#2656

#26568

A Summary Technical Overview of the ESP System

Dr J A Clarke

ABACUS CAD Unit
Department of Architecture
and Building Science
Faculty of Engineering
University of Strathclyde
Glasgow G4 0NG
Scotland, UK

March 1987

Telephone: 041 552 4400 X3013
Telex: 77472 (UNSLIB G)
Fax: 041 552 0775
Electronic Mail: joe%uk.ac.strath.abacu@ukacrl

Preamble

This paper presents a summary technical overview of the ESP system. The modelling techniques used within ESP are summarised and the theories which underlie each algorithm are referenced. This document should therefore be read in conjunction with the user manual and other publications as given in the Appendix.

Technical Overview

Figure 1 shows the program modules of the ESP system. ESPsim uses a numerical method to integrate the various equation types (algebraic, ordinary differential and partial differential) which are used to represent heat and mass balances within a building/plant network as typified by figure 2. The system is non-building type specific and can handle any building geometry, construction and operation. It can also handle any plant system as long as the necessary component models are installed in the plant components' database. Components, if missing, can be added by a user so that they become available for general selection to participate in any multi-component plant configuration. But since component models must conform to state-space formulations, new component derivation and insertion is often a non-trivial task: the price of plant modelling in the transient domain.

In addition to the ESPsim/out facilities - full transient energy analysis of combined building/plant systems, with comfort assessment, condensation checking, and the like - ESP provides

- climatic severity analysis (ESPclm)
- spectral analysis of glazing systems, including thin films (ESPwin)
- time varying shading caused by site obstructions (ESPshd)
- solar ray tracing (ESPins)
- pressure and buoyancy induced air movement (ESPair & sim)
- detailed view factor assessment (ESPvwf)
- and distributed control system modelling (ESPsim).

A conceptual explanation of ESP's calculation technique would go something like:

> The system offers a way to rigorously analyse the energy performance of a building and its environmental control systems. For each observable energy flow-path in the real world, ESP has a corresponding mathematical model. Within a simulation, a special numerical technique ensures that all flow-paths evolve simultaneously to fully preserve the important spatial and temporal relationships. Stated briefly, ESP will accept some building/plant description in terms of 3-D geometry, construction, usage and control. This continuous system is then made discrete by division into many small, finite volumes of space according to in-built rules (which can be changed!) - perhaps as many as 10,000 for a medium sized building. These finite volumes will represent the various regions of the building and plant within and between which energy and mass can be exchanged. Throughout the subsequent simulation, ESP will track the energy and mass balance for all finite volumes as they evolve under the influence of the system boundary conditions (climate & control) and any constraints imposed on the inter-volume links. The technique ensures that all regions of the building are correctly connected across space and time so that any excitation at some point in space or time will have the correct causal effect.

ESP has a number of mechanisms to ensure stability. For example, all finite volume time constants are tracked throughout a simulation and the corresponding conservation equation made fully implicit or mixed implicit/explicit depending on the relationship between this time constant and the computational time step.

In reference 2 of the Appendix, ESP's mathematical approach is derived and the numerical method used to achieve the repetitive and simultaneous integration of each flow-path over time is explained. Other publications on ESP are also listed in the Appendix.

The overview now continues with a brief, but balanced, description of each facet of ESP.

Machine Environment

The following table gives the size statistics (bytes) for each ESP program module.

Program Module	Text	Initialised Data	Uninitialised Data	Total
ESPimp	280576	74752	262788	618116
ESPsim	333824	128000	1069240	1531064
ESPout	225280	134144	1279668	1639092
ESPcon	77824	24576	21832	124232
ESPpro	69632	19456	21724	110812
ESPpdb	63488	26624	27428	117540
ESPwin	99328	32768	42160	174256
ESPclm	106496	36864	58336	201696
ESPshd	112840	32768	47088	192496
ESPins	110592	32768	32804	176164
ESPair	79872	23552	37408	140832
ESPvwf	69632	75776	77664	223072
ESPdbm	92928	101812	21720	216460
Total				5465832

ESPsim and ESPout are therefore the largest modules, requiring about 1.5 Mbytes each at runtime. The ESP system is supported on two machine types

1. a VAX 11/750 or 11/780 series running VMS
2. or any system running the UNIX (a trade mark of AT&T) operating system (either 4.2 BSD or System V).

