CHAPTER 6

BUILDING ENERGY SIMULATION METHODS

> *t (modelling and simulation) is more than an art, but not a fully developed science. Human judgement, experience and computer programming skill still play an important role in the formulation and solution of problems by this method." – (Neelamkavil, F., 1987, Preface)*

Although simulation methods are often used for building energy analysis, their concepts, theories and techniques are not always clearly understood. To master the skills and develop full strength of building energy simulation, it is essential to understand the nature of the process and the characteristics of the tool. This chapter focuses on simulation and modelling for the analysis of building energy performance. A base case office building model for Hong Kong is developed on detailed building energy simulation programs. Sensitivity analysis is carried out to examine the important design parameters; regression analysis is performed to generate and analyse energy equations for Hong Kong.

6.1 Simulation and Modelling

The principle of simulation and modelling is explained; the basics of energy modelling are described; the importance of developing simulation skills is pinpointed.

6.1.1 Principle of the approach

imulation' and odelling' are inseparable procedures used to analyse the complex behaviour of real processes. Modelling deals primarily with the relationships between actual dynamic processes and models; simulation refers above all to the relationships between the model and the simulation tool (Matko, Zupancic and Karba, 1992, pp. 1).

Modelling and simulation cycle

Problem solving by modelling and simulation is an iterative and interactive process which involves cyclical and evolutionary procedures. Figure 6.1 shows the crucial stages of a computer modelling and simulation cycle as suggested by Matko, Zupancic and Karba (1992) and Neelamkavil (1987). When applied to building energy simulation, the general cycle is reduced. Program developers usually handle the modelling of system dynamics which form the basis of the simulation tool; modellers use the tool to build their models and carry out simulation and analysis for their problems.

The model and its descriptions are very seldom formulated in one pass. The information and experience gained during the process will help adjust and fine-tune the model into an effective and accurate form. Radford (1993) considered simulation as a fundamental part of an nalysis – synthesis – evaluation' sequence of design activity, where each cycle of this sequence occurs at a slightly greater level of detail. This coincides with the nature of the building design process in which complete information is available only at the final stage (see Section 2.2).

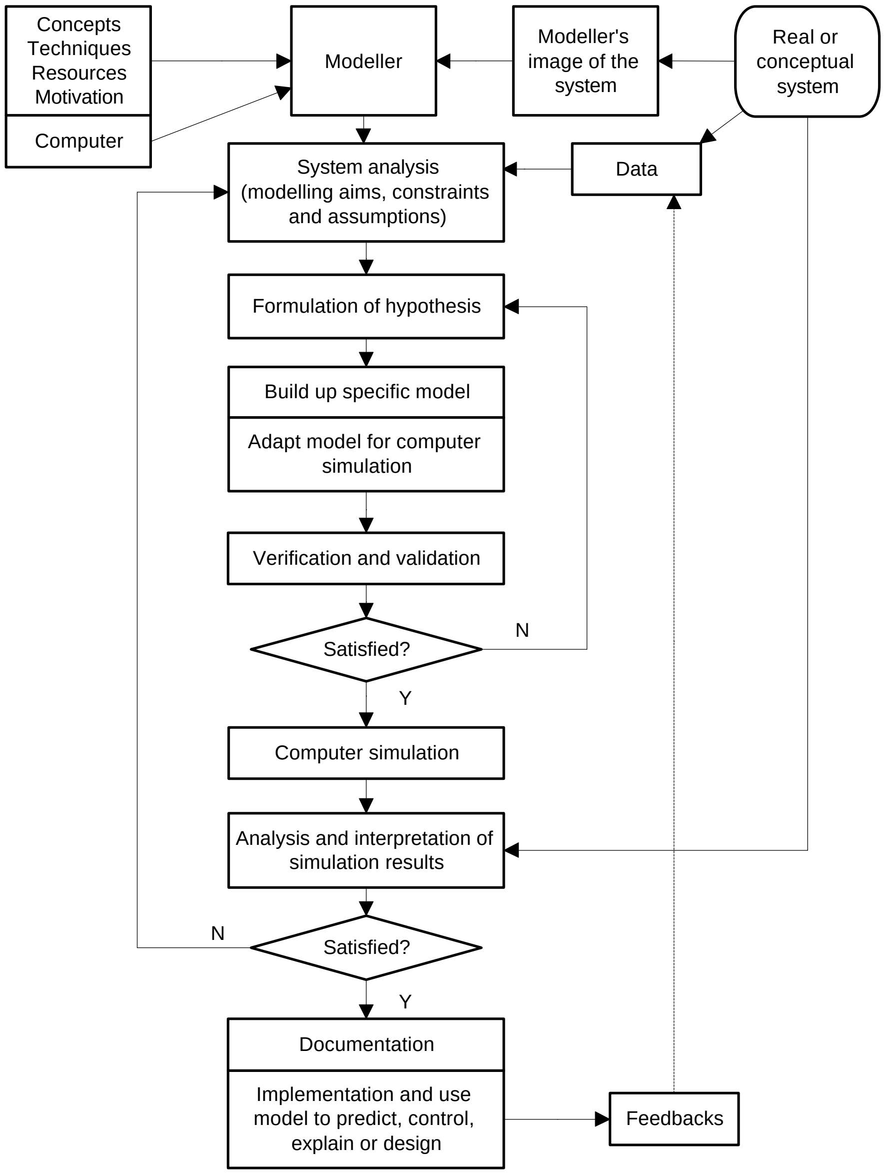

Figure 6.1 *Computer Modelling and Simulation Cycle*

rt’ or cience’

Building energy simulation is rtful’ as there are a lot of subjective judgements on what inputs and methods should be taken. The many physical, engineering and numerical assumptions, which are often difficult to justify, have significant influences on the results. There is also considerable controversy about which algorithms and solution techniques are most appropriate to describe the thermophysical processes and building responses. Even though dedicated component modelling algorithms have been used, simulation of the whole building is by no means an exact science when the complex interactions and human behaviour in real life are considered. Neither the computer nor the model can completely replace human decisions, judgement, intuition and experience which still play a significant role in determining the validity and usefulness of models (Matko, Zupancic and Karba, 1992). The merit of the simulation method is to provide a system approach to learn, design, change, preserve, optimise and possibly control the behaviour of the system. It is the methodological science in simulation which ngineers’ the building design and enhances the assessment of building performance. Although a modeller does not have to investigate the system dynamics within the simulation tool, he/she should apprehend the modelling approach, the building and the aims of the study.

6.1.2 Energy modelling basics

Clarke (1985, Chp. 2) has described the common modelling approaches of detailed energy simulation and they include (in order of popularity): (a) response function method under time domain, (b) numerical method using finite differences, (c) response function method under frequency domain, (d) numerical method using control volume heat balance and (e) numerical method using finite element approach. The time-domain response function method, also known as esponse factor method’ (Stephenson and Mitalas, 1967 & 1971), is preponderant and has been adopted in many simulation programs, such as DOE-2 (LBL, 1981) and BLAST (BLAST, 1991). The next one is the finite difference approach which is adopted in ESP-r (Clarke, 1985 & 1993); this approach is very general in concept and may produce models whose quality depends heavily on how the schemes are implemented. The other methods are very seldom implemented nowadays for energy simulation of the whole building. No definitive statement have yet been made on the performance of different methods when applied in practice.

Modelling strategies

Modelling strategy is concerned about how the various sub-systems in building energy simulation are integrated. In most simulation tools, the building and its energy systems are represented by three basic models [*]:

- *Load model* – It represents the thermal behaviour of the building structure and its contents. Building envelope, internal loads and infiltration are considered in the load calculations to determine the amount of heat added to or extracted from the space to maintain comfortable indoor conditions.

- *System model* – It represents the thermodynamic behaviour of the air-side or secondary system. Air handling equipment, fans and terminal units are simulated to determine the energy required by the air-side equipment and the system demands on HVAC main plant.

- *Plant model* – It represents the relationship for load versus energy requirements of the primary energy conversion equipment. The fuel and energy required by the main plant (such as chiller and boiler plants) to meet the building loads are estimated by considering equipment efficiencies and partload performance.

The most common approach to link these models is the sequential method in which the load model is executed for every space and every hour of the simulation period, followed by the systems model, and then plant simulation, consecutively. Each sequential step is based on ixed’ outputs from the preceding step. Figure 6.2 shows the basic concept of the sequential method. Coupling of the models in this way allows solving of the mathematical equations consecutively and serially, thus greatly reducing the efforts for iterative computations.

