CHAPTER 2

LITERATURE REVIEW

he driving force behind all these studies has been a desire to understand the factors that affect energy use in practice, a need to find ways of measuring and evaluating building energy performance, and doubts about the accuracy of the design predictions provided by current building simulation methods." – (Baird, et al., 1984, Preface)

The problems surrounding building energy performance arise from a lack of theoretical framework and the ambiguity of building design and energy analysis methods. This chapter outlines the research problems and explains the current development and understanding in this field. The basic concepts of energy performance are described; the characteristics of building design process are studied; the essential theories of load and energy calculations are explained; the problems surrounding building energy simulation are discussed.

2.1 Energy Performance of Buildings

Energy performance is a general and abstract concept which is ill-conceived and not well-defined. International efforts expended in the study of building energy performance are diverse and disperse.

2.1.1 Basic concepts

The concept of uilding performance', which has only recently received systematic study, assumes that uilding' can be defined and their performance assessed (Baird, *et al.*, 1984; BRE, 1983; Hartkopf, *et al.*, 1992). Although the bases for assessing energy performance of many building components and individual systems have been fairly well established, there is a lack of full understanding of the energy performance of the hole building’, which involves complex interaction of the building components and systems, and consideration of their combined dynamic behaviour.

What is building energy performance?

There is no standard and agreed definition *per se* of what building energy performance is. Even the briefest review immediately reveals great difficulties in transforming the concept of building performance into a useful tool (Baird, *et al.*, 1984). An encyclopaedia will perhaps tell you that nergy’ is the capacity for doing work and erformance’ is how well the work is done. A general definition has also been provided in ASHRAE (1990a): nergy performance – the energy consumption or use for an existing or proposed building.” The total building energy consumption in a year is usually a major index of the performance. Actual energy analysis may involve other aspects, such as monthly consumption, peak demands and component breakdowns.

Generally speaking, energy performance can be expressed for the whole building, for its components and systems, as well as for the individual elements. When the whole building is considered, the energy performance will lump together individual performances, complicating the analysis and optimisation process. Figure 2.1 shows the major components of building energy consumption and there are two main groups: (a) the HVAC related components and (b) the components related to general building equipment. The present study focuses on the HVAC related components since they are usually the most complicated part of building energy analysis.

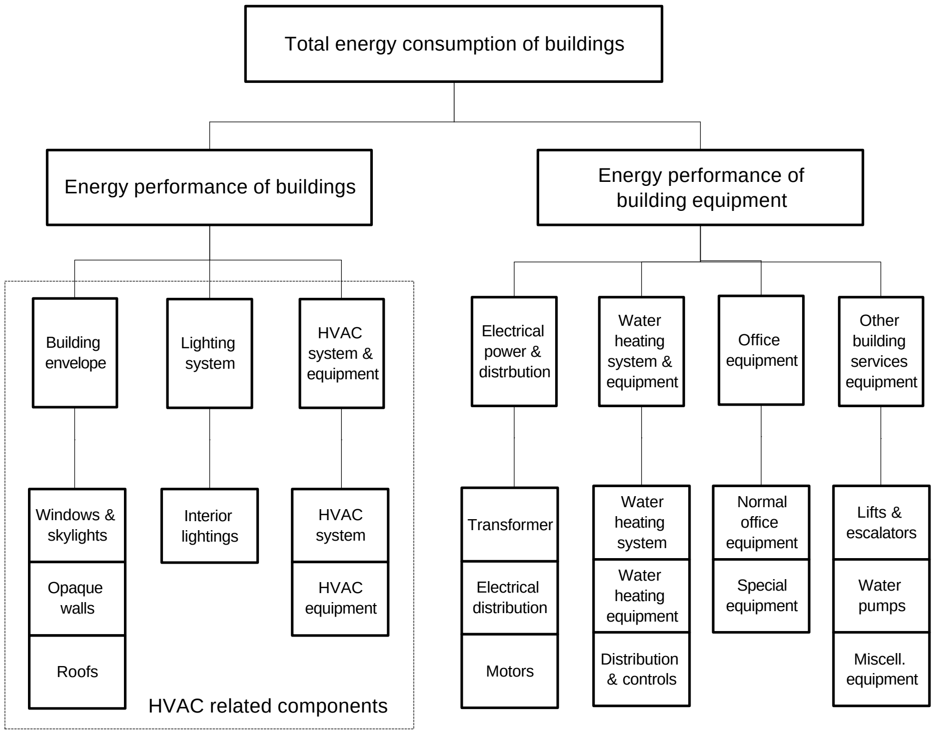

Figure 2.1 *Major Components of Building Energy Consumption*

The whole-building approach is a direct and effective method for analysing building design and can provide a simple measure for building performance that facilitates comparisons of buildings in the same way as appliances and motor vehicles. Under this concept, all aspects of energy use within the building are treated in an integrated, olistic' manner to allow maximum design flexibility. However, because of the great variety of building types and designs, it is difficult to provide a common base for the assessment of energy performance for all kinds of buildings.

Measuring index

In order to measure the energy performance of buildings (or their components) on a uniform base, performance indicators, such as the energy utilisation index (EUI), are often used (Schipper, 1983; Monts and Blissett, 1982; Turiel, *et al.*, 1987; Loh, 1988; Piette, Wall and Gardiner, 1986) [*]. The most common practice is to use a determinant which is in some way related to the facilities provided by the building. For example, the overall energy performance of a building is usually indicated by the annual building energy consumption per gross floor area (GFA), expressed in $kWh/m^2/annum$ [†]. Someone may argue that the use of GFA may be misleading if some buildings contain a lot of non-air-conditioned areas and have very different functions and hours of operation. Therefore, it has also been suggested that the performance index might be expressed in consumption per air-conditioned area, per hour of operation, per defined function and per defined functional activity within the facility (Patterson, 1980; EIA, 1994b; Field, 1992; Spielvogel, Orlando and Hayes, 1978).

At present, not many bodies collect and establish energy consumption data for buildings systematically. Examples of some useful data sources are EIA (1992b) in USA, BOMA (1994 & 1986) in Australia, CIBSE (1977), RICS (1993) and Moss (1994) in UK, and Nakahara, *et al.* (1984) in Japan. However, the information and data are often expressed in incompatible ways and may not contain all the necessary details for in-depth analysis. To avoid mis-interpretations, comparison of energy performance data should consider carefully the data source, background assumptions and wide range of building behaviours. Spielvogel (1980 & 1982) found that even for identical buildings with identical HVAC equipment and hours of operation, the actual energy use can vary widely. A survey by Matthysen (1986) has indicated wide variations in the specific energy consumption of buildings of the same

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[*] Energy utilisation index (EUI) are sometimes called energy intensity, energy use intensity, energy use index or energy target in some literature. Unlike a measure of 'energy efficiency', intensity does not take into account quality improvements, such as brighter lighting or increased use of equipment.

