taken into consideration. In addition, the user can specify any type of multi-layer walls, roofs or partitions by specifying the physical and termal properties of the composite layer. Moreoever, unconditioned zone (s) can also be simulated by SHEAP, and this has also increased its flexibility.

In order to increase the accuracy of SHEAP, future versions should incorporate a routine to specifically determine the weighting factors for a specific building being analysed.

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APPENDIX A

Input Data Summary

Latitude = 1.3 deg. N
Building operation = 8 am - 5 pm ; 5.5 days per week

Figure 1 shows the plan and elevation views of the building model.
Weather data : Singapore (from BUNYIP weather file)
(NOTE: sm = square meter)
For the perimeter zones 1 to 4:-
Glass area, Ag = 297 m^2, U = 3.19 W/m2/K.
Wall area, Aw = 693 m^2, U = 2.64 W/m^2/K.
Floor area, Af = 920 m^2, U = 3.58 W/m^2/K.
For the interior zone 5:-

- no window or external wall
Partition area = 1243 sm (exposed to an enclosed, unoccupied space at temperature halfway between the zone and outdoor air temperature).
Af = 1440 sm, U = 1.87 W/m^2/K.

Design air flow rates:-
zone 1 = zone 3 = zone 5 = 6000 1/s; zone 2 = zone 4 = 6500 1/s
Building material description:-
Wall - 8 mm spandrel glass on exterior, 20 mm air space, 100 mm concrete (walls are vertical; solar absorptivity = 0.45).
Glass window - double glazed, vertical and shading coefficient, SC = 0.55; and no external/internal shading
Partition - 16 mm gypsum board, 100 mm air space, 16 mm gypsum board
Floor - 150 mm concrete ; SHEAP classified the building as "heavy"
* Ground reflectance = 0.20

Internal loads:-
Occupants - 1 person/10 sm; heat release 94 W/person sensible (100 % convective) and 141 W/person latent
Lights - 15 W/sm of floor area, 80% convective
Equipment - 2 KW sensible per zone, 100% convective
Peak infiltration : zones 1-4 = 607 1/s, zone 5 = 950 1/s
(BUNYIP and SHEAP used the same 24 hour schedules for occupancy, lighting usage and equipment usage, and infiltration schedule)

System Data:-
Amount of fresh air = 10% design flow rates (fixed)
Cooling coil : design capacity = 650 KW
coil air off temperature = 13.3 C (fixed)
Supply air fan : design power = 25 KW, motor in air stream
(For VAV system, inlet guide vane fan was used).
Thermostat : set point = 23 C; throttling range = 0.1 C, no deadband

Chiller:-

- hermetic centrifugal, design capacity = 650 KW; compressor power = 100 KW; chiller pump power = 4 KW.
  (identical part load performance equations were used by BUNYIP and SHEAP).
- cooling tower design fan power = 6 KW, condenser pump = 5 KW
  (cooling tower fan assumed to cycle on and off to maintain a fixed condenser entering water temperature)