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[*] An additional module for economic and life-cycle analyses is also common for estimating the life-cycle costs of the building. But, in general, the ‘economic module’ has little interactions with the other models, from thermal calculation point of view.

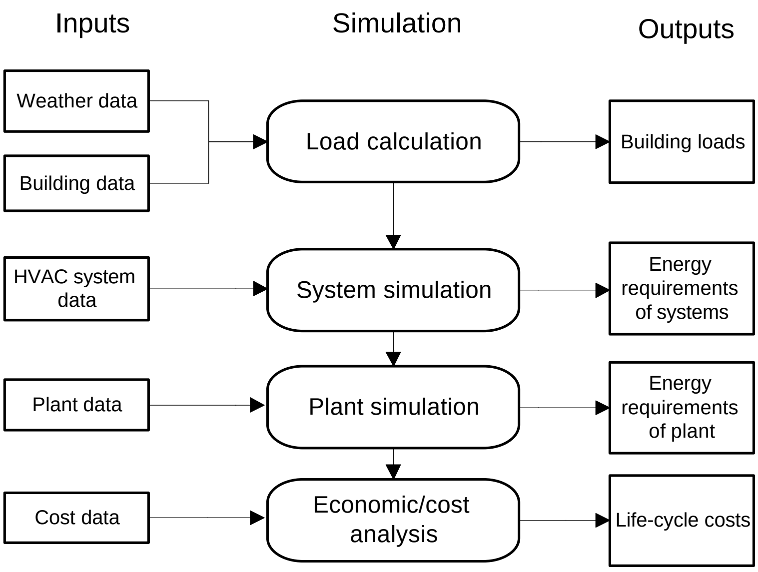

Figure 6.2 *Basic Concept of Sequential Simulation*

Weighting factor method

In order to compensate for the lack of interactions between the building and system models, a eighting factor method’ is commonly used for adjusting the building loads (Kerrisk, *et al.*, 1981; LBL, 1982, pp. II.30-95). This method represents a compromise between steady-state methods and complete energy-balance methods. It was first introduced by Mitalas and Stephenson (1967), and is employed for energy calculations by ASHRAE (ASHRAE, 1976). Descriptions of the method can be found in ASHRAE (1993, Chp. 28) and LBL (1982, Chp. II). Witte, Pedersen and Spitler (1989) found that this technique works well for cases where the system response is well-defined, but it loses accuracy in situations where the system response is heavily dependent on the building load and the outside conditions or when the space temperatures are allowed to float drastically.

Heat balance method

Another way to translate the instantaneous loads between the load and system models is the heat balance method which requires solving of a set of equations for heat transfer surfaces and air temperature in order to determine the space loads. For example, BLAST uses the heat balance method by setting a control profile to model the system response during the simulation (Witte, Pedersen and Spitler, 1989; Taylor, *et al.*, 1991). The load simulation is performed first, and the space temperatures and building loads are then calculated based on environmental conditions, internal loads, interactions between zones, infiltration, ventilation, and air handling system. An energy balance is done to find the space temperature at which the zone load balances with the heating or cooling provided by the system. The heat balance method is more fundamental than the weighting factor method, but it requires more computations at each point in the simulation and careful representation of the heat transfer surfaces and mechanisms. Different forms of simulation outputs will be produced if different methods are used.

6.1.3 Simulation skills

Detailed building energy simulation programs are complex. They requires input for a large number of parameters and produces large quantities of output. Efficient use of the programs (which takes time and experience to attain) requires a clear understanding of the simulation and analysis method. Currently, a building designer is often left with little help and guidance on the understanding and planning of simulation methodology and techniques. Since the big part of the cost and efforts for building energy studies is in doing analysis, computer advancement alone does not help much in this primary engineering function. Remember arbage in, garbage out'.

Wright, Bloomfield and Wiltshire (1992) found that most simulation programs are difficult to use, with complicated user interface and requiring considerable experience for effective use. Experience with one program is often little help with another since each program has unique characteristics and there is little modelling consistency between the programs. In a large simulation exercise, control and management functions are often left up to the user, usually at the level of the computer operating system. It is time-consuming, demanding and error-prone for an inexperienced user to carry out detailed simulation exercises. It requires skill and insight even from an experienced user to translate correctly the physical systems and control schemes into program inputs.

Developing skills

To solve problems correctly and systematically using building simulation, modellers should pay attention to, *inter alia,* the nature of the problem and the functioning of the tool. Much of the success of modelling relies on the experience, skill and integrity of the modeller (Kaplan and Caner, 1992). Current generation of simulation tools requires the user to have background in building physics, knowledge of computing methods, insight of simulation logic and intuition for detecting irrational data, in order to ensure sensible and reasonable results. It is believed that a ualified’ modeller should be an experienced and competent designer as well as an experienced and competent user of the particular computer program.

To build up simulation skills, the guidelines and philosophy of energy modelling from Kaplan and Caner (1992) are useful. Newton, James and Bartholomew (1988) have also suggested, from the user point of view, seven essential steps for building energy simulation:

- Step 1 – Defining the problem or identifying the opportunities.
- Step 2 – Specifying the model.
- Step 3 – Data acquisition.
- Step 4 – Implementation.
- Step 5 – Planning.
- Step 6 – Experimentation.
- Step 7 – Analysis of results and reporting.

Analysis techniques

Although simulation programs can provide detailed information about building performance, the parameters generated are often either inappropriate to the problem or, if relevant data are produced, they are embedded among large quantities of output which is irrelevant (Bloomfield, 1989a). The inference that can be drawn from the simulation outputs is numerous and will vary according to the standpoint of the analyst. To avoid ambiguity, the objectives, assumptions, omissions and limitations should be stated as clearly as possible. The usual task of detailed simulation is to use the simulation results to develop simplified relationships for design purposes, such as Turiel, *et al.* (1984) and Chou and Lee (1988). Common techniques used for performing analysis using simulation include:

- *Sensitivity analysis* (Corson, 1992; Stoecker, 1989, Chp. 7; Spitler, Fisher and Zietlow, 1989; Mahone, *et al.*, 1992; Corson, 1992).

- *Regression analysis* (Leslie, Aveta and Sliwinski, 1986; Sullivan, *et al.*, 1985; Sullivan and Nozaki, 1984).

- *Graphical methods* (Fadel and Rueda, 1984; Haberl, MacDonald and Eden, 1988) [*].

Importance of training

Undoubtedly, the importance of training and understanding of simulation methodology should not be underestimated. Hand (1993) found that the efficacy of dynamic thermal simulation tools in practice depends not only on the facilities offered by the tools and the rigour of the underlying calculations but also on the skills of the user *vis-à-vis* abstracting the essence of the problem into the model, choosing appropriate boundary conditions, setting up simulations and interpreting their results. It is necessary for users of a particular energy program to be trained in its use, application and theoretical basis. Unfortunately, very limited information is available now for training of modellers, except the often wful’ program manuals. Proficiency in modelling techniques with the existing tools is often built up through long periods of usage and learning by mistakes.

[*] Geometric and logic check through visualisation of data is often a useful tool to eliminate errors, mostly human.

6.2 Building Energy Simulation Tools

The common detailed simulation programs are assessed and two simulation tools (DOE-2 and BLAST) are selected for this research. Supporting computer programs have been developed to facilitate weather file generation, automated simulation process, extracting of key results and data analysis on microcomputers.

6.2.1 Simulation programs for this study

ASHRAE (1993, pp. 28.2; 1991c, Chp. 36) and NSW Public Works (1993, Chp. 16) have provided some general considerations for selecting energy analysis programs. However, it is hard to judge which program is suitable and adequate for an application since there are no definite criteria to help select the programs wisely in all situations. Generally speaking, each program has its particular features and limitations. The decision for selection often depends on previous experience of the user, popularity of the program, computer hardware available to run them and specific requirements of the application (Evans, 1987).

Comparing different programs in perspective

Since the existing programs (see Section 2.4.1) are developed by different bodies based on different approaches to the modelling problem, it is very difficult to compare them on a common basis. The input requirements, output quality, simulation capability and user supports of these programs vary significantly. No one program is likely to satisfy all users and the requirements of all projects. To choose the simulation tools for this research, the common building energy simulation programs have been reviewed. Based on their capabilities and usage by other researchers, five detailed simulation programs which can met the requirements of detailed research studies have been examined. Table 6.1 gives a brief comparison of them showing their program designs, input and output features, weather files used and simulation approaches.