[†] The unit '$kWh/m^2/annum$' is used throughout this thesis for the sake of consistency, and the magic figures for converting the various units are as follows:

1 $MJ/m^2/annum$	=	0.278 $kWh/m^2/annum$
1 $MJ/ft^2/annum$	=	2.989 $kWh/m^2/annum$
1 $kWh/ft^2/annum$	=	10.76 $kWh/m^2/annum$
1 $Btu/ft^2/annum$	=	0.00315 $kWh/m^2/annum$

type. Unlike products from an industrial process, every building is an individual and the approach of comparing ike-with-like’ is not so often taken with buildings. Analysis of the behaviour of buildings is essential for comparing and understanding building performance.

Energy, thermal and environmental performances

Not only the measuring basis is diverse, there is also a variety of ways taken in the world to study the energy aspects of building performance. The three terms nergy performance’, hermal performance’ and nvironmental performance’ have been commonly used in literature to describe the thermo-physical behaviour of a building (or its components and systems). These terms are sometimes used interchangeably and are difficult to be distinguished from each other. In general, thermal performance focuses on thermal loads (cooling and heating) and projects the energy used by equipment to meet these loads (Van Straaten, 1967); energy performance concentrates on energy end-uses of the building and its energy-consuming equipment; environmental performance, which has more general objectives, is concerned with all indoor environmental factors including thermal comfort, lighting, air movement and acoustic (Irving, 1989; Jackman, 1987).

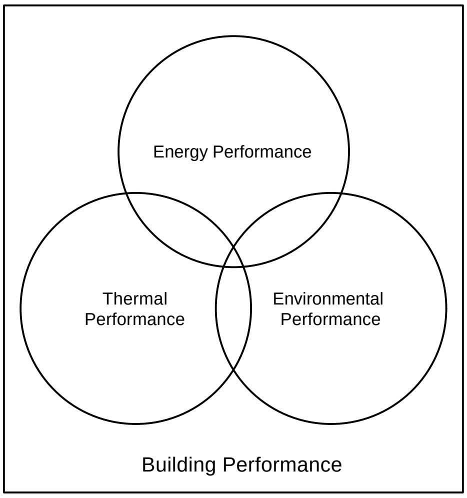

Figure 2.2 *Energy, Thermal and Environmental Performances of Buildings*

Figure 2.2 briefly shows the concept of these three kinds of building performances. It is believed that there are overlappings between them; the precise meaning and implication will depend on the context of the respective study. Although the terminology in different bodies and different places may vary, many of the research studies basically have the overall goals aiming at improving the energy efficiency of buildings. A short review of the major concern and research efforts is provided in the next section.

2.1.2 Worldwide concern

The quest for higher building energy efficiency in the world has encouraged much critical focuses on the intimate relationship between design variables and energy performance.

Importance of energy performance assessment

Assessment of building energy performance is fundamental in making decisions regarding energy-efficient design of buildings and in quantifying the impact of energy conservation measures. In new building design, energy analysis help determine the appropriate type and size of building systems and components; it can also explore the effects of design tradeoffs, evaluate the benefits of innovative control strategies and study the efficiency of new equipment and design options. For existing buildings, study of energy performance is an essential task in energy audits and surveys (CIBSE, 1991; Chan, 1994; RICS, 1993) which aim at optimising the building operation.

At the community level, the relative efficiency of building groups and the building stock can be studied by analysing the performance of prototypical models (Huang, *et al.*, 1991; Crawley and Schliesing, 1992). Evaluation of energy characteristics of buildings also serve as a critical base for developing building energy standards and assessing their effectiveness (Dubin and Long, 1978; Deringer and Busch, 1992; Hadley and Halverson, 1993; Chou and Lee, 1989; Janda and Busch, 1994). As building design involves a range of multi-disciplinary input (such as architecture and building services), efforts have been made in different fields to study and improve building energy performance from different perspectives.

Multi-disciplinary discussions

Energy efficiency in buildings is a major concern in the architectural and scientific fields (AJ, 1993; Rosenfeld and Hafemeister, 1988; Roaf and Hancock, 1992). Analysis of building energy performance is also a hot debate issue in the HVAC and building services disciplines. A round-table discussion by ASHRAE has concluded that development of appropriate energy analysis tools is a critical component of energy-efficient design (ASHRAE, 1981g); discussion by CIBSE has suggested that dynamic simulation of energy use can offer good potentials as well as frustrations to designers (Bowman and Lomas, 1986; CIBSE, 1986b; Clarke, 1986; Holmes, 1986) [*]. With growing demands for building energy simulation, some cooperative bodies have been formed to promote research and development in this field across the world, such as the International Building Performance Simulation Association (IBPSA) (IBPSA, 1993) and the Building Environmental Performance Analysis Club (BEPAC) (Irving, 1989).

It is generally believed that computer simulation is a powerful and flexible energy analysis tool for buildings. Special issues of professional journals have been published to highlight the state of the affairs, such as *Energy & Buildings*, Vol. 10, 1988 (various papers), *Building & Environment*, Vol. 28, No. 3, 1993 (various papers) and *Computer-aided Design*, Vol. 14 No. 1, January 1982 (various papers). Major research activities were carried out in the developed countries in Europe and North America (Seth, 1989a), but there are very little information available for the developing countries. A list of the major professional institutions and energy research on building energy performance are given in Appendix I. It is hoped that the list can provide a useful resource guide for locating the latest technology and understanding the current development in the world. By reviewing the major research projects

[*] ASHRAE is the American Society of Heating, Refrigerating and Air-Conditioning Engineers and CIBSE is the Chartered Institution of Building Services Engineer.

on the list, it is found that integration of energy performance analysis into the building design process is a key development area nowadays. Ideally, energy analysis should be carried out at the design stage, during construction, and throughout the life of a building so that the performance can be monitored and improvements can be made, if required.

2.2 Energy Analysis and Building Design

The building design process is described and the major impediments to energy analysis in the process are explained.

2.2.1 Building design process

Mayer, *et al.* (1991) pointed out that energy-efficient buildings are the result of not only a responsible attitude toward energy but also how successfully the designer is able to apply energy technology and energy analysis tools during the design process. Building design is a creative process based on iteration: one begins by responding to a situation with an abstract idea, then objectifies it by proposing a trial design, evaluates it, redesigns it, develops it, re-evaluates it, and so on (Brown, 1990). Lorsch (1993) explained that design consists of a continuous back-and-forth process as the designer selects from the universe of available components and control options to synthesize the optimum solution within the given constraints. It is essential to understand the relationship between design and performance variables in the context of practical design development. Figure 2.3 shows the applications of energy analysis at various phases of the building design process, including feasibility, pre-design, detail design, completion, commissioning and operation.