Disk requirements will amount to approximately 0.5-1 Mbytes of permanent storage for ESP's databases (for climate, constructions, etc.) and, say, 1 Mbytes and up of temporary storage for the simulation results.

Defining a Building for Simulation

A building model is created via ESPimp with constructions, profiles and plant components taken from the appropriate databases.

The *modus operandi* of ESP is to define each building zone (a zone is not necessarily a room) independent of the others, and to then interlink these zones to define the building in whole or in part. In the latter case, some part of the problem will require a boundary condition other than external climatic. A number of linkage types are offered to cover the range of eventualities. For example, user specified conditions, identical conditions, adiabatic case etc.

Section 3 of the user manual lists the options.

A plant system can then be constructed by linking components from the plant database. This is a new feature of ESP and so should be used with some care.

Finally, a number of control loops are established to define the environmental requirements and the relationship between building zones and zone-side appliances.

Technical Information: reference 3.

Mode of Operation

ESP can be used in one of two ways: *interactive menu* and *expert function* modes. In the former mode, the user picks a path through the various program modules by selecting commands from the menu drivers displayed on the terminal. The user is therefore the expert; both in controlling ESP and devising appropriate simulation schemes to test performance. In the latter mode, the user need not be expert. Now a number of performance assessment *scripts* exist which can be used to control ESP automatically against the *rules* of a particular performance appraisal such as comfort assessment, plant sizing, regulations compliance and the like. This mode requires a 32 bit workstation, offering a bit-mapped screen, window manager and the UNIX operating system. Such systems are now available from 5,000 Pounds.

Technical Information: reference 3.

System Discretisation

With multi-layered constructions, nodes are placed at the centre and boundaries of each homogeneous element. This gives rise to a 2n+1 nodal scheme per construction, where n is the number of homogeneous elements. The nodal scheme can be increased by simply increasing the number of elements. Each air volume - representing a zone in whole or part - is assigned one node. Windows and doors are either node-less, in which case the conductive flux (convective + radiative components) is applied at the corresponding air node and transmitted solar flux at the surface(s), or can be processed rigorously as a multi-layered construction with an independent nodal structure (called a transparent wall in ESP). In the latter case, the convective and radiative exchanges are modelled separately and in a manner which accords with the reality.

Technical Information: reference 2, pp72-7.

Time-Stepping

The computational time-step can be assigned for building-side and plant-side equations separately. It can be any length less than or equal to one hour. Note that very small time-steps will lead to very large results file sizes. It is also possible to invoke a time-step controller to monitor accuracy. Two options are offered: boundary condition look-ahead in which time-steps are reduced in anticipation of rapid boundary condition changes; and a heuristic technique in which the effect of reducing the time-step is tracked.

Technical Information: reference 36.

Boundary Conditions

These are climatic time-series at hourly intervals. ESP operates with dry bulb temperature, wind speed, wind direction, relative humidity, diffuse horizontal solar intensity and direct normal (or global horizontal) solar intensity. All data is assumed to act on the hour, with linear interpolation for smaller time-steps.

Technical Information: reference 2, pp215-31.

Transient Conduction

The assumption is made that conduction is uni-directional. Four conservation equation types (in finite difference form with the implicit/explicit weighting determined at run time) are available to represent the transient conduction in multi-layered constructions. These are for a homogeneous volume, a heterogeneous volume, a cavity volume and a cavity/homogeneous volume. It is also possible for construction elements to be transparent so that shortwave flux can be internally absorbed. Conduction is a function of

conductivity
density
specific heat
dimensions
cavity longwave radiation
cavity ventilation
internal heat generation (shortwave or plant)

At a theoretical level, fabric thermo-physical properties can vary with time. But note that there is no user-orientated data handling to support this feature.

