

Energy Systems Modelling: Energy flow-paths

Computer tools for energy systems design have traditionally been constructed by reducing the complexity of the underlying system equations in an attempt to lessen the computational load and the corresponding input burden placed on the user. Some aspect of the system may be neglected (e.g. longwave radiation exchange), some system parameters may be assumed to be time invariant (e.g. convective heat transfer coefficients) or simple boundary conditions may be imposed (e.g. steady state or steady cyclic). Within a simulation program such assumptions are heresy. Instead, a mathematical model is constructed to represent each possible energy flow-path and flow-path interactions. In this sense simulation is an attempt to emulate reality.

1. Simulation overview

This course addresses the modelling of the energy performance of buildings and the myriad technical systems that deliver heating, cooling and electrical power.

Buildings

Figure 1 depicts the energy flow-paths encountered within a building and which interact, in a dynamic manner, to dictate comfort levels and energy demands. To understand the simulation approach, it is useful to visualise such a system as an electrical network of time dependent resistances and capacitances subjected to time dependent potential differences. The electrical current that flows in each branch of the network are equivalent to the heat flows between the building's parts when driven by temperature and pressure differences (analogous to voltage differences), and stochastic heat and power inputs from sources such as occupants, climate control equipment, photovoltaic panels and directly from the sun.

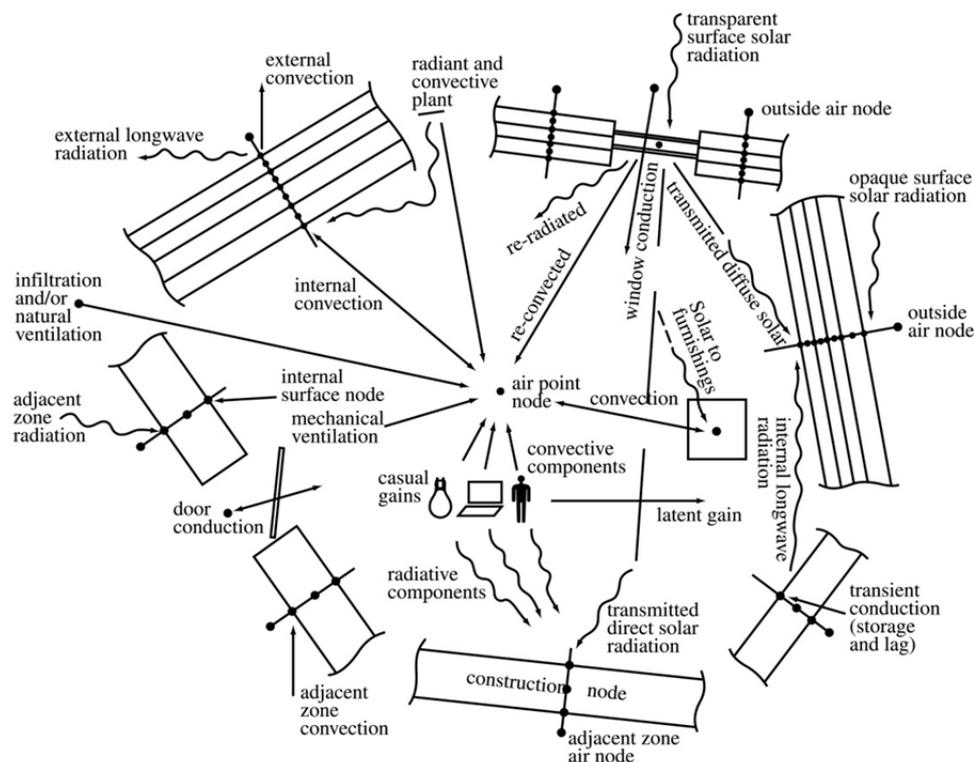


Figure 1: Typical building energy flow-paths.

Continuing the analogy, constructional elements, room contents, glazing systems, plant components, renewable energy devices etc. may be treated as a network of nodes

characterised by capacitance, with the inter-node connections characterised by resistance. Nodes possess 'variables of state' such as temperature and pressure (analogous to voltage) and since nodes have different capacitances, the problem is essentially dynamic; each node responding at a different rate as it competes with its neighbours to capture, store and release energy. It is this distributed dynamic behaviour along with the non-linear nature of the network parameters that imparts complexity to the building modelling task.

The resolution of such a model – that is, the number of nodes employed – is a function of the analysis objectives: an early design stage estimation of summertime temperatures will require a lower level of discretisation than a detailed study of indoor air quality.