Table 6.1 Comparison of Detailed Simulation Programs

	BESA	BLAST	BUNYIP	DOE-2	ESP-r
Country	Canada	USA	Australia	USA	UK
Version	2.0	3.0	3.0	2.1E	Version 8
Weather data required	Full hourly	Full hourly	inned' weather	Full hourly	Full hourly
Weather file processor	EW_WTH' (available upon request)	IFE'	Not available to users	OE2WTH'	SPclm' climate database management
Calculation method	Not known	Heat balance	Finite difference	Weighting factor	Finite difference
Input method	Menu-driven input forms	TEXT' or ASCII file	UNYIS' input system	ASCII file [1]	SPimp' input management
Input checking	Internal	BLAST error check	UNYED' error detect	BDL error check	Internal
Output method	Output Manager forms, graphs	ASCII file, report writer	UNREP' report, spreadsheet output	ASCII file	SPout' (statistics, graphics, tables)
Parametric runs	Not available	Not available	Very limited	Limited	Limited
User Manual	Acceptable	Good	Poor	Fair	Fair
Engineer manual	Not available	Not available	Not available	Yes (but not updated)	Yes
Accepted by energy standard?	ASHRAE 90.1-1989	ASHRAE 90.1-1989	–	ASHRAE 90.1-1989	As a reference in Europe

Note: 1. Some third party utility programs, such as OE-Plus', have been developed for the DOE-2 program.

As discussed earlier in Section 2.4.2, most validation studies of the simulation programs are inconclusive. Errors resulting from inadequacy of the programs and their solution techniques are often masked by uncertainties in the input data. Even though much effort is taken to eliminate possible errors, the various programs, when applied to the same problem, can produce quite different results which are very difficult, if not impossible, to verify. Any comparison of the simulation results is an assessment not only of the program itself but also of the model interface which is susceptible to user skills and input uncertainty. It is believed that the performance of a detailed simulation program will depend more on how it is implemented and used, than how it is designed. The ability of a user to use the program effectively and to understand the implications of each item of input data is of prime importance. As long as the program can model the required features and give easonable' results, it is considered suitable for the application *.

Selected tools for this research

The two programs, DOE-2 (LBL, 1981) and BLAST (BLAST, 1991), were selected as the imulation engines' in this research because:

- They are widely used simulation programs and their results are generally accepted as easonable' for different building types.

- They can offer a wide range of simulation features for a detailed whole-building energy performance analysis.

- To some degree, DOE-2 and BLAST have been alidated'. Extensive studies have been conducted for DOE-2, such as Diamond, Cappiello and Hunn (1985 & 1986), Diamond and Hunn (1981), Diamond, Hunn and Cappiello (1981 & 1985), Bahel, Said and Abdelrahmen (1989) and USDOE (1984). Some efforts for BLAST verification have been made by Yuill (1986) and Yuill and Philips (1981).

- DOE-2 have been used by many researchers and governments for developing building energy standards, such as California Title 24, ASHRAE 90.1, ASHRAE 90.2 and the OTTV standards in Hong Kong and ASEAN.

- Both DOE-2 and BLAST are recognised by the ASHRAE Standard 90.1-1989 as acceptable simulation tools (ASHRAE, 1989c).

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* Since there is no 'correct' program, judgement about the program's accuracy and reliability is often based on 'confidence' in the program and reasonableness of the results. Confidence in a program is developed as a result of validation efforts, extensive usage by a wide class of 'independent' users, and by producing consistent and reasonable results.

- DOE-2 is a public-domain program and BLAST has its source code distributed for scrutiny.

DOE-2 seems to be the most widely adopted simulation program nowadays and BLAST is interesting since it adopts a eat balance’ method for the load calculations [*]. The author has selected DOE-2 for the majority part of the parametric analysis in this thesis and the two programs have been used for evaluating the multi-year weather data in Section 5.4. Simulation for this research were performed on 386 and 486 microcomputers using the microcomputer versions of DOE-2 and BLAST: MICRO-DOE2 (ERG / Acrosoft International, 1994) and PC-BLAST (BLAST, 1991) [†].

6.2.2 Performing the analysis

Weather files and climatic information for Hong Kong established in Chapter 4 and Chapter 5 were used as the weather input in the simulation. The year 1989 selected in Chapter 5 was taken as the base weather. The 1989 weather file used in the parametric studies is in TMY format (see Section 5.3). TMY format has an advantage that the direct and diffuse components of the global solar radiation (GSR) data can be supplied by the user instead of being estimated internally by the simulation program (see Appendix IV for the method for separating the direct and diffuse components for Hong Kong). The use of an entire year of real weather data ensure continuity and consistent holidays schedules for the simulation (see also Section 5.3.2).

Automated simulation process and supporting programs

To standardise and simplify the simulation process, the procedure for creating and running the parametric simulations was automated as much as possible. uilding energy simulation stations’ (BESS) have been set up

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[*] Recently, there is a plan proposed by the Lawrence Berkeley Laboratory (LBL) to combine the best features of DOE-2 and BLAST into one program so as to develop improve building energy simulation software (LBL, 1995).

[†] The DOE-2.1D (extended DOS) version of MICRO-DOE2 (Acrosoft International, Inc., 1990) was used initially for the early studies. The simulations were then transferred to the ‘E’ version in 1994. There are some differences in loads calculated by the ‘D’ and ‘E’ versions because some improvements in conduction and radiation heat transfer have been introduced in the ‘E’ version (Winkelmann, *et al.*, 1993, pp. 14).

on 386 and 486 microcomputers to perform the simulation. Figure 6.3 gives an overview of the automated building energy simulation and analysis process developed in this research.

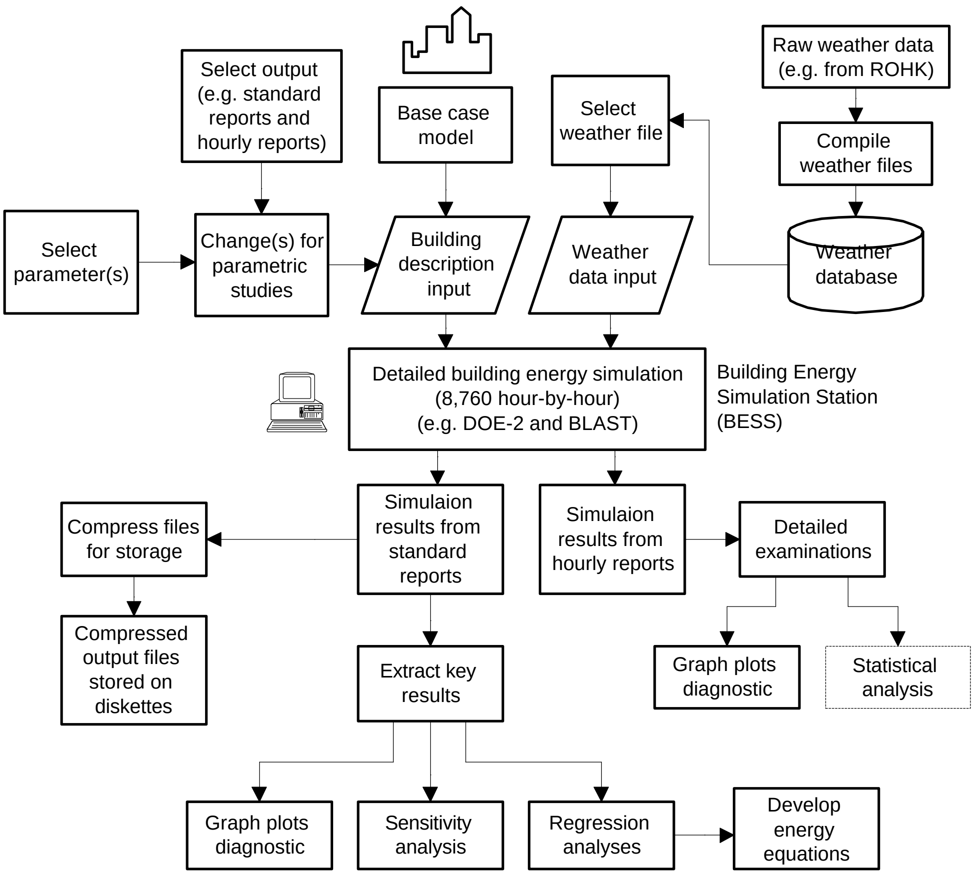

Figure 6.3 *Automated Building Energy Simulation and Analysis Process*

It is found that the existing building energy simulation programs are not designed to perform parametric studies efficiently. Some programs (such as DOE-2 and ESP-r) allow simulation runs in batch mode but the operation is not flexible. Performing large-scale parametric studies, say several thousand simulations, requires an effective batch facility and data management. To facilitate the analysis in this research, the author has developed some supporting computer programs for carrying out the simulation efficiently. These programs automate the simulations with multiple weather files, extract key results, store and handle the large volume of simulation input and output.