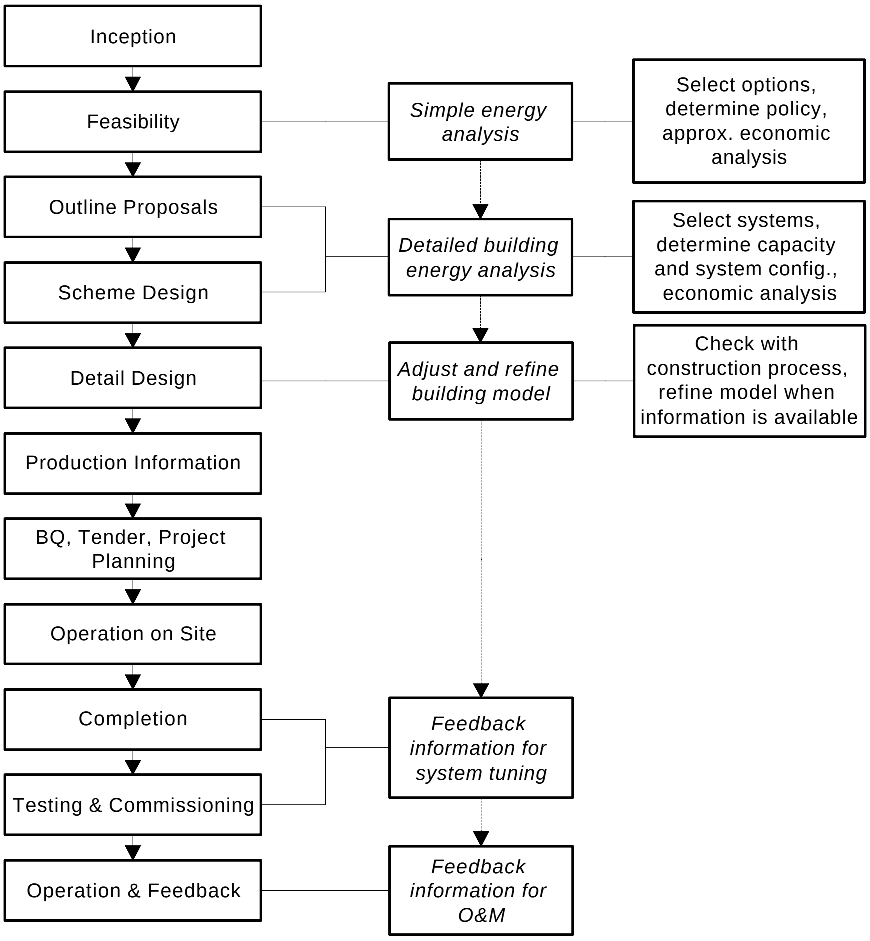

Figure 2.3 *Energy Analysis in the Building Design Process*

At early design stage, energy analysis is based on conceptual sketches and schematics (often rough and incomplete). As the design proceeds, detail models and refining of current models will be done. For completed or existing buildings, a model for the building will be developed and then fine-tuned or calibrated with measured data; once a calibrated model is made, any energy saving option can be run through computer simulation to determine the impacts. Nall and Crawley (1983) has proposed building energy analysis to be started earlier in the generative design phases so that building form and design strategies can be integrated into considerations. It is believed that the best opportunities for improving a building energy performance occur early in the design process (Goulder, Lewis and Steemers, 1992, Chp. 1).

Information required and major tasks

Mayer, *et al.* (1991) found that the common information required by energy advisor include building envelope design, HVAC equipment selection, lighting systems, building operating costs, energy targets, climatic data, energy standards and local codes. Major design tasks that affect building energy consumption are (NSW Public Works, 1993):

- Selection of materials for and design of the building itself (architecturally).
- Air conditioning zoning, load estimation and plant sizing.
- Air handling and primary plant system selection and controls.
- Equipment selection (full and part-load performance and plant loading).
- Piping system design (pump energy).
- Air distribution system design (fan energy).
- Solar water heating systems (if any).
- Lighting design.

2.2.2 Major impediments

In practical situation, energy analysis is not easy within the building design process. The important characteristics of building design which hinder the analysis of energy performance are:

- *Multiple goals* – Besides energy efficiency, building designers must also consider other constraints and performance criteria, such as costs, building codes, availability of equipment and visual quality. Hitchcock (1991) explained that the presence of multiple goals, some of which may be conflicting, preclude the use of an algorithmic problem-solving approach. Impacts of various subsystems must be understood and a successful integration of various building systems (such as structural, interior and building services) is the key for achieving a total building performance (Hartkopf, *et al.*, 1993).

- *Vaguely defined criteria and procedures* – Building design is an amorphous process which is poorly defined (Nall and Crawley, 1983). Design criteria and procedures are in an ill-structured fashion and vaguely specified (Hitchcock, 1991; Papamichael and Selkowitz, 1990). The design problem itself may have some missing parameters and a lot of possible answers.

- *Reliance on designer knowledge and experience* – The design process is heuristic and relies heavily on the designer knowledge and experience. The building performance and its assessment will depend on the designer ability to master the design and analysis skills.

- *Full of assumptions* – A lot of assumptions and conjectures must be made to generate potential design solutions before these solutions can be evaluated. Simplifications and approximations are unavoidable in representing the complex behaviour of a building (Mitalas, 1965) and designers have to make many decisions on how to approximate the real-world problem to fit the limitations of the design model (Bland, 1992).

- *Incomplete information* – The search for design solutions often takes place with incomplete information. Accurate estimation with detailed input data is possible only after the building design is complete.

- *Influence of early design decisions* – Major decisions made in the early design stages are difficult to change at later stages. Holm (1993) has drawn an interesting analogy that by that time the building owner and/or the architect may have fallen in love with the design or even be married to it, in which case the cost of divorce will exceed the cost of hanging on.

- *Time constraint* – The design fees for the consultants' work seriously limits the amount of time that can be allocated to studies of alternative systems and thorough design optimisation (Lorsch, 1993). Clarke (1985, pp. 326) found that formulation of a design problem, in a manner conducive to simulation processing, is a skill often difficult to acquire in the hustle and bustle of professional life.

Lack of usable energy analysis tools

Hanby (1992) pointed out that research-oriented (simulation) programs have been around for a number of years but their development into usable tools has not paralleled the progression of building simulation models. Since building energy analysis is a complex process involving much technical skills, an effective mechanism is needed to transfer the energy technology and knowledge into practical use by the design offices. The large gap between what is available on the market and what is actually used and comprehended by the design professionals suggests that implementation, rather than just technical advancement, is key to increasing energy efficiency (U.S. Congress, Office of Technology Assessment, 1992). It is important to consider energy performance as an integral part of the design process and to facilitate the process of transferring application know-how into practice. With the development of computer-aided design, building energy simulation and analysis will be one component in an integrated building design methodology (Augenbroe and Winkelmann, 1991). To ensure successful implementation, designers must understand clearly the concepts of load and energy calculation which form the basis of energy performance analysis.

2.3 Concepts of Load and Energy Calculations

Essential concepts of load and energy calculations which affect the analysis of building energy performance are explained.

2.3.1 Load calculations

Traditional HVAC system design focuses on load calculation which aims at finding the maximum values of building loads at the peak time of day. Under standard HVAC design calculations, maximum cooling and heating loads are computed based on selected indoor and outdoor design conditions (Wang, 1993, Chp. 7). The likely peak load is estimated so that the correct size of equipment can be selected (Stephenson, 1968; Bloom, 1993). The load calculation methods developed by ASHRAE (ASHRAE, 1993, Chp. 25 & 26; McQuiston and Spitler, 1992), Carrier (Carrier Air Conditioning Company, 1965, Chp. 1 - 7) and CIBSE (CIBSE, 1986a, Section A9) are most widely adopted in the HVAC industry.