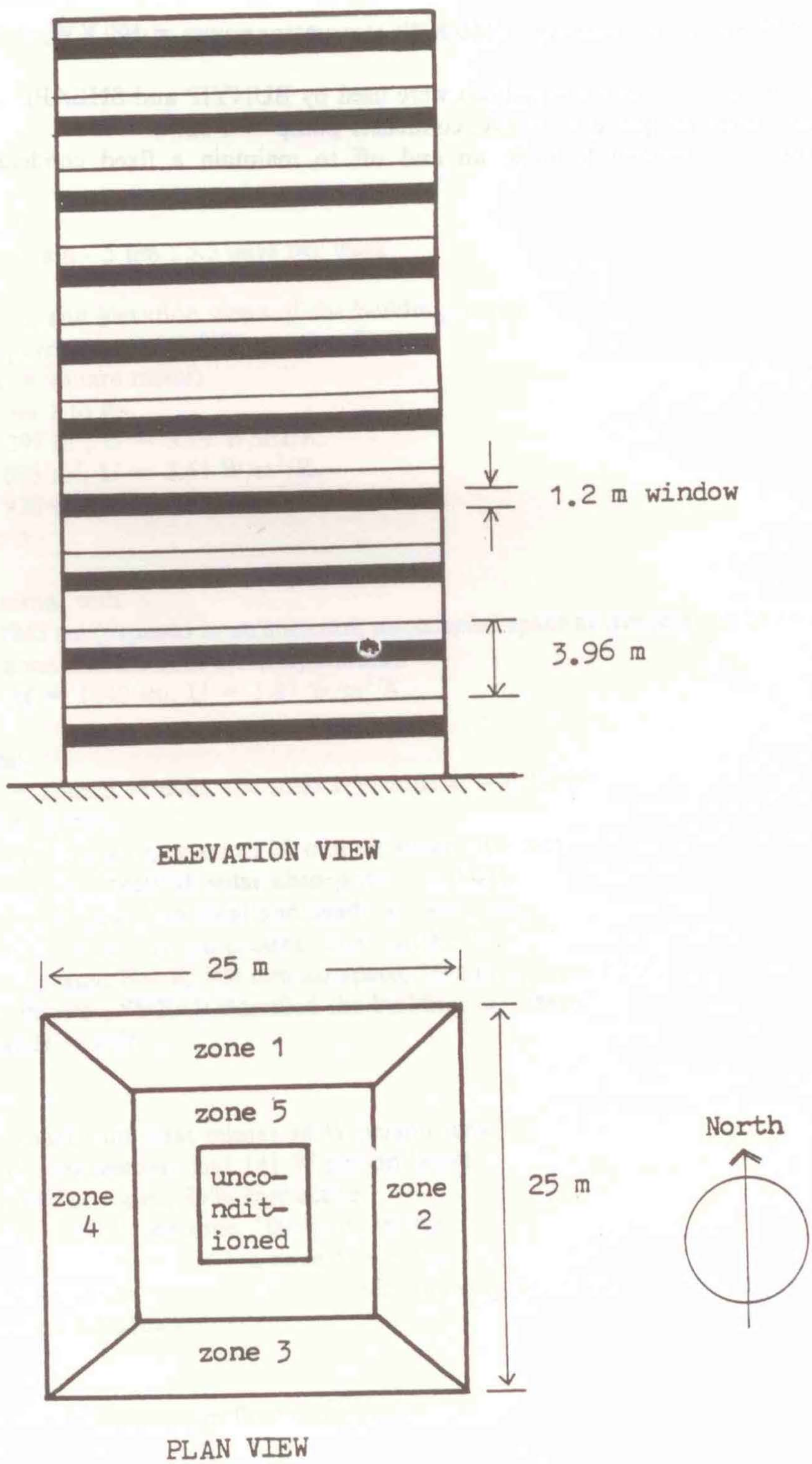

Figure 1: Plan and elevation views of a ten-storey office building model

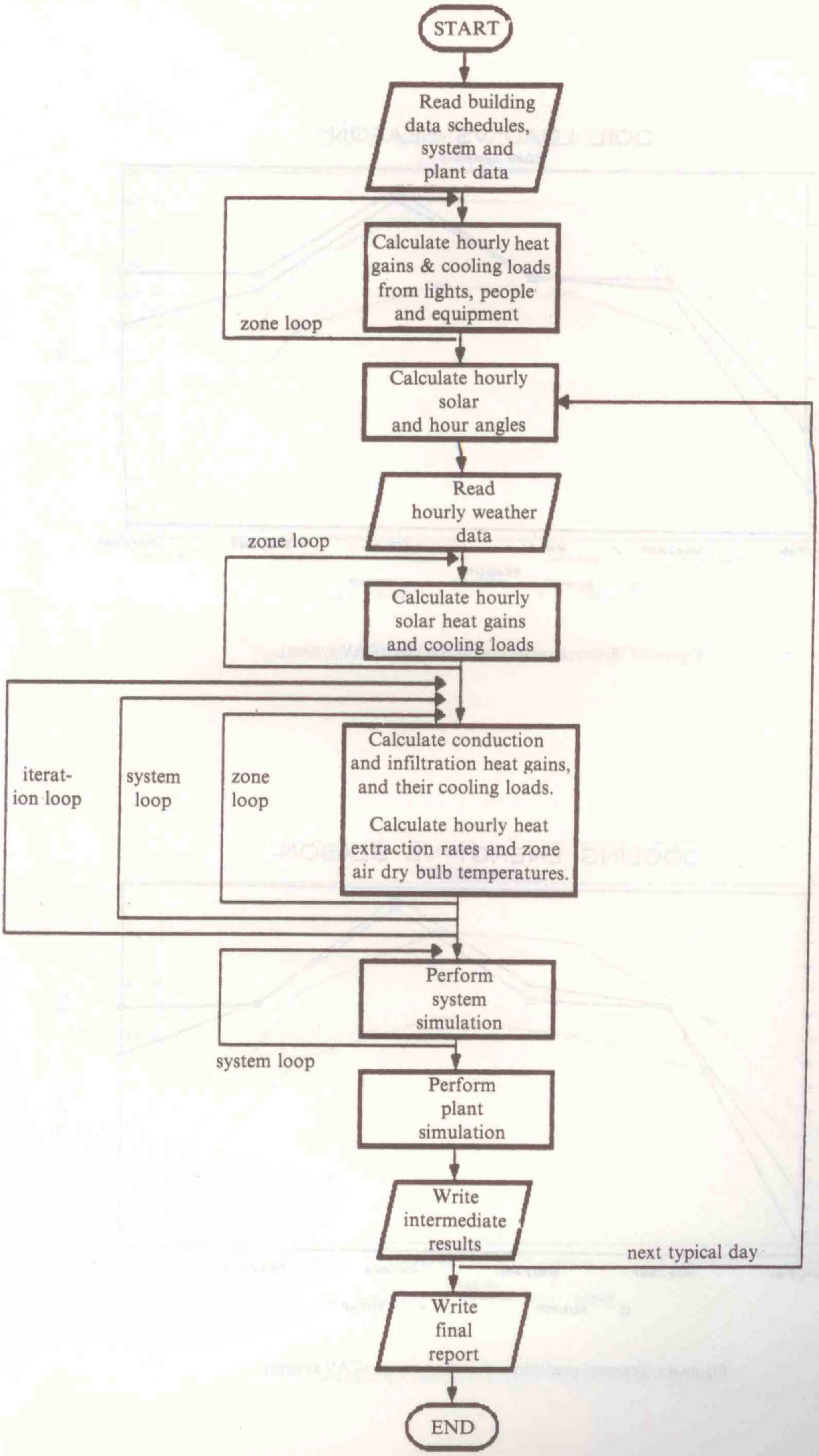

Figure 2: Simplified flow chart for building energy calculation in SHEAP.