If the modelling tool is the imulation engine', then the supporting program will form the ear' of this machine. The two supporting programs developed for DOE-2 and BLAST are respectively:

- *UTODOE2'* – This program serves as a pre- and post-processing module for DOE-2 for performing parametric simulations, extracting key data from the output and storing the output file in ompressed' format.

- *KBLAST'* – This newly developed program is similar to the previous program for DOE-2 (its data extracting option is currently under construction).

Figure 6.4 gives a general overview of UTODOE2' and KBLAST'. Detailed descriptions of the supporting programs can be found in Lam and Hui (1995c). The supporting programs for statistical analyses on weather data in Chapter 4 and Chapter 5 are so designed that they can also be used to analyse the hourly simulation outputs extracted by UTODOE2' and KBLAST' (since the hourly data are 8,760 datasets similar to the weather data). This can provide a flexible way for studying the complex hourly simulation outputs.

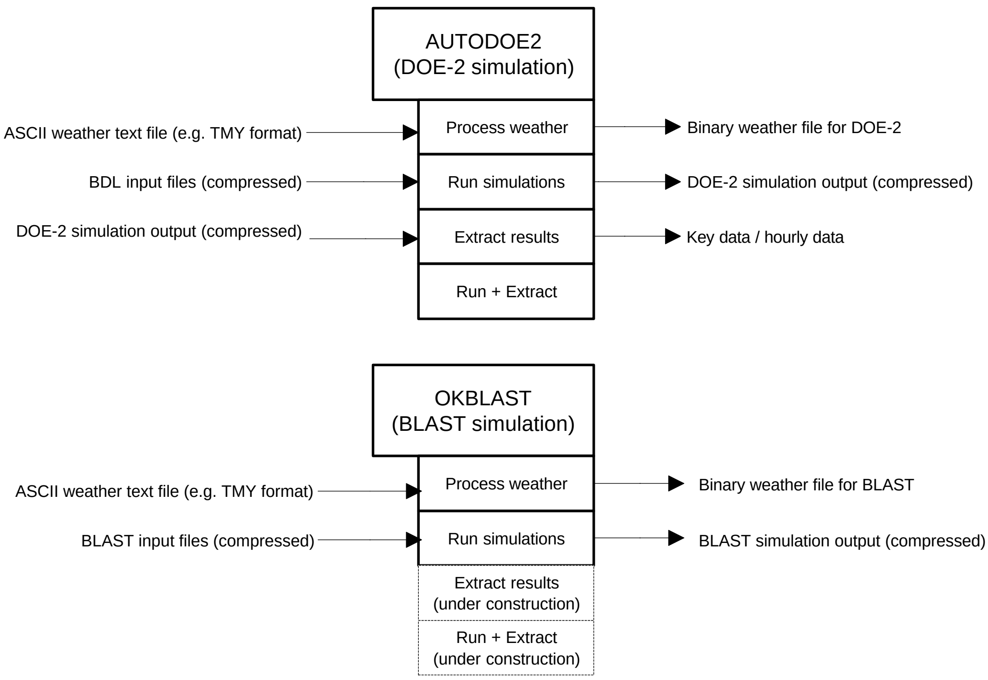

Figure 6.4 *Overview of the UTODOE2' and KBLAST' Programs*

6.3 Base Case Model

The reference building approach is discussed and a base case office building is developed for the simulation.

6.3.1 Reference building approach

A reference building is needed in most simulation studies to serve as a benchmark or base case for comparison and evaluation. Development of easonable', standardised input data for the reference building is subjective and depends on application.

Standardised building specification

Leighton and Pinney (1990) found that there are no simple range of tandard' office or building plan for use in modelling studies since each building is an individual solution. In principle, materials properties and constructions can be presented with consistency since the existing datasets for them are often similar. But it is hard to give recommended values for the living pattern of the occupants and their mode of operating the building. These uncontrollable factors (especially when the final occupant of the building is not known) are usually significant in determining thermal behaviour and building energy consumption. In most cases, a standard occupancy must be assumed and all proposals are assessed based on it. Ideally, the building descriptions should be developed from data accumulated through actual, detailed surveys and audits conducted locally. However, detailed building surveys are usually very limited, and the available data are often inconsistent or incomplete for simulation needs. Therefore, professional judgement is used to select and determine the necessary inputs for the reference building.

Experience from other countries

In areas where local information is lacking, experience from other countries is useful since large offices and commercial buildings share general characteristics, equipment requirements, and energy consumption patterns. Useful references studied by the author include:

- Typical buildings of ASEAN (Deringer and Busch, 1992).
- Reference building specified in ASHRAE 90.1-1989 (ASHRAE, 1989c).
- Recommendations on standard building designs for energy standard development by PNL (1983).
- Commercial building energy consumption survey by EIA (EIA, 1994a, 1992a, 1992b & 1986).

It is believed that the information from ASEAN are the most useful as their climate and construction practices are similar to Hong Kong. The U.S. practices are instructive since they have much experience in HVAC design and many HVAC equipment and system design concepts in Hong Kong come from USA. For the present study, a base case model for typical large office buildings in Hong Kong has been set up and analysed. In principle, other building prototypes, such as hotels and retails, can be developed using similar procedure and approach.

Implications

Development of building descriptions that reasonably represent the energy-related features of the building stock is critical to producing an appropriate building energy standard (Deringer and Busch, 1992, Chp. 4). Heldenbrand and Petersen (1982) point out that the reference building approach served to link component performance standard to whole-building energy performance standard. Descriptions of the reference building are often used not only for the research analyses for determining the prescriptive criteria in the energy standard, but also for compliance purposes in the standards with the hole-building performance' path *. Acceptance of the proposed building design is based on comparison of its nergy budget' with that of an equivalent-size reference building that is well-defined in terms of component specifications. The designer is free to use any approved evaluation technique to demonstrate equivalence but is required to use the same technique for both the reference and proposed buildings. Nevertheless, it should be noted that the specification of the prototypes are necessary to assure repeatability but have no other significance. Designs of the reference building do not necessarily reflect the nergy-efficient' option.

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* A reference building is defined in ASHRAE (1989c, pp. 5) as a specific building design that has the same form, orientation, and basic systems as the proposed design and meets all criteria of the prescriptive compliance method.

6.3.2 Office building model

Information on commercial buildings in Hong Kong has been studied. It is found that very limited information about the energy performance of the commercial building stock in Hong Kong is available. There is no authoritative source of reliable data on building design and energy characteristics. Some disperse small-scale studies or surveys have been carried out by individuals, but the scope is very narrow and the data are usually not complete and detailed enough for building energy study.

Base case model

The major features found in medium to large commercial buildings in Hong Kong are summarised as follows:

- High-rise office buildings are popular.
- Full air-conditioning with central system is used extensively.
- Curtain wall construction and reflective glazing is common for the building envelopes (Goodsall and Lam, 1991; Goodsall, 1994; HKIE, 1992).
- Air-cooled heat rejection system is often used (Yip and Hui, 1991).
- VAV system with simple electric reheat coil is a common design for large office buildings (Wang, 1987).

The base case model developed in this research is a 40-storey square office building (35 m by 35 m) with curtain-wall construction and a central HVAC system. Figure 6.5 shows the typical floor of the base case model. Table 6.2 gives a summary of the key parameters of the model. The base case building has a floor-to-floor height of 3.4 m and a window height of 1.5 m. The window-to-wall ratio (WWR) is about 44% and the shading coefficient (SC) of window glass is 0.4. The building and its HVAC system operate 10 hours per day (08:00 to 18:00) and 5½ days per week, which is very common in Hong Kong.