Technical Information: reference 2, pp79-97.

Ground Floor Conduction

The model is the same as for the wall conduction case except that the ground must now be specified. This is done in terms of thermo-physical properties as before, and seasonally dependent ground temperatures. ESP offers a number of geographically typical profiles or will accept user defined values. If 3D conduction is to be modelled it is possible to represent the floor slab by a number of small volume, thick wall contiguous zones. It is relatively easy to enable 3D transient conduction, conservation equations within ESP. However, the corresponding modification to ESP's matrix processing would be both radical and difficult.

Thermal Bridging

ESP has no distinct model of window frames and other thermal bridges. Either such features can be lumped together and treated as a resistance only area or one or more surfaces must be entered to the zone geometry definition to represent the feature explicitly and dynamically.

Windows and Doors

If these areas are defined in the standard way, conduction is handled by a U-value calculation with the surface resistances (defining combined convection and radiation) computed at each time-step as described later. In this case the conductive gain/loss is with the zone air point so that the window/door does not exchange long-wave flux directly with the surrounding surfaces. Window shortwave absorption and transmission is determined as a function of the angle of incidence as described later. Alternatively, windows and doors can be entered as general zone surfaces so that their capacities are represented explicitly. Now longwave radiation exchanges and all internal thermal storage effects are modelled in detail. In either case, it is possible to recover surface temperatures via ESPout.

Convection Coefficients

These are computed, for each surface (internal and external) at each time-step, from buoyancy correlations. For internal surfaces, the coefficients are a function of

surface temperature
adjacent air temperature
aspect and direction of heat flow
characteristic dimension

and for external surfaces

wind speed
wind direction.

It is possible to substitute user-specified values for any surface(s) at any time within a simulation.

Technical Information: reference 2, pp195-200.
reference 34.

Internal Longwave Radiation

Three algorithms are available for use within ESPsim to compute the net longwave flux exchange between surfaces at each time-step.

- The first is an analytical approach which determines a linearised radiation coefficient for all combinatorial surface pairings. These coefficients are then inserted in the system matrix equation to influence the simultaneous solution. This is the default algorithm.
- The second establishes a zone radiosity matrix. This is then inverted at each time step to give the net flux gain/loss at each surface (based on the latest surface temperature data) which are then applied as excitations to the system matrix equation.
- The third is a recursive ray tracing technique which also establishes the net flux gain/loss to each surface based on the latest surface temperature data.

In each case, the calculation depends on

surface temperature
surface emissivity
inter-surface view factors.

Technical Information: reference 2, pp173-84.

View Factors

If the zone geometry is precisely known then the internal, inter-surface view factors can be calculated by ESPvwf. For a zone of arbitrary complexity, ESPvwf uses a finite element, ray tracing technique to determine the angular relationship between surface pairings. If no view factor data is passed to ESPsim, then a simple area weighting technique is employed to establish approximate view factors.

Technical Information: reference 2, pp184-93.

External Longwave Radiation

At each time-step, ESPsim determines the equivalent ambient temperature with which an external surface will exchange longwave flux. This temperature has three components - sky, ground and surroundings - with the proportion of each depending on the site exposure. Evaluation of the sky component involves an estimation of the cloud condition from the prevailing direct and diffuse beam. During the night hours, the cloud cover level is held at the average value prevailing at the hours immediately preceding sun set. Ground temperatures are found by surface energy balance, and the temperature of a surrounding building surface is assumed to be the same as the corresponding surface of the target building. The final flux exchange is therefore a function of

direct and diffuse solar radiation
air dry and wet bulb temperatures
surface, ground and sky emissivities
scene view factors
monthly deep ground temperatures.