From a mathematical viewpoint, several complex equation types must be solved to accurately represent such a system and, because these equations represent heat transfer processes that are highly inter-related, it is necessary to apply simultaneous solution techniques if the performance prediction is to be both accurate and preserve the spatial/temporal integrity of the modelled system.

Conventional systems

Figure 2 illustrates some typical heating, ventilating and air conditioning (HVAC) components as employed to control internal environmental conditions.

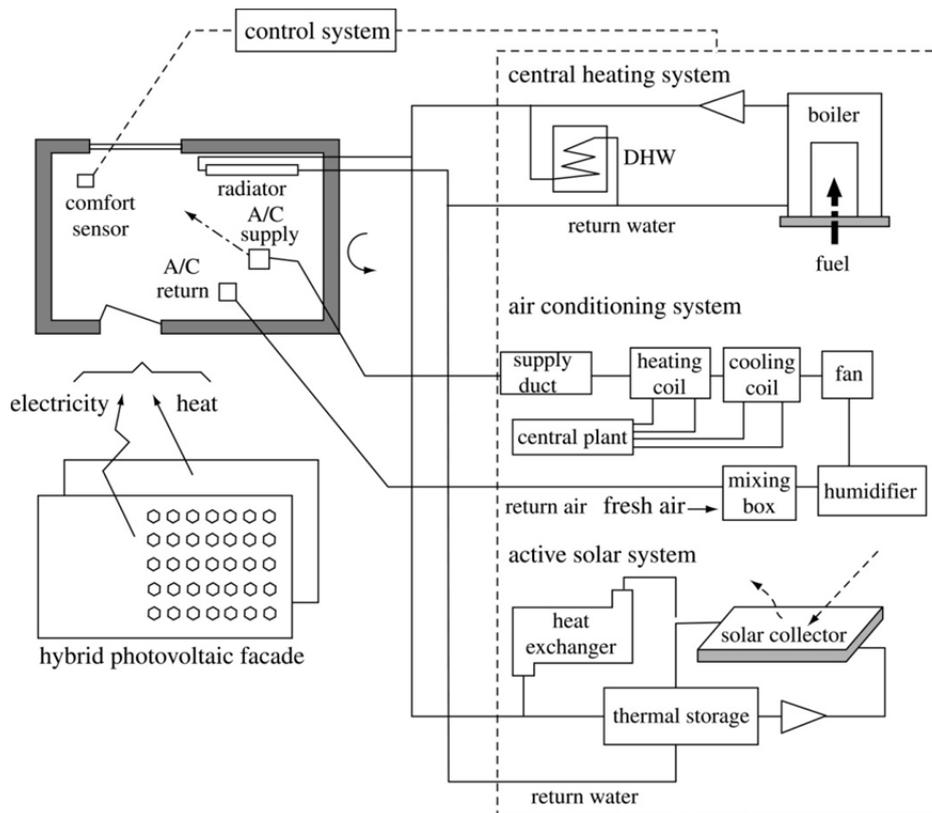


Figure 2: Typical HVAC systems.

Because the building and its plant are strongly coupled, accuracy considerations dictate that they be handled simultaneously. One approach is to incorporate plant characteristics within control statements, which are then embedded within the solution of the building-side equations (or used to influence their formulation). Alternatively, for more accuracy, dynamic plant system models can be established for solution in tandem with the building model so that the spatial and temporal interactions are respected.

New and renewable energy systems

Future cities are likely to be characterised by a greater level of new and renewable energy systems deployment in the form of combined heat and power plant, hydrogen fuel cells, photovoltaic components, ducted wind turbines and heat pumps). To date, renewable energy technologies have been deployed mostly at the strategic level, with the connection of medium-to-large scale hydro stations, bio-gas plant and wind farms to the electric grid. The further introduction of renewable energy systems at this scale will eventually give rise to network balancing and power quality issues due to the intermittent nature of renewable energy sources, requiring controllable, fast responding reserve capacity to compensate for fluctuations in output, and energy storage to compensate for non-availability. The attainment of high levels of renewable energy systems penetration may best be assisted by the introduction of active network control and the embedding of heat and power generation at the urban level matched to the loads they serve: by utilising energy efficiency and demand management measures, a building's energy demand may be reduced and the profile of this demand reshaped to accommodate the low power densities of embedded micro-generators; any energy deficit may then be met from the public electricity supply.