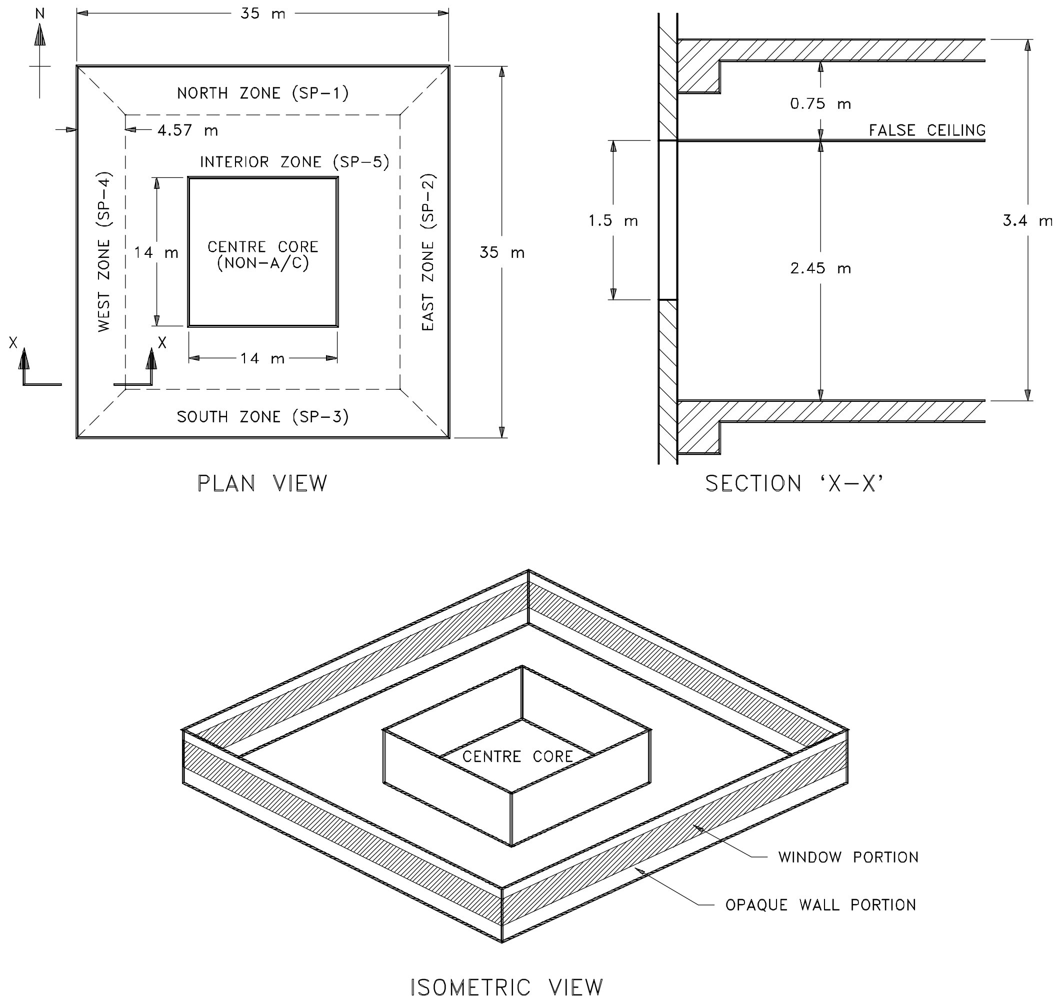

Figure 6.5 *Typical Floor of Base Case Office Building*

Table 6.2 Descriptions of Base Case Office Building for Hong Kong

General Information

Location:	Hong Kong (latitude 22° 18’ N, longitude 114° 10’ E)
Building type & storeys:	Office building, 40 storeys above ground
Floor area:	Total gross floor area = 49,000 m^2 Air-conditioned floor area = 41,160 m^2
Dimensions & heights:	35 m x 35 m (square); floor-to-floor = 3.4 m window height = 1.5 m; window-to-wall ratio = 0.44
Operating hours:	Mon. to Fri. – 09 to 17 hr; Sat. – 09 to 13 hr; Sun. & holidays – closed

Building Constructions

Building envelope:

- Opaque walls (spandrel portion of curtain wall) – 6mm glass + 25 mm airspace + 19 mm plywood + wall paper [U-value = 2.005 $W/m^2 K$]
- Windows – 6 mm reflective glass [shading coefficient = 0.4, U-value = 5.6 $W/m^2 K$]
- Roof – 13mm slag + 10mm roof build-up + 50mm roof insulation + 200mm h.w. concrete + ceiling void + 19mm ceiling panel [U-value = 0.539 $W/m^2 K$]

Internal structure:

- Floor (typical middle floor) – carpet + 50mm screeding + 150mm l.w. concrete + ceiling void + 19mm ceiling panel [U-value = 0.599 $W/m^2 K$]
- Internal core wall – 5mm mosaic tile + 19mm plaster + 200mm h.w. concrete + 19mm plaster + wall paper [U-value = 1.930 $W/m^2 K$]
- Internal partitions – 16mm gypsum board + 25mm airspace + 16mm gypsum board [U-value = 1.680 $W/m^2 K$]

Major Design Parameters

For building load:

- Occupancy density = 5 m^2/person
- Lighting load & type = 20 W/m^2, fluorescent recessed, not vented
- Design illuminance (offices) = 500 lux
- Equipment load = 15 W/m^2
- Infiltration rate = 0.6 air change per hour (during plant off period)
- Space design temperature & humidity = 25.5 ^oC, 40-60 %

For HVAC system:

- HVAC system type = VAV terminal reheat
- Outdoor fresh air = 7 L/s/person
- Thermostat setpoints – cooling = 25.5 ^oC, heating = 21 ^oC
- Thermostat type & throttling range = 1.1 ^oC, reversed action
- Night-time setback – cooling = 37 ^oC, heating = 10 ^oC
- Economiser – outdoor air control by temperature

For HVAC refrigeration plant:

- Type of chiller plant = package air-cooled reciprocating (direct air-cooled)
- Chiller coefficient of performance (COP) = 1.2 kW/TR (or 2.93 kWr/kWe)

Table 6.3 Comparison of Building Envelope Parameters for Base Case Model

	Window shading coefficient	Window U-value (W/m² · K)	Wall U-value (W/m² · K)	Window-to-wall ratio	Type of window glass	Nos. of bldgs.
Maximum	0.93	6.3	3.91	0.85	Reflective	32
Minimum	0.14	2.38	0.35	0.2	Tinted	4
Mean	0.44	5.32	1.84	0.45	Clear	3
Median	0.40	5.7	1.82	0.42	Others	1
Base case	0.40	5.6	2.01	0.44	6mm reflective	

Note: 1. The above data are extracted from a building survey of 40 commercial buildings in Hong Kong (mostly office buildings), conducted by the Building Services Division of the Hong Kong Institution of Engineers (HKIE, 1992). The parameters of the ase case’ at the bottom are selected values for the base case model in this thesis.

Table 6.3 gives a comparison of the building envelope parameters between the base case model and the results from a brief survey for forty commercial buildings (mostly offices) in Hong Kong (HKIE, 1992). The envelope design of the base case model has thermal properties very close to the means and medians of the survey results. It is believed that it can represent a ypical’ office building in the urban district of Hong Kong.

Table 6.4 gives the major characteristics of the base case office buildings used for simulation studies in ASEAN (Deringer and Busch, 1992, Chp. 4; Ang Co, Soriano and Tablante, 1993). The figures for the based case model in this thesis (HK) are also shown for comparison. The basic design of the reference buildings is usually kept simple to facilitate the analysis and reduce ambiguities. It can be seen that the base case office buildings in Hong Kong and ASEAN have some similarities and some differences. A major difference is that ow-rise’ buildings (only 10 storeys high) are taken by ASEAN whereas high-rise buildings are more common in Hong Kong. Based on these configurations and specifications, input files for the base case model have been prepared for the simulation programs and used as a base for the analysis. The base case input files for DOE-2 and BLAST are given in Appendix V and VI, respectively.

Table 6.4 Major Characteristics of Base Case Office Buildings in ASEAN and Hong Kong