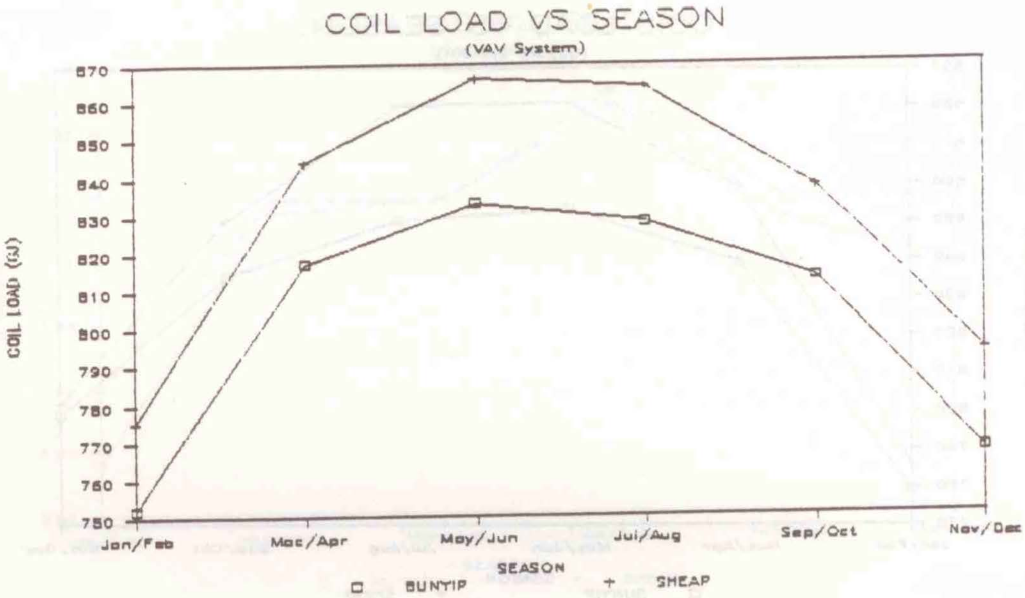

Figure 7: Seasonal prediction of coil load (VAV system).

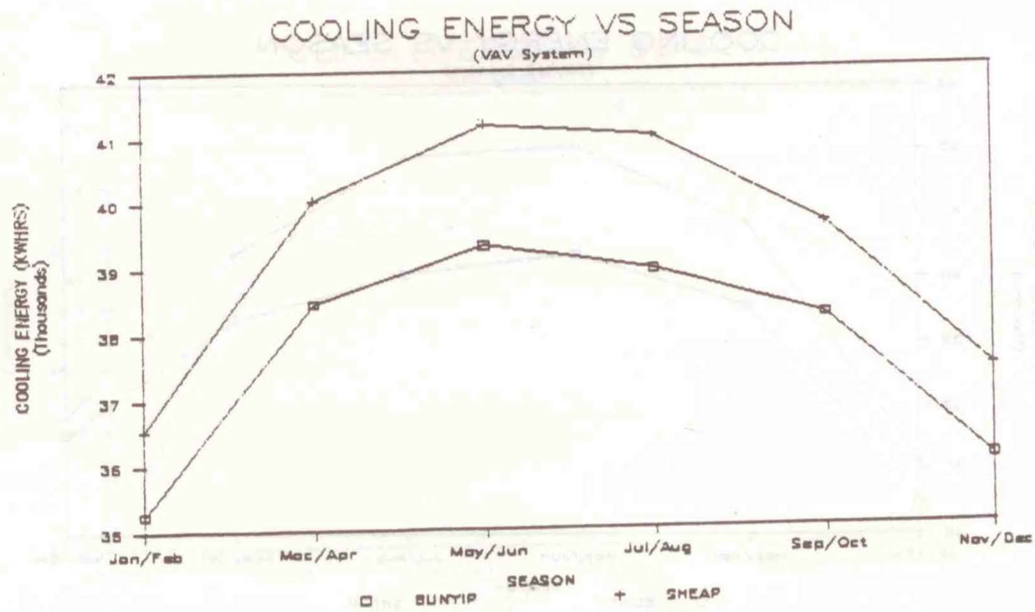

Figure 8: Seasonal prediction of cooling energy (VAV system).