The concept of load calculation is not an issue of right or wrong and the calculated results must be kept in perspective. Because of the many assumptions and simplifications that must be made in the process, load calculation can never be more than a good estimate of the actual cooling load (ASHRAE, 1993, Chp. 26). Romine (1992) explained that the overall process is at least as much rt' as it is science and the implementation of that art is where the load calculation procedure comes in. Whatever method is used to estimate a cooling load must enable the engineer to respond appropriately to recognised realities of building construction and circumstance. This is an important property inherent in building energy performance analysis.

Load calculation methods evolve

Evolution of load calculation method is closely linked with the use of digital computer (Stephenson, 1968). Until the 1960 , all HVAC calculations were performed manually; nowadays, the availability of low-cost micro-computers has significantly changed the way in which practising engineers design HVAC systems (Lorsch, 1993). Although the process of load calculation is gradually enhanced and is getting more and more complicated, the fundamental principles have not been changed very much. For example, the thermal response factor method which was developed in the 1960 by Stephenson and Mitalas is still commonly used to determine building thermal responses (Stephenson and Mitalas, 1967; Mitalas and Stephenson, 1967; Stephenson and Mitalas, 1971; Mitalas, 1972). In the past decades, much of the research efforts in load calculation has been directed towards computer implementation and software enhancements; little is towards more fundamental changes in the calculation method (Ayres and Stamper, 1995).

It is essential that the development of load calculation method should match with the available computational power at that time. In the past, load calculations for a small simple system may require only the peak time of day, but now several different times of day and several different months must be analysed to determine the time of peak load. There is a tendency that the load calculation process will gradually overlaps with the energy calculation procedure. The former will include some energy estimates to establish system performance while the later will incorporate design load procedure as one of its integral parts (NSW Public Works, 1993).

2.3.2 Energy calculations

Energy calculation is performed to estimate the energy consumption and characteristics of buildings under actual weather conditions. A significant part of energy analysis is built upon the load calculation concept and methodology, therefore, load and energy calculation requires similar information and technique. Although the procedure for estimating energy use vary considerably by methodology and sophistication, the approach to calculate building energy requirements will include three basic steps (ASHRAE, 1976):

- Calculate heat gain or heat loss to the space.

- Determine the cooling and heating loads imposed on the system.
- Calculate the energy input to the system components to satisfy these loads.

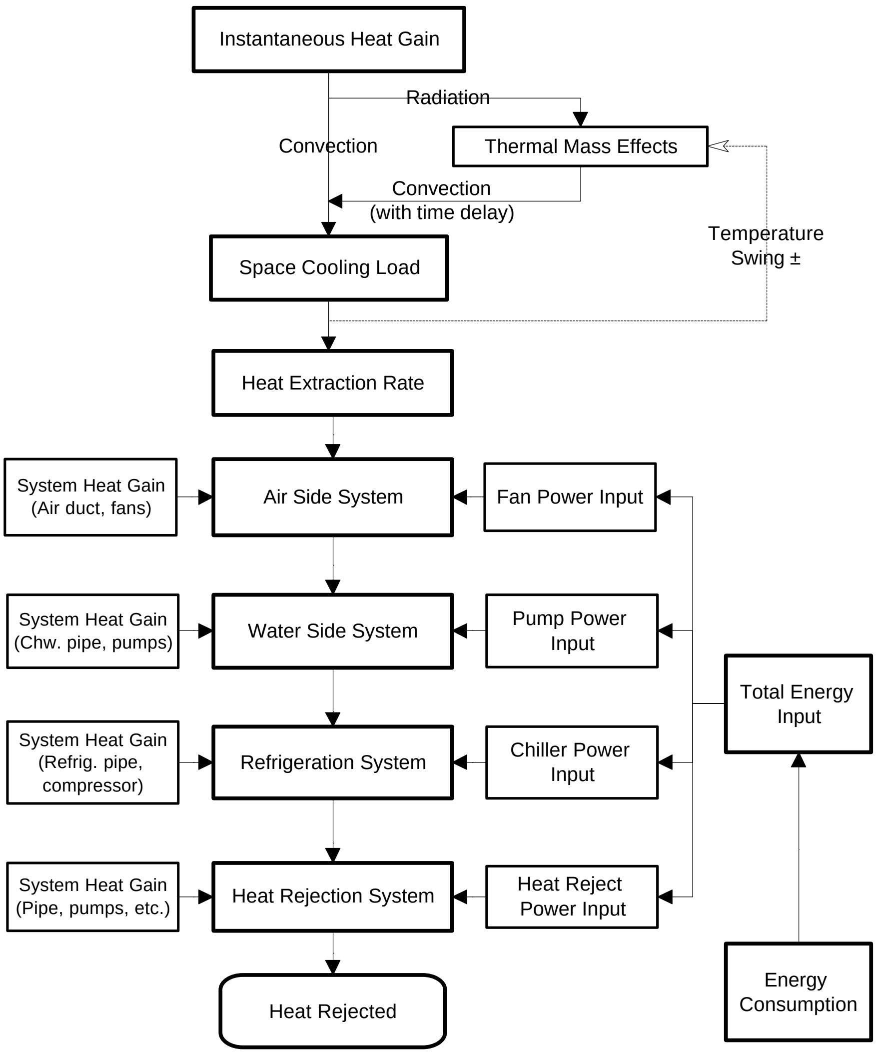

Figure 2.4 *Cooling System Architecture and Energy Flow Paths*

It appears that an essentially linear relationship exists between annual space load and annual energy use, although the translation from space load to energy use are affected by control strategies and HVAC system performance (Bloom, 1993). Figure 2.4 shows the general architecture and principal energy flow path in a cooling system. This block diagram combines the ASHRAE load concept (ASHRAE, 1993, pp. 26.2) and the idea suggested by Yip and Hui (1991), so as to explain the full picture of load and energy relationship.

In moving from load calculation to energy calculation there are four important differences in the approach. First, (design) load calculation is based on severe weather conditions whereas energy calculation consider typical weather conditions. Second, the effects of HVAC system performance and control strategies are not fully addressed in load determination. Third, heat transfer between spaces that are conditioned to the same temperature is of no consequence in load calculation, but not energy calculation. Fourth, peak values of internal loads (occupancy, lighting and equipment) are important in load calculation, but the actual load profiles are more useful in energy analysis.

Methods for estimating building energy requirements

Depending on the application and the level of detail required, different methods can be used to estimate building energy requirements. In general, the methods can be divided into three categories (ASHRAE, 1993 & 1989a; Meier, Busch and Conner, 1988; Rabl, 1988; Winkelmann, 1988):

- *Steady-state methods* – They include degree-day method, variable-base degree-day method, bin method and modified bin method *. Based on steady-state assumptions and correlation, these methods only require simple inputs, but their accuracy and capability are also limited.