Technical Information: reference 2, pp193-5.

Solar Shading and Insolation

ESPshd is the program which generates external, opaque and transparent, direct surface shading. Surrounding and facade obstructions are projected onto the target building and the time-series shading factors determined for each opaque surface and window separately. It is also possible to determine diffuse shading factors. ESPins is the complementary model which determines which internal surfaces would be insolated by sunlight falling on each external window. These data are then transmitted to ESPsim for use in the solar gain calculations. If this data is not available then ESPsim reverts to its default treatment: no shading with the direct solar beam causing user-defined internal insolation.

Technical Information: reference 2, pp150-61.

Solar Gain

Externally, an anisotropic model is used to determine the sky diffuse radiation whereas the ground and surroundings are assumed to be isotropic. The equation of time is incorporated in the sun position calculation to represent the difference between the site and the local reference meridian.

The direct and diffuse beams are treated independently. For each window, a direct and total transmittance curve is held as distinct data values corresponding to angles of incidence of 0, 40, 55, 70 and 80 degrees. ESPwin is the module which allows a spectral analysis of any window to produce this data. Linear interpolation is then used in ESPsim to determine the values appropriate for the prevailing angles of incidence. The transmitted and absorbed, direct and diffuse flux is then determined and applied to a model of the zone's internal shortwave distribution which includes the effects of retransmission on to another zone or back to the outside. The transmitted diffuse beam is applied to each internal surface except the window wall. The transmitted direct beam is applied to the surfaces deemed to be insolated by the ESPins generated insolation data (or by the user-specified default).

If windows have been specified to ESPimp in the default manner, then that portion of the absorbed shortwave flux which is transmitted inward is applied to the corresponding zone air point. However, if the window has been entered as a transparent multi-layered construction, then the absorbed flux at each layer will be applied directly to the element nodes so that the eventual convection and longwave radiation effects at the surface layers are modelled explicitly.

Technical Information: reference 2, pp161-73.

Window Devices

As a function of time, solar intensity or ambient temperature, window coverings (blinds and insulation) can be in place. This allows the thermo-physical properties to vary with time.

Air Flow

ESP will accept time dependent air change rate information to represent zone infiltration and zone coupled air flow. Alternatively, it is possible to specify a leakage network to represent the distributed air flow paths. This is done in terms of characteristic equations which represent the volume flow rates as a function of pressure difference and opening characteristics. The network can be time dependent to allow the modelling of occupant interaction. A database exists to hold sets of representative pressure coefficients which can be associated with network nodes to generate surface pressure as a function of the prevailing wind speed and direction. An air flow simulation can now be performed via ESPair (pressure and fixed buoyancy driven flows) or ESPsim (pressure and variable buoyancy driven flows with combined heat transfer). The mass balance solution algorithm employs a Newton Raphson iterative technique with a number of convergence devices imposed.

Technical Information: reference 2, pp200-7.
reference 35.

Zone Contents

ESPsim automatically makes allowance for the effects of the zone air mass but not the contents. It is possible to model contents by creating another zone of the appropriate volume, surface area and thermal capacity and then to locate this zone within the first. Contents capacity is then explicitly represented but at the cost of a more extensive data structure.

Casual Gains

Any time based schedule can be defined with different convective/radiant splits applied to each gain. Convective flux is applied at the corresponding air point. Radiant flux is apportioned to the zone surfaces on an area weighted basis.

Technical Information: reference 2, pp207-15.

Explicit Plant Modelling

ESPpdb coordinates the database which contains a number of models which represent the dynamic energy behaviour of common plant components such as boilers, coils, calorifiers, pumps, solar collectors, etc. These components can be connected to form a plant network which is then processed concurrently with the multi-zone building.

It is possible for a user to develop a new plant component model, in the form required by ESP, and then to install it in the database. The procedure is as follows.