To facilitate the modelling of embedded generators, an electrical power flow model is required along with related models for each generation technology.

2. Integrative modelling

The aim of integrative modelling is to preserve the integrity of the entire building/plant system by simultaneously processing all energy transport paths at a level of detail commensurate with the objectives of the problem in hand and the uncertainties inherent in the describing data. To this end, a building should be regarded as being systemic (many parts make the whole), dynamic (the parts evolve at different rates), non-linear (parameter values depend on the thermodynamic state of the system) and, above all, complex (there are myriad intra- and inter-part interactions). The essential challenge is to solve a large number of partial differential equations that describe the conservation of mass, energy and momentum within a system comprising many sub-parts.

Once established, an integrated simulation program can be applied throughout the design process, from the early concept stage through detailed design. Indeed, it may be argued that it is more appropriate to use a single simulation program throughout the design process than to use a progression of tools – from simplified to detailed – and ignore the many theoretical discontinuities and pernicious assumptions.

Simulation allows users to understand the interrelation between design and performance parameters, to identify potential problem areas, and so implement and test appropriate design modifications. The design to result is more energy conscious, with better environmental conditions maintained over time.

Underlying the flow-paths of figures 1 and 2 is the concept of energy, mass and momentum balance, governing the fundamental processes of conduction, convection, radiation and fluid flow. Any unified representation of the building and its environmental control systems will therefore require models of the heat, air, moisture, light and electricity flows as they occur within the building/plant system when subjected to weather factors and influenced by distributed control action and occupant interactions.

3 Energy flow-paths and causal effects

Before considering techniques for the development of an integrative mathematical model, it is

necessary to consider the various heat and mass transfer mechanisms to be modelled and the factors that give rise to them.

Transient conduction

This lies at the heart of the energy model and is the process by which a fluctuation of heat flux at one boundary of a solid construction (within a building or plant component) finds its way to another boundary, being diminished in magnitude and shifted in time due to the construction's thermal inertia. Transient conduction is a function of the temperature and heat flux excitations at exposed surfaces, the possible generation of heat within the construction, the temperature- and moisture-dependent (and therefore time-dependent) hygro-thermal properties of the individual materials comprising the construction, and the relative position of these materials. With the external weather excitations known time-series data, the modelling objective is to determine the intra-construction temperature and moisture distribution and hence the dynamic variation of heat flux at the exposed surfaces. In many situations it is important to consider heat flow in more than one direction, for example in cases where thermal bridging might be expected to occur or where corner and edge regions are large relative to the planar area of a wall.

The thermo-physical properties of interest include conductivity, k (W/m.K), density, ρ (kg/m^3), and specific heat capacity, C (J/kg.K). These properties are time-dependent because of material temperature and/or moisture fluctuations, and may be position or direction dependent if the material is non-homogeneous or anisotropic respectively. In some applications such dependencies may be ignored and the thermo-physical properties assumed constant.

The material properties comprising a construction can be combined to provide simple indices for use at an early design stage to differentiate the performance of different constructional approaches. For example, the overall steady-state thermal transmittance, or U-value ($\text{W/m}^2\cdot\text{K}$), is given by

$$U = \frac{1}{\left[\left(\sum_{j=1}^N \frac{x_j}{k_j} \right) + R_i + R_o + R_c \right]}$$

where N is the number of layers in the construction, x_j the thickness of layer j (m), R the combined radiative and convective thermal resistance ($\text{m}^2\cdot\text{K}/\text{W}$) and subscripts i , o , and c refer to the innermost surface, outermost surface and air gap (if any) respectively.

Traditionally, designers have relied on this steady-state concept to assess the heat loss characteristics of a building's fabric. In addition to ignoring the dynamic (thermal capacity) aspect of fabric response, the approach does not preserve spatial integrity since different constructional arrangements will perform differently even though each may have the same U-value. The combined effect of these shortcomings can have significant impact on other energy flow-paths. For example, if insulation is located at the innermost position of a wall then any shortwave solar radiation penetrating windows and striking that internal surface cannot be readily stored in the construction since the insulation will act as a barrier. Instead, the solar energy will cause a surface temperature rise which, in turn, will increase the rate of energy release to the adjacent air by the process of natural convection. A space experiencing high solar energy penetration is therefore likely to overheat if cooling is not introduced. Conversely, if the insulation is relocated externally, with capacity elements exposed to the inside, then internal surface shortwave gain can access capacity to be stored. By proper design this stored energy can later be harnessed passively (rather than by mechanical means) to minimise heating requirements and avoid overheating. On the other hand, internal capacity may give rise to increased peak plant demand due to the initial high rate of transfer of energy to capacity at plant start-up in an intermittent scheme. With continuous operation, capacity