- *Dynamic methods* – They estimate and analyse the building energy consumption by modelling the dynamic behaviour of buildings. The most popular one is generally known as building energy simulation which

* *'Degree-day'* method is based on statistic of outdoor temperatures above and below a balance point temperature (such as cooling/heating degree-days); *'variable-base degree-day'* method is a generalised degree-day method using variable reference temperature; *'bin'* method is a simplified multiple-measure method involving instantaneous energy calculations at several different outdoor dry-bulb temperatures weighted by the number of hours of temperature occurrence within each temperature interval (bin) centred around that temperature; *'modified bin'* method is an improved version of the basic bin method, with various refinements to cater for seasonal variation of solar gains and diversified off-peak loads (ASHRAE, 1983; Sud and Kusuda, 1982).

models building energy performance over the time domain. A set of acro-dynamic' methods and ybrid' methods are now being developed, but not yet fully implemented (Rabl, 1988).

- *Measurement-based methods* – These methods focus on the actual building operation and behaviour rather than on a prediction based on physical properties and performance specifications (Meier, Busch and Conner, 1988). Short-term measured data are used to predict energy performance for average conditions using statistical analysis, such as PRISM (Fels, 1986) and the weather normalisation technique of Rabl and Rialhe (1992).

Energy analysis using simulation methods

Computer building energy simulation is the most popular and flexible nowadays for building energy analysis. Figure 2.5 gives a general picture of the major elements of building energy simulation (Clarke, 1982; Clarke and Irving, 1988).

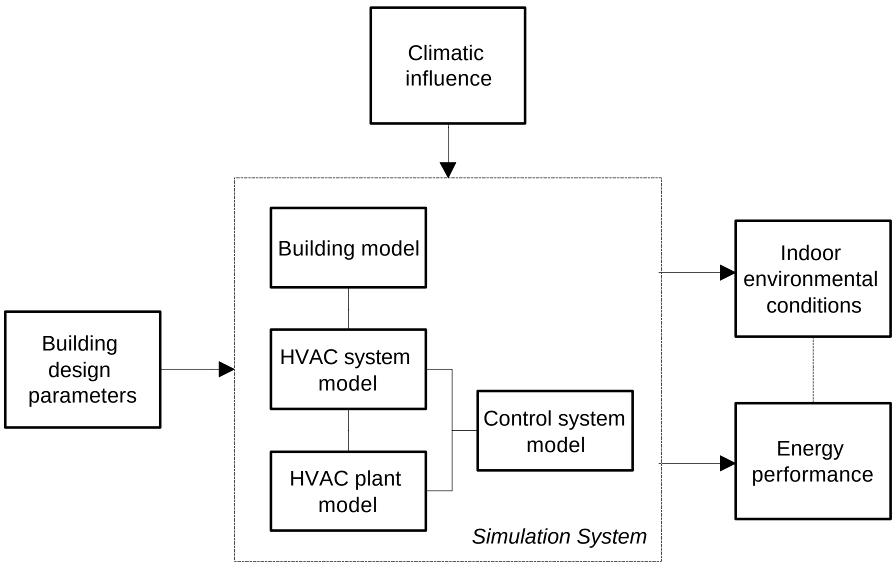

Figure 2.5 *Major Elements of Building Energy Simulation*

Building design parameters are the input; indoor environmental conditions and energy performance are the output. The climate is the boundary condition of the simulation system and forms the basic driving potential for the variation of building loads. Building simulation allows us to see the effects of all kinds of changes in a fraction of the time it takes to study the same alternative in realities and at a much smaller cost (International Energy Agency, 1990). Computer simulation programs and methods required to carry out building energy simulation are described in the next section.

2.4 Building Energy Simulation

Computer simulation tools for building energy analysis are reviewed and the key factors surrounding building energy simulation are explained. Climatic data for load calculation and building energy simulation are described; the implications of simulation methods to building energy standards are pinpointed.

2.4.1 Simulation tools

Computer programs designed for energy modelling and analysis of buildings are generally known as uilding energy simulation programs’. These programs are intended for modelling of large, multizone building and their HVAC systems (ASHRAE, 1993, Chp. 28). The interactions in buildings are by their nature very complex. While some simplified design tools and guidelines exist to help designers understand the phenomena involved, more elaborate, often computer-based tools are required for detailed analysis.

Existing programs

Most of the building energy analysis programs are developed in USA and Europe; directories and lists of energy analysis software have been published to show people what is available on the market, such as AEE (1991), ASHRAE (1991d), Williams (1992), Degelman (1987) and Weiss and Brown (1989). There are more than 200 programs in USA and 100 programs in Europe and elsewhere (Seth, 1989b), but only a handful of them are frequently used by building designers (Bloomfield, 1989b; BEDTDC, 1988). Table 2.1 gives a list of the programs commonly used nowadays. A list of the programs common in Europe can also be found in Goulder, Lewis and Steemers (1992, pp. 251-254).

Table 2.1 List of Common Building Energy Simulation Programs

Program	Reference source(s)	Country	Remarks [1]
APEC ESP-II	(Wickham, 1985)	USA	D
ASEAM2.1	(Ohadi, Meyer, and Pollington, 1989)	USA	S
BESA	(BESA, 1993)	Canada	D
BLAST	(BLAST, 1991)	USA	D, P
BUNYIP	(Moller and Wooldridge, 1985)	Australia	B
Carrier HAP	(Carrier Corporation, 1990) [2]	USA	S, Com
DOE-2	(Birdsall, *et al.*, 1990; LBL, 1981)	USA	D, P
ESP-r	(Clarke, 1993)	UK	D
HVACSIM+	(Clark, 1985)	USA	D, P
TRACE 600	(Trane Company, 1992a & b)	USA	S, Com
TRNSYS	(TRNSYS, 1988)	USA	D

Notes: 1. Abbreviations used in the remarks are: D = detailed program (8,760 full hourly); S = simplified program (one-day per month or others); B = program using bin weather data; Com = commercialised, proprietary program; P = public domain program or source code available for inspection.

2. The latest version of Carrier HAP program is a fully 8,760 hourly program.

These packages have different levels of detail and input requirements; they may come from research institutions, equipment manufacturers or private consulting firms; some of them are public domain programs and some are proprietary programs. Procedures established from recognised professional bodies are often used in their algorithms, such as G. K. Yuill and Associates Ltd. (1990), ASHRAE (1976), ASHRAE (1975b) and Petherbridge (1985) [*]. Apart from energy analysis, many of them also allow for standard HVAC design load calculations. It is believed that each program has its own

[*] The algorithms developed by ASHRAE are the most widely adopted. ASHRAE Task Group on Energy Requirements (TGER), later renamed as ASHRAE Technical Committee

areas of application and it is difficult to determine which one is the best for a specific job. Generally, the detailed simulation programs (such as BLAST (BLAST, 1991), DOE-2 (LBL, 1981) and ESP-r (Clarke, 1993)), which perform calculations for every hour of a year (8,760 hours), are considered more accurate and capable than those programs using simplified procedures. But a lot more input efforts are usually required by the detailed programs.

Development trends

Building energy analysis programs have undergone a slow evolution since arrival over a decade ago (Beranek and Lawrie, 1989). The simulation techniques are rapidly changing with decreasing cost and increasing flexibility of computer systems. In the 1970 , the cost of conducting an energy analysis was high (Rubin, 1973); most energy programs in those days were developed on mini- or mainframe computers and so, due to the cost of these machines, were inaccessible to the vast majority of potential users (Mac Randal, 1988). In the 1980 and 1990 , profligate of microcomputers and emerging of microcomputer versions of the simulation programs makes it more affordable and accessible to carry out detailed energy studies. Like human beings, simulation tools are born, grow, evolve and die. Many of the current simulation programs are succeeding generations of some previous ones. Experience suggests that only a few of the many models will survive over time; some will fall into disuse, some will be replaced by new generations (Radford, 1993). Care must be taken to keep abreast of the latest development and updates of the programs.