- Firstly the component is represented as one or more finite volumes between which energy and mass can be exchanged.
- Then, by formal energy and mass balance techniques, a state-space equation is established for each finite volume (see reference).
- The topology of the component's state-space matrix equation is then entered to ESPpdb along with the component's describing data as required by the mathematical model.

- A FORTRAN subroutine is created according to a specified template and installed in ESPsim. Its function is to generate the coefficients of the state-space equations, at each simulation time-step. At simulation time ESP will accept these coefficients and install them in the system matrix equation for simultaneous processing.

Technical Information: reference 2, pp234-73.
reference 37.

Controls

Any number of control loops can be established and imposed on the building and/or plant systems. These loops then act at each simulation time-step to influence energy or mass balance by influencing the matrix equation construction at each time-step. Each control loop is comprised of

a sensor
an actuator
a number of time intervals
and a control law for each.

A sensor is defined in terms of its location, the condition it senses (temperature, enthalpy, flowrate, etc.) and its characteristics (deadband for example). An actuator is similarly defined and exists to set any nodal variable as a function of the output from a control law. Note that in ESP it is possible to actuate quantities like flux and temperature as well as the more usual ones such as valve position. The control laws define the mapping from the sensed condition to the actuated state. A number of standard laws are offered and specials can be developed and entered by a user.

Technical Information: reference 3.

Conceptual Plant Modelling

It is possible to include plant characteristics without explicitly modelling the plant. A building only model is first established and subjected, at simulation time, to a number of control loops which represent the desired environmental conditions *and* plant characteristics. For example, it is possible to select a control law which embodies part load efficiency data to convert energy requirements to consumption estimates.

Comfort Considerations

Resultant Temperature, Standard Effective Temperature, Predicted Mean Vote and Predicted Percentage Dissatisfied are offered by ESP as indices of comfort..

Technical Information: reference 38.

Moisture

ESPsim performs a moisture balance for each zone at each time-step. It is also possible to invoke surface and interstitial condensation calculations.

Appendix
ESP References

General .....

1. Maver T W, 'The Impact of Computer Based Models on Design Decision-Making', *Rebuild*, Wiley, pp95-141, 1982.
2. Clarke J A, *Energy Simulation in Building Design*, Adam Hilger Ltd, Bristol and Boston, 1985.
3. ----------, *ESP Manual: Version 5, Release 3*, ABACUS, University of Strathclyde, 1986.
4. ----------, Guest Editor, Special Energy Issue, *Computer-Aided Design*, V14, Jan. 1982.
5. ----------, 'Energy implications in Building Design', *Proc. 3rd Int. Symp. Use of Computers for Env. Eng. Related to Buildings*, pp3-20, Canada, 1978.
6. ----------, 'ESP: Computing Building Energy', *Building Services*, pp54-6, Oct. 1980.
7. ----------, 'Climatic Severity Assessment', *Proc. 3rd Int. Symp. Energy Conservation in the Built Env.*, V2, pp87-101, Dublin, 1982.
8. ----------, 'ESP: An Energy Simulation Model', *Proc. Int. Seminar on Energy Saving in Buildings, The Hague, Nov. 1983.*
9. ----------, 'Computer Modelling of Passive Solar Architecture', *Proc. Passive Solar Architecture Conf.*, Cannes, Dec. 1982.
10. ----------, 'Dynamic Simulation: The Integration of Building and Plant', *Proc. Int. Conf. on Systems Simulation*, Liege, Dec. 1982.
11. ----------, 'The Issue of Integrity in Building Energy Modelling', *Proc. Seminar on Dynamic Thermal Behaviour of Buildings*, Saint-Remy-les-Chevreuse, Dec. 1984.
12. ----------, 'Building Fabric: Its Impact on Energy Requirements', *ABACUS Occasional Paper*, 1980.
13. ----------, 'ESP Documentation: System 5, Release 3', *ABACUS User Manual*, 1985.
14. ----------, 'The ESP System: Towards a New Generation of Building Energy Analysis Program', *Proc. Building Simulation Conf.*, Seattle, Aug. 1985.
15. ----------, 'Simulation of Solar Systems', *Proc. UK ISES Conf.*, Birmingham, 1985.
16. McLean D J, 'Case Studies in Dynamic Energy Modelling', *Proc. Parc83*, Brighton, 1983.
17. Markus T A & Clarke J A, 'The Performance and Economics of Single and Double Glazing', *Proc. 2nd CIB Symp. on Energy Conservation in the Built Env.*, Copenhagen, May 1979.
18. ABACUS & VALTOS, 'Deemed to Satisfy?', *Architect's Journal*, pp872-4, Oct. 1979.
19. Bridges A, Clarke J A & Sussock H, 'Computer graphics for Building Energy Analysis', *Advanced Engineering Software*, V3(2), 1981.
20. Sluce A J, 'Modelling Reality', *Building Services*, June, 1982.
21. ---------, 'Designer's Requirements of a Building Design Appraisal Program Using ESP as an Example', *Computer-Aided Design, V14(1), pp45-8, Jan. 1982.*
22. Clarke D, 'Housing for the Elderly in Birmingham', *Sun at Work in Britain*, N17, Nov. 1983.
23. Littler J G F, 'Review of Some Promising Simulation Models for Passive Solar Design', *Sun at Work in Britain*, N16, June 1983.