can help to minimise the peaks and maximise the troughs of plant demand and so promote good load levelling. This, in turn, will give a stable environment and encourage efficient operation by allowing plant to operate consistently at or near full load. The risk of interstitial condensation is greater in the case of internally located insulation since a portion of the construction may fall below the dew point temperature of moist air permeating through the construction in the absence of an effective vapour barrier. The use of a model based on a U-value approach cannot readily differentiate between such cases.

In summary, transient conduction will affect energy requirements, load diversity, peak plant demand, load levelling, plant operating efficiency and condensation potential. Unfortunately, there is no simple design paradigm that can be used to select an optimum construction.

Thermal diffusivity, $\alpha = k/\rho.C$ (m^2/s), and effusivity, $\varepsilon = (k.\rho.C)^{1/2}$ ($J/m^2.K.s^{1/2}$), are useful dynamic performance indicators. Materials with high α values transmit boundary heat flux fluctuations more rapidly than do materials with correspondingly low values, while materials with high ε values will more readily absorb a surface heat flux. These parameters can be usefully applied to real constructions by reducing the multiple layers to an equivalent homogeneous layer:

$$(k\rho C)_e = \frac{1.1R_i(k\rho C)_i + \sum_m 1.1R_m(k\rho C)_m}{R_e} + \frac{(k\rho C)_o}{R_e} \left(R_o - 0.1R_i - \sum_m 0.1R_m \right)$$

where subscripts e, i, m and o refer to the equivalent, innermost, intermediate and outermost layers respectively ($m=0$ for a 2 layer construction and $k\rho C=0$ for an air gap). If the second term on the right-hand side of this equation becomes negative (i.e. $R_o \rightarrow 0$) then it should be neglected. The equivalent resistance is given by

$$R_e = \frac{x_o}{k_o} + \sum_m \frac{x_m}{k_m} + \frac{x_i}{k_i}$$

where, for the case of an air gap, x_m/k_m is the combined convective/radiative resistance. The equivalent (ρC) value is obtained from

$$(\rho C)_e = \frac{(k\rho C)_e R_e}{\left(x_o + \sum_m x_m + x_i \right)}$$

so that the thermal diffusivity/effusivity of the equivalent layer may be determined from the equivalent k and ρC values.

The time constant, τ , of a multi-layered construction may be evaluated from

$$\tau = \frac{(k\rho C)_o \left(R_o - 0.1R_i - 0.1 \sum_{j=1}^M R_j \right) + 1.1 \left((\rho Cx)_i + \sum_{j=1}^M (\rho Cx)_j \right)}{U}$$

Within a simulation, the start-up period (required to eliminate the effects of the arbitrarily assigned initial conditions) can be empirically related to the maximum time constant occurring within a given design.

These above derived properties may be use to differentiate the behaviour of different constructional materials, For example, consider two hypothetical materials, A and B, as listed in the following Table.

Table 1.1: Two hypothetical materials.

Material	Diffusivity (m^2/s)	Effusivity ($J/m^2.K.s^{1/2}$)
A	7.7×10^{-7}	1.5×10^3
B	8.3×10^{-4}	6.4

Material B will transmit a boundary heat flux fluctuation the fastest because its thermal diffusivity is largest but will absorb a surface heat flux less readily because its thermal effusivity is lowest.

Surface convection

This is the process by which heat flux is exchanged between a surface (opaque or transparent) and the adjacent air layer. In building modelling it is usual to differentiate between external and internal exposures. In the former case, convection is usually wind induced and considered as forced whereas, at internal surfaces, natural and/or forced air movement can occur depending on the location of mechanical equipment and the flow field to result. It is normal practice to make use of time-varying, but surface-averaged, convection coefficients, h_c ($W/m^2.K$), corresponding to walls, floors and ceilings subjected to different flow regimes.

Forced convection is a function of the prevailing fluid flow vector. Typically, for external building surfaces, wind speed and direction data are available for some reference height and techniques exist to estimate non-reference height values in terms of characteristic vertical velocity profiles. Forced convection estimation for internal surfaces is more problematic, requiring knowledge of the distribution and operation of air handling equipment.