In other engineering disciplines, such as civil and structural, simulation tools have been used extensively and routinely for design. But in the building industry, designers are often reluctant to use simulation tools. In Hong Kong, the simplified and commercialised packages, such as Carrier HAP (Carrier Corporation, 1990) and TRACE 600 (Trane Company, 1992a & b), have now been gradually accepted in design offices, but the detailed simulation

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TC 4.7, Energy Calculations, is responsible for the development of the ASHRAE procedure for computerised energy calculations.

programs are very seldom used. The variety and diversity of simulation tools give rise to a practical need for evaluating the applicability and credibility of the existing programs.

Evaluation and validation of tools

In the past decade, some research efforts have been made to evaluate and validate the building energy simulation and design tools. The major evaluation and validation studies are listed in Table 2.2. Although these studies have not characterised and verified every program, useful information and experience have been generated to help understand the properties and limitations of the existing tools. The major findings of these studies are briefly outlined in the following paragraphs.

Table 2.2 Evaluation and Validation Studies of Building Energy Simulation and Design Tools

Program evaluation studies:

- *valuation Procedure for Building Energy Performance Prediction Tools*' by Building Energy Design Tool Development Council (BEDTDC, 1988).
- *esign Tool Evaluation*' by Task VIII Passive and Hybrid Solar Low Energy Buildings of the IEA Solar Heating and Cooling Programme (Bloomfield, 1989b; Holtz and Wortman, 1989).
- *valuation of Software*' and *nergy Edge*' projects by Bonneville Power Administration (Gale C. Corson Engineering, 1990; Kaplan and Caner, 1992; BPA, 1993; Diamond, *et al.*, 1992).

Model validation studies:

- *SERI* – Solar Energy Research Institute (Judkoff, 1988; Judkoff, Wortman and Burch, 1982; Wortman, O oherty and Judkoff, 1981) [1].
- *BRE/SERC* – Building Research Establishment and the Science & Engineering Research Council (BRE and SERC, 1988; Bloomfield, 1985; Bowman and Lomas, 1985; Irving, 1988 & 1982; Lomas, 1991).
- *Model Validation Sub-group* of the PASSYS project (Jensen, 1993b).

Notes: 1. The Solar Energy Research Institute (SERI) has been renamed as the National Renewable Energy Laboratory (NREL) in 1991.

It has been found in the evaluation studies that little work has been done to determine the best applications and limitations of existing programs.

BEDTDC (1988) has suggested that tools should be placed in specific classifications so that their uses can be better understood and appropriate tools for the job more easily selected. Instead of using the detailed programs directly to assess and predict building performance, most people use them to perform parametric sensitivity studies to generate simple guidelines and design information (Bloomfield, 1989b). To guard against modelling errors, quality control for simulation analysis is important (Kaplan and Caner, 1992); benchmark test and empirical validation are useful quality assurance procedure to ensure reliability (Bloomfield, 1989a & b).

However, most of the results from past validation research were inconclusive (Bloomfield, 1989a). Detailed simulation programs, though powerful and sophisticated, are very seldom used effectively by practising building designers. Generally, people are confused and uncertain about the simulation results since the discrepancies between the actual and predicted energy consumption, and between the predictions from different programs, are found very large in validation studies. Clarke (1985, pp. 318-319) pointed out that model validation is fraught with difficulties, due to the lack of comprehensive data relating to the performance of real buildings and the shortcomings inherent in even the most sophisticated technique. Many uncertainties about the building, the climatic data, occupants' behaviour, measurement accuracy, etc. often existed and no sound statistical basis had been used to interpret the results (Bloomfield, 1989a).

It is understandable that designers are now not confident in detailed simulation since almost all the existing detailed simulation tools are hard to use and will certainly contain some errors, approximations and shortcomings. Wright, Bloomfield and Wiltshire (1992) found that current building simulation programs fail to offer adequate facilities for user needs, and have structures which are too inflexible for continued development and modification. Seth (1989a) commented that those programs available today are far from ideal. The problems of current tools stem from a number of factors which will be described in the next section.

2.4.2 Key factors

Simulation models when used as design tools suffer from several fundamental limitations as they fail to tackle the problematic issues surrounding data preparation in the face of uncertainty in the design environment (Clarke, Rutherford and Mac Randal, 1989). The author believes that there are four key factors creating the limitations: complexity, accuracy, validity and human factors.

Complexity

For a long time, the complexity of energy analysis programs has discouraged their use in the average engineering office (Ayres, 1977). Spielvogel (1977) found that a large amount of detail is required for input and frequently it takes so much time and effort to become familiar and competent with just one program. Newton, James and Bartholomew (1988) discovered that current models and analysis methods demanded a lot from their users and the naive user was as likely to be mislead as helped. Nall and Crawley (1983) pointed out that many designers do not understand exactly what kind of information is required and provided by building energy analysis tools. The inherent complexity of the simulation model often distances the user from a clear appreciation of the underlying physical processes. As analysts become overwhelmed by specific aspects, they tend to lose sight of the overall objective and interrelationships within the procedure. Seth (1989a) found that it becomes increasingly difficult to keep track of the intentions of the internal assumptions in the computer codes and to interpret the results. Because of the complex and lengthy computational procedures, step-by-step verification of simulation results is generally impractical.

Accuracy

A controversial issue with simulation is whether the program is capable of delivering ccurate’ results (CIBSE, 1995). Wright, Bloomfield and Wiltshire (1992) pointed out that program accuracy has to be taken on trust. Spielvogel (1978) found that results of different simulation programs may range from very good agreement to no agreement at all; the degree of agreement depends on the interpretations made by the user and the ability of the programs to handle the building in question. A large number of uncontrolled and unknown factors generally preclude the use of simulation methods for predicting the absolute energy consumption (ASHRAE, 1993, Chp. 28); results within 10% to 20% are generally considered easonable' (Kaplan and Caner, 1992). Although some promising, innovative prediction methods have recently emerged, such as the methods in the ASHRAE reat Energy Predictor Shootout' (Kreider and Haberl, 1994a & b), the aspirations still remain ahead of the present systems to deliver.

Clarke (1985) found that it is impossible to establish *a priori* the optimum level of model accuracy and flexibility in the field of energy systems appraisal, and the trade-off between accuracy and flexibility is itself a dynamic concept which will vary according to the modelling and design objectives. Indeed, the accuracy level changes as a function of the quality of design information supplied (see also Section 2.2.2) and it is also influenced by the selection of the model and input data. If the accuracy of input data is inferior to the quality of the simulation model, then improving the model alone will not reduce the uncertainties in the respective output. Experience from practitioners reveals that program users should either abandon the technology or learn to work within their limitations (CIBSE, 1995).