24. Annon., 'Alternatives: Winning House Design Needs Cash', *Energy in Buildings*, Oct. 1982.

On validation .....

25. Clarke J A & McLean D J, 'Results from the Analysis of the Collins Building Second Floor and Plenum by the ESP System', *IEA Annex 4 Final Report*, Oct. 1983.

26. Tang D C, 'IEA Annex 10: Report on Exercise 2', *IEA Annex 10 Interim Report*, Dec. 1984.

27. McLean D J & Clarke J C, 'Results of the Collins Building VAV Air Conditioning Simulation', *IEA Annex 10 Interim Report*, April 1985.

28. Gough M, 'ESP: Comparison with Monitored Direct Gain Test Cells', *Building Research Establishment Report*, IEA Task 8, 1984.

29. Clarke J A & Forrest I, 'Validation of ESP Against Test Houses', *ABACUS Occasional Paper*, 1978.

30. Oscar Faber & Prtns., *IEA Annex 1 Final Report*, 1980.

31. Dupagne A, 'Selection of a European Reference Model for Passive Solar Design', *EEC Handbook*, 1981.

32. Bloomfield D, Various Reports on the Progress of the SERC Validation Project.

33. Williams T, 'The Goodness of Fit Between ESP Predictions and Monitored Data from Two Australian Test Houses', *ABACUS Occasional Paper*, University of Strathclyde, 1984.

Miscellaneous .....

34. Alamdari F and Hammond G P, 'Improved Data Correlation for Buoyancy-Driven Convection in Rooms', *Report SME/J/83/01*, Applied Energy Group, Cranfield Institute of Technology, 1983.

35. Cockroft J P, 'Heat Transfer and Air Flow in Buildings', *PhD Thesis*, University of Glasgow, 1979.

36. Winklemann F C and Clarke J A, 'Implementation of Time-Step Control in ESP', *Simulation Research Group Technical Note*, Lawrence Berkeley Laboratory, 1986.

37. Hanby V and Clarke J A, 'Catalogue of HVAC Component Models', *SERC Final Grant Report*, Dept. of Civil Eng., University of Loughborough, 1987.