	Singapore	Malaysia	Philippines	Indonesia	Thailand	HK
Year created	1983	1986	1989	1989	1989	1992-94
Source of data	Judgement	Judgement	Survey database	Judgement	A real building	Judgement
Number of floors	10	10	10	10	15	40
Shape	Square	Square	Rectang.	Rectang.	Rectang.	Square
Aspect ratio	1 : 1	1 : 1	2 : 1	2 : 1	2.5 : 1	1 : 1
Orientation	N-E-S-W	N-E-S-W	Long side E-W	Long side E-W	Long side N-S	N-E-S-W
Gross flr area (m^2)	6,200	6,200	15,650	15,650	N / A	49,000
A / C flr area (m^2)	5,200 m^2	5,200 m^2	11,350 m^2	11,350 m^2	20,160 m^2	41,160
Wall U-value (W/m^2 K)	2.13	2.43	2.15	2.15	2.88	2.005
Absorptivity	0.45	0.45	0.65	0.65	0.3	0.7
Wall mass (kg/m^2)	N / A	250	247	247	N / A	25.2
WWR	0.44	0.4	0.49	0.50	0.4 (tower)	0.44
Window SC	0.47	0.69	0.88	0.69	0.63	0.4
Glass type	2-pane, tinted	1-pane, tinted	1-pane, clear	1-pane, clear	1-pane, tinted	1-pane, reflective
Glass U-value (W/m^2 K)	3.2	5.79	4.59	4.59	5.81	5.6
Exterior shading	None	None	Overhang	Overhang	Overhang	None
Occup. density (m^2/person)	12.4	12.4	12.4	10	N / A	5
Lighting load (W/m^2)	20	21	17.2	15.9	18.4	20
Design illuminance (lux)	N / A	500	N / A	500	400	500
Outdoor air (l/s/person)	3.3	3.3	9.4	9.4	N / A	7
Infiltration rate (air change/hr)	0.6	1	1	1	Not known	0.6 (during plant off)
Space temp. (^oC)	23.3	24	23.3	24	25	25.5
Air-conditioning system	VAV	VAV	CAV single zone	CAV single zone	CAV single zone	VAV reheat
Refrig. plant	Centrifugal	Centrifugal	Centrifugal	Centrifugal	Centrifugal	Recipro.
Chiller COP (kW/TR)	1.28	1.17	1.08	1.08	1.28	1.2
Capacity	Auto-sized	Auto-sized	Auto-sized	Auto-sized	Auto-sized	Auto-sized
Heat rejection method	Cooling tower	Cooling tower	Cooling tower	Direct air-cooled	Cooling tower	Direct air-cooled

Note: 1. WWR = window-to-wall ratio; SC = shading coefficient; COP = coefficient of performance; VAV = variable air volume; CAV = constant air volume.

6.4 Sensitivity Analysis

The basic principle of sensitivity methods is explained and the properties of the base case model are evaluated. Major sensitivity findings are presented and the significance of sensitivity techniques are discussed.

6.4.1 Basic principle

Sensitivity is a general concept. If a parameter A causes a change in another parameter B and we can measure the change of both, we can determine the sensitivity of A with respect to B. The aim of sensitivity analysis is to observe the system response following a modification in a given design parameter. The fundamental principle can be explained by an nput-output' analysis of the simulation system, as shown in Figure 6.6.

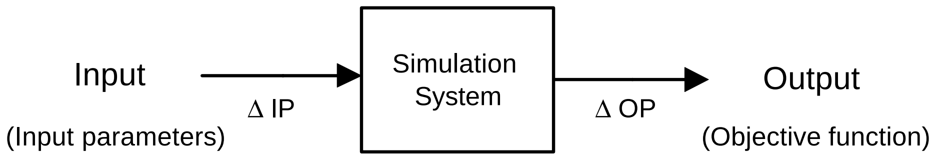

Figure 6.6 *Input-output Analysis of Simulation System*

Sensitivity analysis is a kind of techniques developed in optimisation methods and mathematical programming. The basic optimisation problem of HVAC design is to minimise the value of an bjective function', such as energy consumption and operating cost, by searching the system variables and equipment ranges (Hanby and Wright, 1989). There is no formal rule for performing sensitivity analysis. The choice of the objective function and the procedure of the analysis are governed by the nature of the problem. The sensitivity techniques which might be useful for building energy simulation have been described by Irving (1988), Lomas and Eppel (1992) and Palomo, Marco and Madsen (1991); some studies have also been initiated by Spitler, Fisher and Zietlow (1989) and BRE and SERC (1988) to apply the techniques in simulation studies.

Sensitivity coefficients

ensitivity coefficient' is often used in the fields of mathematics and controls engineering (Deif, 1986). In economics, the concept of elasticity is employed to measure the sensitivity and responsiveness of a system (Case and Fair, 1989, pp. 114-126). For thermal system and building energy simulation, the term nfluence coefficient' (IC) has been used (Spitler, Fisher and Zietlow, 1989; Stoecker, 1989, Chp. 7 & 8). It is defined by the partial derivatives of output with respect to input, like this:

$$IC = \frac{change\ in\ output}{change\ in\ input} = \frac{\partial\, OP}{\partial\, IP} \approx \frac{\Delta\, OP}{\Delta\, IP} \tag{6.1}$$

where *OP* is the output and *IP* is the input; the last two terms are the partial derivative and the ratio of simple difference respectively.

If only one step change is used to calculate the sensitivity, the influence coefficient can be determined by two sets of data:

$$IC = \frac{\Delta\, OP}{\Delta\, IP} = \frac{OP_1 - OP_2}{IP_1 - IP_2} \tag{6.2}$$

where OP_1 and OP_2 are the output values, IP_1 and IP_2 are the corresponding input values.

If more perturbations are used, the coefficient can be determined from the slope of the regression line for the data. The sensitivity (the slope) will vary from point to point if the correlation between the output and input variables is not a linear function. Table 6.5 shows five different forms of sensitivity coefficient. Form (1) is the most common; forms (2a) and (3b) are useful for expressing sensitivity in dimensionless quantity.

Table 6.5 Different Forms of Sensitivity Coefficient

Form	Formulae	Dimensions	Common Name(s)
1	$\dfrac{\Delta OP}{\Delta IP}$	With dimension	Sensitivity coefficient, influence coefficient
2a	$\dfrac{\Delta OP \div OP_{BC}}{\Delta IP \div IP_{BC}}$	Dimensionless	Influence coefficient, point elasticity
2b	$\dfrac{\Delta OP \div OP_{BC}}{\Delta IP}$	With dimension	Influence coefficient
3a	$\dfrac{\Delta OP \div \left(\dfrac{OP_1 + OP_2}{2}\right)}{\Delta IP \div \left(\dfrac{IP_1 + IP_2}{2}\right)}$	Dimensionless	Arc mid-point elasticity
3b	$\left(\dfrac{\Delta OP}{\Delta IP}\right) \div \left(\dfrac{\overline{OP}}{\overline{IP}}\right)$	Dimensionless	N / A

Notes: 1. ΔOP, ΔIP = changes in output and input respectively; OP_{BC}, IP_{BC} = base case values of output and input respectively; IP_1, IP_2 = two values of input; OP_1, P_2 = two values of the corresponding output; $\overline{OP}$, $\overline{IP}$ = mean values of output and input respectively.

2. For form (3 b), the slope of the linear regression line divided by the ratio of the mean output and mean input values are used to determine the sensitivity coefficient.

Direct comparison of the sensitivity coefficients in quantitative terms is not always feasible since the parameters might have different dimensions, units of change and base case values. Only if the input parameters are measured in the same units and are of the same nature are the coefficients comparable. When the parameters differ substantially, the sheer magnitude of their sensitivity coefficients does not reveal anything about the relative importance. Whichever form is chosen, the sensitivity coefficients should be clearly defined to avoid confusion.

Categorisation of input parameters

To determine the parameters for this study, the building inputs to the simulation tool were examined carefully. A total of 62 input parameters (47 numeric and 15 non-numeric) were defined for the base case model and they were categorised into three main groups: building load, HVAC system and

HVAC refrigeration plant. Each of these groups can be sub-divided into sub-groups as shown in Figure 6.7 (Lam and Hui, 1993).

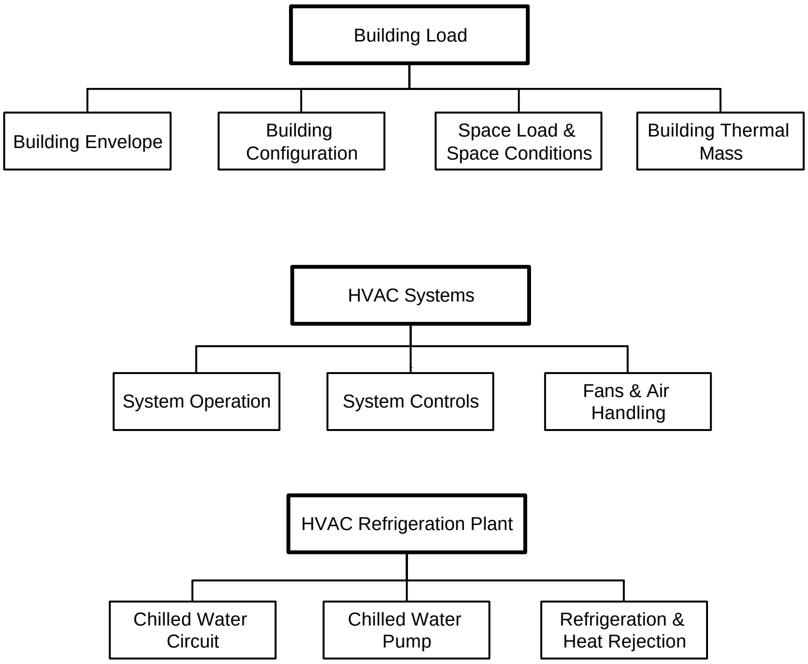

Figure 6.7 *Categorisation of Input Parameters*

For a sequential simulation approach (see Section 6.1.2), the simulation results from the loads subprograms will not be affected by the parameters of HVAC system and HVAC refrigeration plant; the results from the system subprogram will not be affected by the parameters of HVAC refrigeration plant. By categorising the input parameters, a clear picture of the energy-related factors can be established. The tables in Appendix VII show the input parameters selected, their base case values and the number of perturbations performed for the sensitivity analysis. A total of about 400 simulations on DOE-2 have been performed for the sensitivity study, which covered the most common building design variables.