Natural convection is a more tractable problem to study and many formulations have emerged which give convection coefficients as a function of the surface-to-air temperature difference, surface roughness, direction of heat flow and characteristic dimensions.

Internal surface long-wave radiation exchange

In most simplified methods, surface heat transfer coefficients are treated as combinations of convection and long-wave radiation although the values used are often dubious. In reality, the two processes are related by the fact that they both can raise or lower surface temperatures and so influence each other.

Inter-surface long-wave radiation is a function of the prevailing surface temperatures, surface emissivities, the extent to which the surfaces are in visual contact (represented by a view factor), and the nature of the surface reflection (diffuse, specular or mixed). The flow-path will tend to establish surface temperature equilibrium by cooling hot surfaces and heating cold ones. It is an important flow-path where temperature asymmetry prevails, as in passive solar buildings where an attempt is made to capture solar energy at some selected surface. A standard energy efficiency measure is to upgrade windows with glazings incorporating a low emissivity coating. This increases the reflection of long-wave radiation flux and so acts to break inter-surface heat exchange. The mathematical representation of the flow-path is non-linear in the temperature term and this introduces modelling complications.

External surface long-wave radiation exchange

The exchange of energy by long-wave radiation between external (opaque and transparent) surfaces and the sky vault, surrounding buildings and ground can result in a substantial lowering of surface temperatures, especially under clear sky conditions and at night. This can lead to sub-zero surface temperatures, especially with exposed roofs, and can give rise to high heat loss in cases of low insulation level. Conversely, the flow-path can result in a net gain of energy, although under most conditions this will be negligible.

The adequate treatment of this flow-path will require an ability to estimate several contributing factors: the effective sky temperature as a function of the prevailing cloud cover and type; the temperature of surrounding buildings; the temperature of the ground as a

function of terrain conditions; the local air temperature; the surface warming effect of any incident short-wave solar flux; and view factor information to geometrically couple the surface with the three possible portions of its scene – sky, ground and surroundings. The mathematical representation of the flow-path requires that the describing data model be extended to include a building's surroundings.

Short-wave radiation

In most buildings, the gain of energy from the sun constitutes a significant portion of the total cooling load (or overheating potential if cooling is not available). The method of treatment of the shortwave flow-paths will therefore significantly dictate the accuracy of the overall predictions.

Some portion of the short-wave energy impinging on an external surface – arriving directly from the sun or diffusely after atmospheric scatter and terrain reflections – may, depending on subsequent temperature variations affecting transient conduction, find its way through the fabric where it will contribute to the inside surface heat flux at some later time. It is not uncommon for exposed surfaces to be as much as 15-20°C above ambient temperature.

In the case of completely transparent structures, the shortwave energy impinging on the outermost surface is partially reflected and partially transmitted. Within the glazing layers and substrates of the system many further reflections take place and some portion of the energy is absorbed within the material to raise its temperature. This temperature rise will augment the normal transient conduction process and, thereby, help to establish inner side and outer side surface temperatures which, in turn, will drive the surface convection and long-wave radiation flow-paths. Thus, in effect, absorbed shortwave radiation penetrates the building envelope via convection and longwave radiation.

The component of the incident beam which is transmitted will strike (with no perceptible time lag) one or more internal surface where it behaves as did the external surface impingement: opaque surface absorption/reflection, transparent surface absorption/reflection and transmission (back to outside or onward to another zone), and giving rise to behind-the-surface transient conduction where the flux is stored and lagged.

Accurate solar irradiation modelling therefore requires methods for the prediction of surface position relative to the solar beam, and the assessment of the moving pattern of insolation of internal and external surfaces. The former method is a function of site latitude and longitude, time of day/year and surface geometry, while the latter method requires the existence of ray tracing techniques.

The thermo-physical properties of interest include shortwave absorptivity and reflectivity for opaque elements and absorptivity, transmissivity and reflectivity for transparent elements. The magnitude of these properties is dependent on the angle of incidence of the short-wave flux and on its spectral composition. With regard to the latter, it is common practice to accept properties that are averaged over the entire solar power spectrum.

Shading and insolation

These factors control the magnitude and point of application of solar energy within the building zone or solar device. Both time-series require point projection or hidden line/surface techniques for their estimation, as well as access to a data structure that contains the geometry of obstruction features.