38. Gagge, Fobelets and Berglund, 'Standard Predictive Indices ...', *ASHRAE Trans.* Paper PO-86-14-1, V 92, Pt 2, 1986.

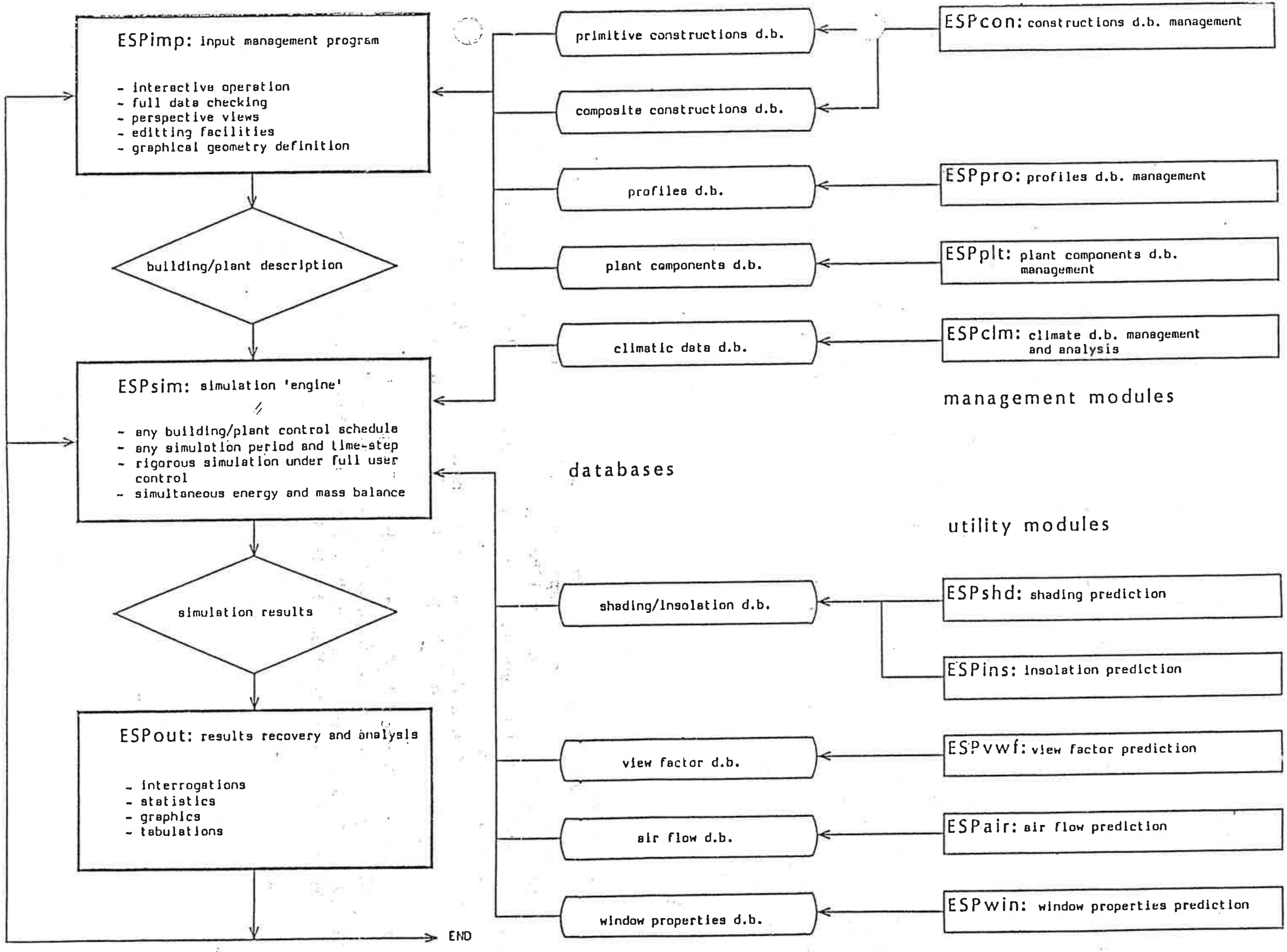