6.4.2 Base case results

Analysis of the simulation results of the base case model is essential for understanding the important components and elements of the model. The annual electricity consumption and peak cooling load of the base case model have been studied and compared with other research studies and surveys so as to develop a picture of the characteristics of building energy performance in Hong Kong.

Annual electricity consumption

The annual building electricity consumption, in Megawatt-hour (MWh) can be broken down into seven components according to DOE-2: (a) lighting, (b) equipment, (c) space cooling (chiller), (d) space heating, (e) heat rejection, (f) pumps and (g) fans. Figure 6.8 shows a breakdown of these components for the base case model.

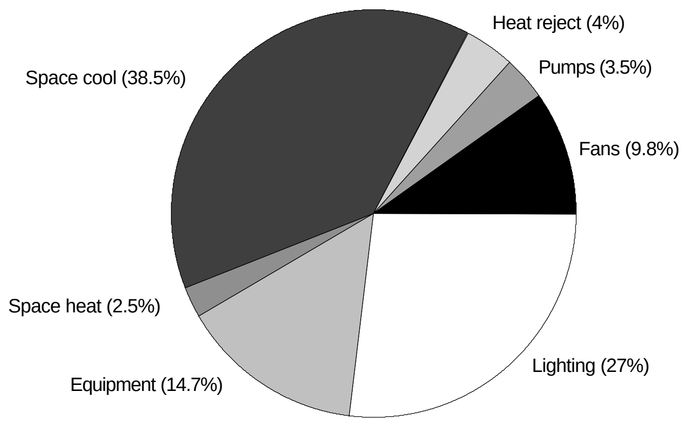

Figure 6.8 *Breakdown of Annual Building Electricity Consumption for the Base Case Model*

It can be seen that energy demands related to air-conditioning system are the most important. Cooling energy requirements dominate the consumption at about 55.8% (including space cooling, heat rejection, pumps and fans) and heating energy use is relatively small, only 2.5%. The consumption by internal loads (lighting and equipment) are very important and have accounted for about 41.7% of the total consumption. Since the HVAC system has to remove all these heat gains from the air-conditioned space, the real influence of the internal loads is even greater than this. As sensitivity tends to follow the end-use components that consume the most energy, it is expected that input parameters affecting the internal loads and pace cool’ (i.e. refrigeration plant) will have significant influence on the annual building energy consumption.

Table 6.6 Comparison of Electricity Consumption Breakdown

Country [1]	Nos. of Bldgs.	Electricity consumption breakdown for office buildings (%)			
		Air-cond. [2]	Fans	Lighting	Misc.
Indonesia	1	36.6	43.5	11.8	8.1
Malaysia	5	60.1	8.7	23.1	8.1
Philippines	24	45.0	16.2	22.5	15.6
Singapore	4	36.6	13.2	24.2	26.0
ASEAN	34	46.0	15.6	22.5	15.5
DOE-2 (LBL)	–	40.0	18.0	23.0	18.0
DOE-2 (HK)	–	48.5	9.8	27.0	14.7

Note: 1. The figures for the four countries, Indonesia, Malaysia, Philippines and Singapore, are taken from energy audit results reported by Loewen (1992). The figures for ASEAN is the average weighted by the number of buildings audited per countries. The figures for OE-2 (LBL)’ are from a DOE-2 simulation study by the Lawrence Berkeley Laboratory for an imaginary office building in Manila (Levine, Busch, Deringer, 1989). The figures for OE-2 (HK)’ are from the DOE-2 simulation of the based case model in this thesis.

2. ir-cond.’ includes energy consumption by space cooling, space heating, pumps and heat rejection equipment.

Table 6.6 gives a comparison of the electricity consumption breakdown for the base case model in this thesis and the research results in ASEAN (Loewen, 1992). The proportions of the components can be seen from the comparison. Lighting energy use is slightly higher in the DOE-2 estimate for

Hong Kong than ASEAN while the energy for air-conditioning plant is very close (see also Table 6.4 for the input parameters).

Table 6.7 Comparison of Energy Utilisation Index

Location (Reference source)	EUI (kWh/m²/annum of gross floor area)				Nos. of Samples	Remarks
	Mean	Max.	Min.	S. D.		
HK base case model for DOE-2	203	–	–	–	Typical	
HK base case model for BLAST	195	–	–	–	Typical	
HK (JRP, 1991)	238	313	202	–	8	
HK (Yip and Hui, 1991)	178	196	157	–	5	
Indonesia (Loewen, 1992)	147	–	–	18	4	
Malaysia (Loewen, 1992)	269	–	–	168	26	
Philippines (Loewen, 1992)	235	–	–	85	26	
Singapore (Loewen, 1992)	222	–	–	112	65	
Thailand (Loewen, 1992)	237	–	–	90	7	
ASEAN (Loewen, 1992)	233	–	–	121	128	See Note 1
Australia (Hughes, 1989)	213	289	136	–	Typical	
Greece (Santamouris, *et al.*, 1994)	187	–	–	–	186	
Japan (Fawkes, 1993)	174	–	–	–	Typical	
Japan (Matsumoto, 1990)	157	–	–	–	9	
New Zealand (Brickell Moss Raines & Stevens Ltd., 1986)	168	402	42	–	15 comm. buildings	
Singapore (Loh, 1988)	145	–	–	–	80	
Singapore (Wong, 1988)	170	–	–	–	65	
Sweden (Morse, 1990)	70	–	–	–	Typical	
South USA (EIA, 1992b, pp. 17)	247	–	–	–	Extensive	

Notes: 1. The figures for ASEAN are the averages weighted by the number of buildings audited per country in the above five ASEAN countries.

The energy utilisation index (EUI) of the base case model, in kWh/m²/annum of gross floor area, have been compared with some typical figures in Table 6.7. It is found that the EUI figures vary a lot from case to case, depending on the method of the survey and the interpretation of the collected data. Purely from these figures, it is difficult to draw conclusions about which countries have more energy-efficient buildings. The simulated figure for the base case model in this thesis is considered satisfactory since it is within 20% from the two survey results in Hong Kong.

Building peak loads

Figure 6.9 shows the components of peak cooling load for the base case model. It can be seen that occupancy loads (sensible 14.6% and latent 15%), lighting (19.3%), equipment (15%) and solar (17%) are the most important components determining the design cooling load, and hence the capacity of the refrigeration plant. Table 6.8 gives a comparison of the base case results with the results from an energy research study in Philippines which has summer conditions similar to Hong Kong.

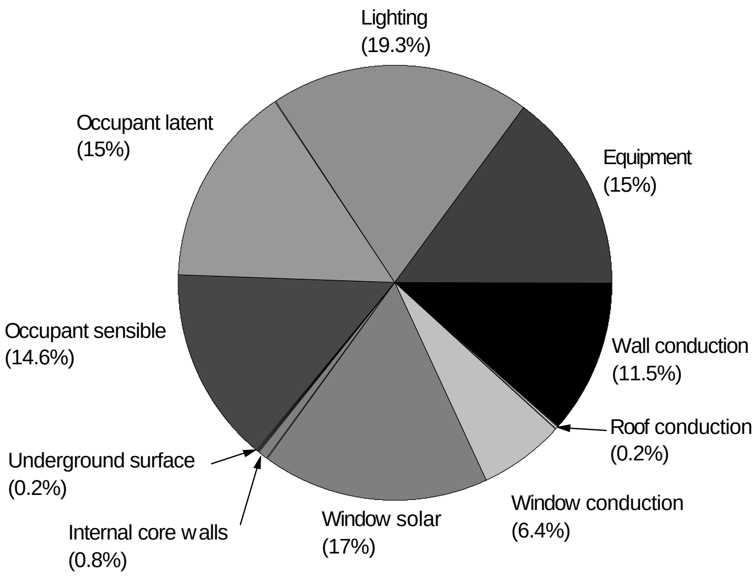

Figure 6.9 *Breakdown of Building Design Cooling Load for the Base Case Model*

Table 6.8 Comparison of Peak Cooling Load Breakdown

Type [1]	Load [2] (in W/m^2)	Peak cooling load breakdown (%) [3]										
		Solr	GC	Wall	Roof	OS	Occ	Ltg	Eqp	Infil	Misc	Int
HK Off	79.5	17	6.4	11.5	0.2	–	29.6	19.3	15	0	–	1
Philip Offices	73.3	18.9	10.3	6.3	2.8	8.6	18	19.1	7.9	5	2.9	–
Philip Hotels	65.4	22.2	12.2	8.3	2.1	7.6	14.2	18.7	6	4.6	4.1	–