It is usual to assume that façade shading caused by remote obstructions (such as surrounding buildings and trees) will reduce the magnitude of direct insolation, leaving the diffuse beam

undiminished. Conversely, shading caused by façade obstructions (such as overhangs and window recesses) might also be applied to the diffuse beam since the effective solid angle of the external scene, as subtended at the surface in question, is markedly reduced.

At any point in time the short-wave radiation directly penetrating an exposed window will be associated with one or more internal surface, depending on the prevailing solar angle and the internal building geometry. The receiving surface(s) may be opaque, a window in another wall (connecting the zone to another zone or back to ambient conditions), items of furniture, or special surfaces included in the model to represent occupants or control system sensors.

Air flow

Within buildings, three air flow paths predominate: infiltration, zone-coupled flow and mechanical ventilation. These flow-paths give rise to advective (fluid-to-fluid) heat exchanges and each are vector quantities in that only air flowing to a region is considered to cause the thermal loading of that region, any loss being the driving force for a corresponding replacement to maintain a mass balance.

Infiltration is the name given to the leakage of air from outside and comprises two components: the unavoidable movement of air through distributed leakage paths such as the small cracks around windows and doors and through the fabric itself; and the ingress of air through intentional openings (windows, vents, etc.) often referred to as natural ventilation.

Zone-coupled air flow, as with infiltration, is caused by pressure variations and by buoyancy forces resulting from the gravitational and density differences associated with the coupled air volumes.

Mechanical ventilation is the deliberate supply of air to satisfy a fresh air requirement and, perhaps, heat or cool a space.

Random occurrences, such as occupant induced window/door opening, changes in the prevailing wind conditions, and the intermittent use of mechanical ventilation, will influence the levels of infiltration and zone-coupled air flow. Notwithstanding the stochastic nature of these occurrences, air flow models of varying complexity can be constructed. At a level appropriate to building energy modelling, air movement is often represented by a nodal network in which nodes represent fluid volumes and inter-nodal connections represent the distributed leakage paths connecting these volumes and through which flow can occur. Numerical techniques are applied to this network to establish the mass balance corresponding to a given nodal temperature field and boundary pressure condition. The method is well suited to the determination of the contribution of air movement to energy requirements. A more comprehensive approach involves the solution of the energy, mass and momentum equations when applied to a discretised flow domain. In addition to supporting energy analysis, such a method will also provide information on the spatial variation of indoor air quality and thermal comfort levels.

Casual gains

In most non-domestic buildings, the effects of the heat gains from lighting installations, occupants, small power equipment, communication devices and the like can be considerable. It is important therefore to process these heat sources in as realistic a manner as possible. Typically, this will necessitate the separate processing of the heat (radiant and convective) and moisture emissions, and the provision of a mechanism to allow each casual source to change its magnitude over time. It is usual to assume that the convective heat emission is experienced instantaneously as an air load whereas the radiant portion is apportioned between the internal opaque and transparent surfaces according to some distribution strategy. Because

of the inherent relationship with the construction capacity, the radiant component will experience a time lag before it can contribute to the cooling load or elevate the internal air temperature.

Some casual gain sources, such as luminaires and communication equipment, will require the elaboration of a model of their electrical behaviour in order to modulate heat emission as a function of the electrical power usage. For example, this would be required in the case of daylight responsive luminaire dimming.

Control

To direct the path of a simulation, the combined building and supply systems model must be subjected to control action. This involves the establishment of several control loops, each one comprising a sensor (to measure some simulation parameter or aggregate of parameters), an actuator (to receive and act upon the controller output signal) and a regulation law (to relate the sensed condition to the actuated state). These control loops are used to regulate HVAC components and manage building-side entities, such as solar control devices, in response to departures from desired environmental conditions. Control loops can also be used to effect changes to the active model at run-time, e.g. to impose alternative heat transfer coefficients or activate a more rigorous treatment of air movement at some critical point in time. Control loops may also be used to emulate plant behaviour in terms of the location of flux addition/extraction, the prevailing radiant/convective split, and any physical constraints imposed on the installed capacity. This is a useful feature where there is insufficient information to allow a detailed plant model to be established.

Moisture

Dampness and mould growth are recognised as major problems affecting a significant proportion of houses throughout the world. Approximately 2.5 million UK residences are affected, with well documented cases for the rest of Europe and North America. It has been estimated that the cost of repairing the damage caused by timber decay in the UK housing stock is approximately £400M per annum. Apart from aesthetic considerations, there is now considerable epidemiological evidence to support the view that mouldy housing has a detrimental effect on the physical and mental health of occupants.