Figure 1 Program modules of the ESP system

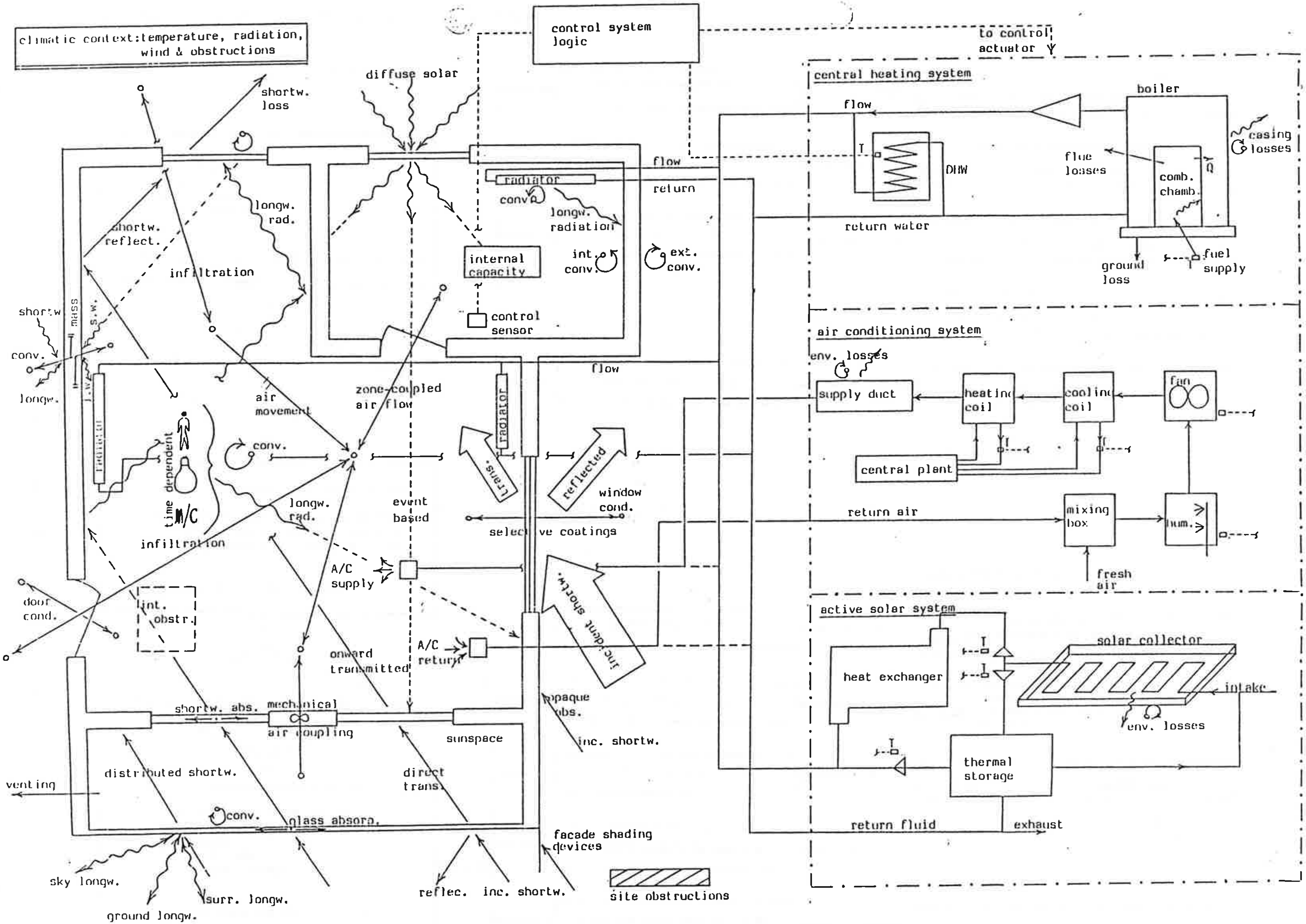

Figure 2 Building/plant energy flowpaths