A matter of validation

In many fields (such as economic forecasting), models are openly accepted as approximations of reality which cannot be subjected to rigorous scientific validation. If they consistently produce results which are meaningful and useful, and whose interpretation is vindicated by the resultant designs, then whether or not they have been subject to technical validation may be irrelevant (Wiltshire and Wright, 1988). Bloomfield (1989a) found that it is not feasible to verify the correctness of every path through detailed simulation programs, to investigate every assumption and approximation, or to take account of every situation in which a program may be used in practice. Judkoff (1988) and Neelamkavil (1987, Chp. 4) also pointed out that an absolute validation of simulation programs could be approached but never achieved.

In building energy simulation, the meanings of program validation and verification must be seen in context [*]. The validation process can ensure the fidelity of the modelling techniques, establish the input data and justify the assumptions that are inherent in any modelling process. Diamond and Hunn (1981) found that the primary purpose of verifying the simulation program is to give users confidence that the program can accurately predict the energy consumption and thermal behaviour of building designs. A systematic approach to validation methodology has been proposed by Judkoff (1988) and it comprises four main components:

- *Initial examination.* Review of a model theory and a thorough inspection of the program source code are performed.
- *Analytical verification.* It involves comparison of predictions with analytical solutions which apply to some well-defined, usually simplified case.
- *Inter-model comparison.* It involves comparison of the target model with several other models which are usually better known to the validators or may have been subjected to a greater degree of previous testing.
- *Empirical validation.* It involves comparison of predictions with measured data for the same problem.

It appears that no definite solution can yet be drawn on model validation. Program users must rely on the documentation and verification provided by the program developers or large independent bodies, since they do not have enough resources to carry out extensive validations (Richter, 1984). Even if the program is regarded as erified’ at some acceptable level, questions may still arise concerning the validity of results obtained by

[*] ‘Validation’ is concerned with demonstrating that the model is an adequate representation of reality whereas ‘verification’ involves checking the design consistency (accuracy and correctness of modelling and solution methodologies, algorithms, computer programs, etc.) (Matko, Zupancic and Karba, 1992).

users who are not familiar with the limitations of the program. The program user often plays an important part in affecting the quality and adequacy of the results produced from the simulation model.

Importance of human factors

Feinberg (1974) found that the computer will not replace the engineer in his role as designer of HVAC systems. Human judgement and experience is still the critical factor in simulation problems which involve both analysis and intuition in an iterative process (see Section 6.1.1). Hitchcock (1991) pointed out that design tools simply provided information that would help designer make decisions. How the information are put together to analyse the energy consumption of a building and its services is the duty and responsibility of the building designer (NSW Public Works, 1993). Results for the same problem are a function of both the program and the user. A critical mind (human beings) is needed to carry out the analysis, interpret the results and determine the consequences. It must be recognised that software knows no context. To conduct the analysis effectively, the aims of the study and the intended use of the tool must be considered carefully.

The level of technical knowledge needed to correctly use the existing tools are usually high so that mis-applications and mis-interpretations are not uncommon in building energy studies. It is generally agreed that a fully integrated design and analysis tool is needed to enhance energy modelling techniques (Mathews and Richards, 1993; Rousseau and Mathews, 1993; Morel and Faist, 1993). An effective building design tool should be powerful, flexible and comprehensive, yet simple, straightforward and intuitive to facilitate user interaction at various building design stages.

User interface is usually the weakest part of a detailed simulation program. There are now many opportunities for an unwary user to make significant errors in performing the simulation. Clarke (1993) found that the application of simulation is problematic because of technological shortcomings in the applications, especially at their interface, and because of the absence of any standards for problem definition, appraisal and evolution. Hanby (1987) believed that the challenge here is not only to improve the technical capabilities of system simulation but also to explore the problems generated by the interface with the design process. To ameliorate the problem of building description, a general scheme for building representation has been proposed in Europe to facilitate better information exchange in building simulation (Wright, Bloomfield and Wilshire, 1992). As some ambitious projects are now being developed, such as COMBINE (Kennington and Monaghan, 1992), EKS-UK (Clarke and Mac Randal, 1993), AEDOT (Brambley and Bailey, 1991) and SPARK (Sowell, Buhl and Nataf, 1989), it is envisaged that integrated tools will arrive at the end of this century to facilitate detailed simulation in practical design (see also Appendix I).

2.4.3 Climatic data

No matter what methods and tools are used, climatic data are required for building thermal design and energy analysis. Every buildings must be designed and constructed with the local climate in mind. The basic climatic data required depend on the nature of the task and the method adopted. Four types of climatic data are often used:

- *Outdoor design conditions* – The outdoor design temperatures are the major element (ASHRAE, 1993, Chp. 24) (see Section 4.2).

- *Design data for climate assessment* – A variety of different climatic data may be used, such as frequency tables of temperatures (CIBS, 1984), bioclimatic charts (Givoni, 1976; Watson and Labs, 1983) and sunpath diagrams (Peacock, 1978).

- *Weather data for simplified energy calculations* – Depending on the method, different forms of weather data may be used, such as degree days and bin temperature data.

- *Weather files for energy simulation* – The weather files, usually span one year, contain 8,760 hours of weather data or a reduced set of them.

Climatic data for load calculation

The usual approach in HVAC system design involves computation of peak design load using indoor and outdoor design conditions (ASHRAE, 1993, Chp. 24). In the past, load calculations using manual methods required only simple outdoor design conditions since hourly load calculations were impracticable (Mason and Kingston, 1988). These conditions, expressed by design temperatures and key climatic data, are usually taken from design handbooks, such as Carrier Air Conditioning Company (1965, Chp. 2), ASHRAE (1993, Chp. 24) and CIBS (1984). Nowadays, computer programs are very often used for design load calculations. A load calculation program, either standing alone or as an integral part of an energy simulation package, requires more weather data than the manual process. Usually, load calculations are performed for some selected design days or one day in each calendar month. The design weather data needed are either supplied by the program user or obtained from the weather library.

Weather input for simulation

Building energy simulation is computationally more intensive than design load calculation. Generally, energy calculations are performed to estimate building energy consumption under average weather conditions. ypicalness' of the weather data is essential for energy calculation whereas everity' is the key for design load calculation. Although the weather methodology in different simulation programs may not be the same, a common approach is to employ two sets of weather data for load and energy calculations, namely, *esign weather'* and *ypical weather'*, respectively. Design weather represents the severe climatic conditions for sizing HVAC plant and equipment; typical weather, usually given for one year, represents the long-term weather conditions for estimating year-round and seasonal energy consumption. Figure 2.6 shows the relationship between design and typical weather in a simulation tool. If the design weather is not specified, the peak design loads and hence the equipment sizes may be determined automatically from the typical weather during the simulation. The purpose of setting up the two sets of weather data is to imitate the conventional design procedure where peak loads are determined from design conditions and year-round energy consumption is calculated from average conditions.