High levels of airborne spores may occur due to the growth of fungi on walls and furnishings. Data from previous Scottish housing condition survey indicate that around 12% of Scottish houses are affected, with inadequate heating, insulation and ventilation cited as the principal causal factors.

Fluctuations in moisture levels within the building's fabric can also be problematic, leading to interstitial condensation or causing variations in a material's thermo-physical properties and, thereby, adversely affecting its thermodynamic performance.

Approaches to the modelling of airborne moisture transport and the flow of moisture within porous media will therefore be required if the simulation program is to anticipate the conditions required for the proliferation of mould growth.

Passive solar elements

Many designers have come to favour the use of design features that act to capture and process solar radiation passively and without recourse to mechanical systems. Figure 3 summarises the range of possible passive solar elements. In each case, factors can be identified which, in particular, will impose technical complexity on any modelling exercise:

a) non-diffusing direct gain systems will require adequate treatment of the mapping of the

- solar beam onto the internal receiving surfaces or obstruction objects such as furniture;
- b) diffusing direct gain systems will require solar energy apportioning to the various internal surfaces;
- c) earth banking will introduce complexity in the modelling of ground heat exchange;
- d) attached sunspaces will require that the model be able to establish the level of penetration of solar radiation to interior contained zones;

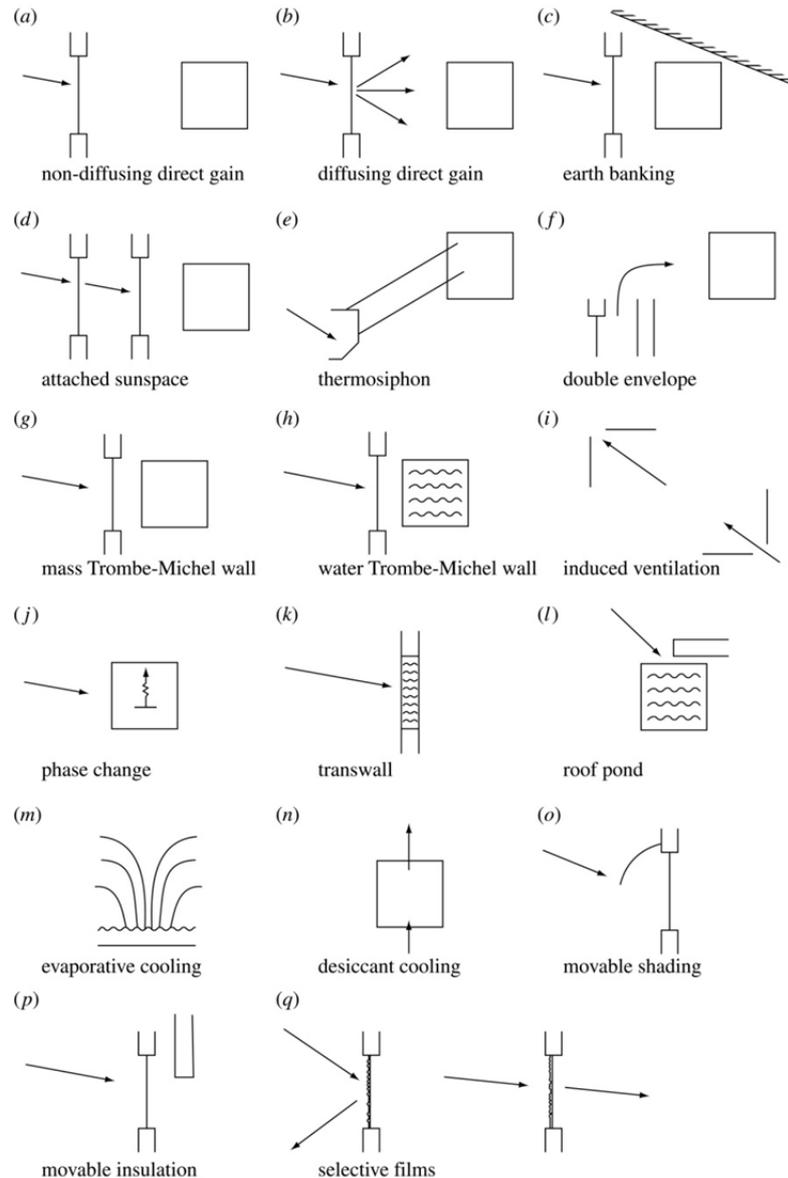


Figure 3: Passive solar elements in architectural design.

- e) thermo-siphon systems will require buoyancy driven air flow modelling;
- f) double envelopes will require sophistication on the part of solar algorithms since radiation may penetrate the external skin to cause 'deep' construction heating;
- g) mass Trombe-Michel walls will require a multi-dimensional conduction model;
- h) water Trombe-Michel Walls will require a detailed treatment of convective heat transfer;
- i) induced ventilation schemes will require accurate modelling of buoyancy and pressure induced air flows;
- j) phase change materials will necessitate the switching from sensible heating behaviour to constant temperature behaviour in the transient conduction schemes;
- k) transwalls will impose demands on the solar and conduction algorithms since direct shortwave transmission and fluid motion will occur;

- l) roof ponds will require accurate external longwave radiation assessment;
- m) evaporative cooling systems will require combined heat and mass flow modelling;
- n) desiccant materials will exhibit a change of dehumidification potential with time and require models for regeneration;
- o) movable shading will require device operation modelling and sophistication on the part of the shading/insolation prediction algorithms;
- p) movable insulation implies a time-dependent system definition; and
- q) selective thin films will require detailed spectral response modelling.

Advanced modelling systems seek to include these and all other energy flow-paths while respecting the inevitable interactions and underlying complexities.

Environmental impact

Buildings will typically account for around 50% of the total energy consumption in a developed country and a similar portion of the carbon dioxide emissions. Significant additional energy consumption is associated with the production and transportation of construction materials. In the UK, for example, this amounts to around 25% of the domestic sector energy consumption. Associated with these consumptions are gaseous emissions that can give rise to atmospheric pollution (SO_x and NO_x) and, it is claimed, global warming (CO₂). The integrated performance modelling approach is able to address all aspects of a building's life cycle and thereby help designers to strike a balance between energy use, indoor comfort and local/global impact.

Uncertainty

Since all design parameters are subject to uncertainty, programs need to be able to apply uncertainty bands to their input data and use these bands to determine the impact of uncertainty on likely performance. Programs so endowed will be able to assess risk, rather than merely presenting performance data to their users. Surely it is better to give the probability of overheating than to output an operative temperature profile and trust to the user's interpretive skill.

4. The need for accuracy and flexibility

It is impossible to establish, in advance, the optimum level of model accuracy and flexibility in the field of energy simulation. Nevertheless, it is important to differentiate between simplified models and comprehensive models which are capable of simplified model emulation. In the former case a number of simplifying assumptions are applied to the underlying thermal network and/or solution scheme. Invariably, some flow-paths are crudely approximated or omitted entirely. The model to result is then valid only when applied to problems that embody the same simplifications. In the latter case, a comprehensive model is designed to operate on input data ranging from simplified to detailed. This is achieved by incorporating context specific defaults to allow the inclusion of any flow-path not explicitly addressed in the input data set. This approach is substantially more flexible, with the accuracy level changing as a function of the quality of the design information supplied.

As a general strategy, it would seem reasonable to aim for a high level of accuracy combined with a model structure that is capable of adapting to the information available at any design stage. It is likely that a truly simple model, as perceived by a user, will be internally comprehensive in its treatment of the energy flow-paths, relying on the proper design of the interface for its operational flexibility. The contention underlying such an approach is that accurate and flexible appraisal tools can only be achieved by an approach that achieves conservation of energy whilst including all flow-paths, ensures integrity of the mathematical model vis-à-vis the reality, and wins acceptability through proper interface design in

conjunction with rigorous validity and applicability testing.

5. Energy modelling techniques

Contemporary simulation programs are based either on response function or numerical methods. The former method is appropriate for the solution of systems of linear differential equations possessing time invariant parameters. In use, it is usual to assume a high degree of equation decoupling. Numerical methods, on the other hand, can be used to solve time varying, non-linear equation systems without need to assume equation decoupling as a computational convenience. Numerical methods are favoured for a number of reasons. First, to ensure accuracy it is essential to preserve the spatial and temporal integrity of real energy systems by arranging that whole system partial differential equation-sets be solved simultaneously at each computational time step. Second, numerical methods, unlike their response function counterpart, can handle complex flow-path interactions. Third, time varying system parameters can be accommodated. Fourth, processing frequencies can be adapted to handle so-called 'stiff' systems in which time constants vary significantly between the different parts of the problem (building fabric, HVAC components, fluid flow domains, control system elements, renewable energy components, radiation distribution, light flow, etc.).