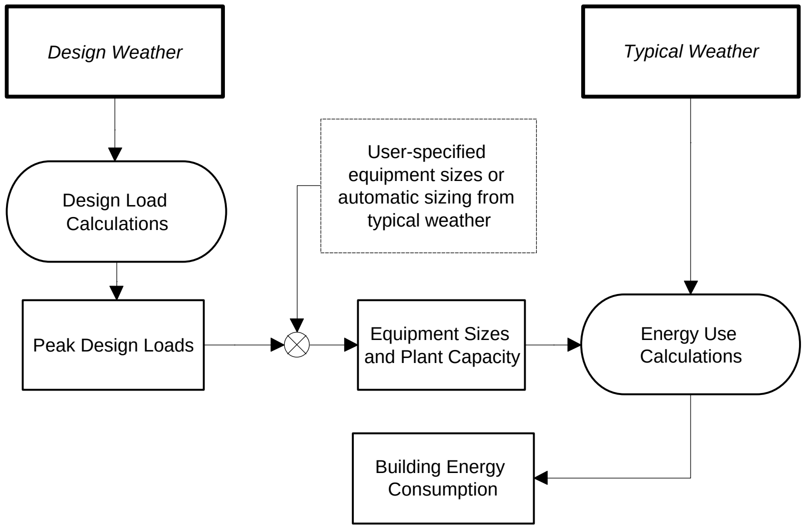

Figure 2.6 *Design and Typical Weather for Load and Energy Calculations*

If the simulation exercise is on a building with known equipment sizes (such as an existing building), then the typical weather may be the only weather input required. For most other cases involving a prospective building or proposed design features, the appropriate equipment sizes are determined using the design weather, and then the building will be submitted to year-round energy simulation using the typical weather. In simplified simulation programs, the two sets of data are similar in format. For example, design/peak weather and typical/average weather in TRACE 600 (Trane Company, 1992a, pp. 4-8) and Carrier HAP (Carrier Corporation, 1990) are both in the form of 12 months by 24 hours. In detailed simulation programs, such as DOE-2 (LBL, 1981, pp. III.25) and BLAST (BLAST, 1991, pp. 458-459), the design weather is specified in the form of esign days’ in which a 24-hour cycle of weather data is created by applying sinusoidal curve-fittings to the outdoor design conditions.

Design weather

Similar to how outdoor design conditions are applied to manual HVAC calculations, design weather is required for peak load calculations using simulation methods. However, the formulation of design weather in simulation are vague and has not been clearly defined, so that designers are often confused about its use and implications. Design days, represented by sets of daily weather profiles, are usually used by simulation programs but they are difficult to determine because:

- Design profiles for all weather variables are hard to define.
- Maxima and minima of different weather variables may occur in different time (such as air temperature and solar radiation).
- Coincident block load of a building may have different characteristics from the loads of individual spaces.

Kusuda and Achenbach (1966) found that there was no straightforward way to predict the daily cycle of psychrometric conditions for extreme weather periods. Knowledge of diurnal cycles of the weather variables is important for identifying suitable weather data for constructing design days. Currently, the design temperature profiles are usually established based on the following assumptions (Carrier Corporation, 1990):

- The profile has a sinusoidal shape and its period is 24 hours.
- The amplitude of the profile is the daily temperature range.
- The maximum temperature occurs at 3 pm and the minimum at 3 am.

Typical weather

To perform year-round energy calculations, the simulation tool requires a set of detailed climatic data. Typical weather data are often used for representing the average long-term climatic conditions. Although typical weather is to represent the average occurrence of weather conditions, it is not to say that a set of time-averaged weather data over the years will be appropriate. Variations of the weather parameters are wiped out during the averaging process; frequency distribution of such a moderate dataset is different from the long term. The system performance of the average dataset will very likely fall below the long-term average and the operation of many plant control actions will also be masked (Hanby and Round, 1992).

To provide a meaningful simulation boundary for long-term energy estimation, a set of typical year data selected from real weather data is often used. However, the definition and selection criteria of such a typical year are uncertain and it is difficult to establish a set of single-year weather data which encompasses the long-term aggregate effect of multi-year weather phenomena – both the extremes and the mean values. For many years there have been quite a number of studies and arguments in this area (Crow, 1981; Hitchin, *et al.*, 1983; Festa and Ratto, 1993). Yet, no consensus of opinions has been reached. Different methods for the selection of typical years have been used in different parts of the world. It is difficult to assess their effects on simulated building energy performance.

2.4.4 Implications for building energy standards

As mentioned before in Chapter 1, building energy standards are often the driving force for building energy performance study. Ayres (1977) has recognised that widespread use of computer for energy calculations is necessary for implementation of an energy conservation standard for building design. In the past two decades, building energy simulation tools have become more and more important for analysing and developing building energy standards (Deringer and Busch, 1992, Chp. 2). Since the process of energy standard development is complicated and often involves large-scale simulation studies, it is essential to develop better understanding and skills in building energy simulation. There is also a general trend that modern building energy standards will adopt a erformance-based’ approach which requires computer energy simulation to demonstrate compliance.

Simulation techniques for developing energy standards

Detailed simulation programs have been used extensively in the development and impact assessment of the building energy standards in USA (Hadley and Halverson, 1993; Callaway, Thurman and Shankle, 1991; Conner and Lucas, 1993) and many other countries, including Hong Kong (JRP, 1991), Singapore (Chou and Lee, 1988), Canada (D.B. Crawley Consulting, 1992) and Australia (SRC Australia Pty Ltd, 1993a). The most popular and well-known program is DOE-2 (LBL, 1981), which is considered as a benchmark reference in USA and the countries in Southeast Asia (Deringer and Busch, 1992; Levine, Busch and Deringer, 1989). Although the simulation tools are powerful, their use in developing countries, like Hong Kong, requires much care in preparing weather input, designing building models, performing parametric studies and analysing the simulation results. As the developing countries are not familiar with these simulation methods, efforts are required to implement effectively the simulation analyses and to ensure that the local context and situations are fully addressed and represented.

Performance-based building energy standards

Performance-based energy standards are energy codes that allow building designers maximum freedom for innovative design, since they only specify the maximum allowable energy consumption level of the whole building. In fact, the idea has been suggested early in 1979 in USA (USDOE, 1979) under a proposal known as uilding energy performance standards’ (BEPS). However, the BEPS plan in 1979 has met with mixed success because of the difficulty in determining accurately the energy performance of buildings and the likely high costs of computer analysis at that time. Baird, *et al.* (1984, pp. 51) found that until there are means for predicting performance and for checking that the required standard has been achieved and maintained, performance standards will be of little use.

After more than ten years time, people believe that the whole building performance approach can be realised with the proliferation of simulation tools (Briggs and Brambley, 1991; Crawley, 1988). It is generally agreed that performance-based approach using simulation methods is a flexible and effective method for modern building energy standards (Oleszkiewicz, 1993). The BEPS concept has been supplanted by a number of energy standard proposal in USA, such as USDOE (1987, 1989b & 1992) and ASHRAE (1989c). It is anticipated that simulation techniques will be extremely important for building energy standards. The more countries and people looking into performance-based energy standards, the more extensive will be the use of simulation tools. This will in turn accelerate the development of building energy performance analysis, stretching the limits of our technical knowledge. The development and characteristics of building energy standards in the world and in Hong Kong will be explained in the next chapter so as to formulate a clear picture for future standard development and energy research.