Note:
1. HK Off = DOE-2 simulation results for the base case model from this study

   Philip Offices = averages for 24 office buildings in Philippines simulated using ASEAM 2.1 program (Loewen, 1992)

   Philip Hotels = averages for 8 hotel buildings in Philippines simulated using ASEAM 2.1 program(Loewen, 1992)
2. Load = peak cooling load per air-conditioned floor area (in W/m^2)
3. Solr = glass solar; GC = glass conduction; Wall = wall conduction;

   Roof = roof conduction; OS = opaque solar; Occ = occupancy (sensible & latent)

   Eqp = equipment; Infil = infiltration; Misc load = miscellaneous load

   Int = interior walls (including partitions and underground surfaces)

The study in Philippines used the ASEAM 2.1 simulation program (Ohadi, Meyer and Pollington, 1989) to estimate the peak cooling load components for a number of surveyed buildings (Loewen, 1992). The peak cooling loads per air-conditioned floor area for Hong Kong and Philippines offices are 79.5 W/m^2 and 73.3 W/m^2, respectively, which are close to each other. But the breakdown for Philippines offices indicates that lighting (19.1%), solar (18.9%) and occupancy (18%) are the most significant components in Philippines. This kind of information on cooling load breakdown is usually taken from the results of the oad’ subprogram before the system and plant simulation (see also Section 6.1.2), since the cooling load/energy requirements at system and plant levels cannot distinguish the building load elements from the total load.

Another index for the peak building cooling load is the ooling load check figures’ which are commonly used by HVAC designers to assist in initial planning and assessment of the design cooling plant capacity

(ASHRAE, 1979, pp. A1.8; Carrier Corporation, 1969, pp. 2). The check figures are often expressed in m^2/kW (or ft^2/TR), which is the ratio of the gross floor area of the building to the required cooling plant capacity or peak cooling load (the peak cooling load here refers to the cooling requirement at the system or plant level, rather than from oad’). The cooling load check figures calculated from automatic sizing of the DOE-2 simulation for the base case model is 5.4 m^2/kW (or 204 ft^2/TR). This compares with a survey results of 6.7 m^2/kW (or 254 ft^2/TR) by Yip and Hui (1991) for 51 office buildings in Hong Kong.

6.4.3 Major sensitivity findings

Since the subprograms of the simulation tools are executed consecutively, different types of cooling, heating and electrical demands are reported at different stages. The output results selected for the present study are the load and energy requirements of the primary HVAC system since they can reflect the final energy end-use of the building. Three kinds of simulation output are of interest:

- Annual building electricity consumption MWh (Megawatt-hour).
- Peak electricity kW (kilowatt).
- Monthly profiles of building electricity MWh.

Significant parameters

Input parameters with significant influence to the annual building energy consumption and design loads have been identified by studying the sensitivity coefficients and their base case characteristics. Significant parameters are those which have high sensitivity coefficients and large effects on the simulation output for the practical design range concerned (see Appendix VII for the ranges and base case values). The most important parameters found in the sensitivity study are:

- *For building load* – Occupancy density, lighting load and equipment load are the most important. Other important parameters include the design variables of the window system and building envelope.

- *For HVAC system* – Cooling thermostat setpoint, supply fan efficiency and fan statistic pressure are essential.

- *For HVAC refrigeration plant* – Chiller coefficient of performance, chilled water supply temperature, chilled water design temperature difference and chilled water pump impeller efficiency are significant.

Corson (1992) found that the building energy models for commercial buildings are sensitive to measures affecting occupancy, weather, air supply, systems and plant. It is believed that similar properties can be found in other geographical locations since design and operation of commercial buildings often share common characteristics. The parameters identified as significant in the sensitivity analysis will be taken to detailed study in Section 6.5.

Sensitivity on annual building energy consumption

The simulation output of interest is the total building electricity consumption in MWh. Sensitivity coefficients calculated for the annual MWh for the most important parameters are summarised in Table 6.9. Three forms of sensitivity coefficients as discussed before in Table 6.5 are calculated and the coefficients of determination (R^2) for linear regression for the correlation of the input parameters are provided. It can be seen that the important parameters have strong linear relationship with the building energy consumption since their R^2 are close to unity.

Table 6.9 Sensitivity Coefficients for Annual Electricity MWh

Abb.	Input parameter [2]	Sensitivity coefficients for annual electricity MWh [1] Form (1) (MWh per input unit)	Form (2 a) (% OP per % IP)	Form (3 b) (% OP per % IP)	Coefficient of determ. (R^2) for linear regression
1. Building Load					
SC	Shading coeff. of windows	1670	0.083	0.099	0.997
WR	Window-to-wall ratio	1101	0.060	0.069	0.996
AT	Space air temperature (oC)	-44.2	-0.140	-0.138	0.996
EQ	Equipment load (W/m²)	135	0.252	0.251	1.000
LL	Lighting load (W/m²)	168	0.418	0.349	1.000
OC	Occupancy density (psn/m²)	8453	0.210	0.308	1.000
2. HVAC System					
OA	Outdoor air flow (l/s/psn)	131	0.114	0.151	0.996
TS	Therm. cooling setpoint (oC)	-283	-0.900	-0.851	0.981
FE	Inverse of fan efficiency [2]	640	0.145	0.234	1.000
FS	Fan static pressure (Pa)	0.869	0.148	0.177	1.000
3. HVAC Refrigeration Plant					
CH	Chw. supply temp. (oC)	-164	-0.136	-0.131	0.931
CP	Chiller COP (kW/TR)	2417	0.363	0.350	1.000

Notes: 1. Please refer to Table 6.5 for definition of the different forms of sensitivity coefficient.

2. The inverse of fan efficiency FE was used for determining the sensitivity coefficients and performing the linear regression.

As discussed earlier in Section 3.3, Hong Kong has recently adopted the OTTV method for the control of building envelope design. To study the properties of the envelope design variables in Hong Kong, the input parameters related to the building envelope are examined in greater details and highlighted in this thesis. Figures 6.10 to 6.12 gives the correlation between the annual MWh and the input parameters for building envelope design, including external shading, window design factors (WR and SC) and the U-values of building structure, respectively.

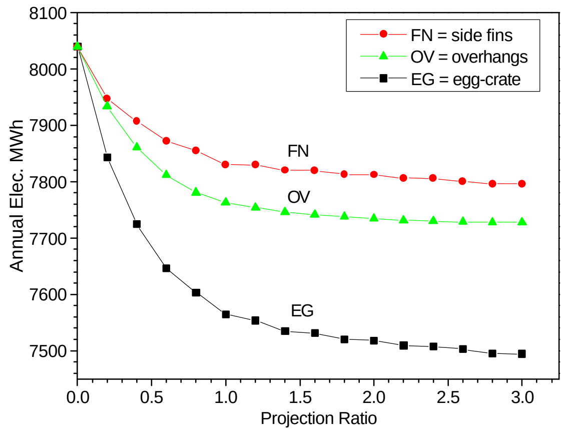

Figure 6.10 *Effects of External Shading on Annual Electricity MWh*

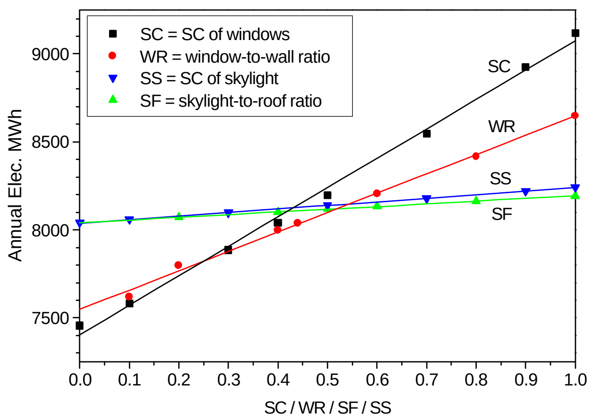

Figure 6.11 *Effects of Window Design on Annual Electricity MWh*

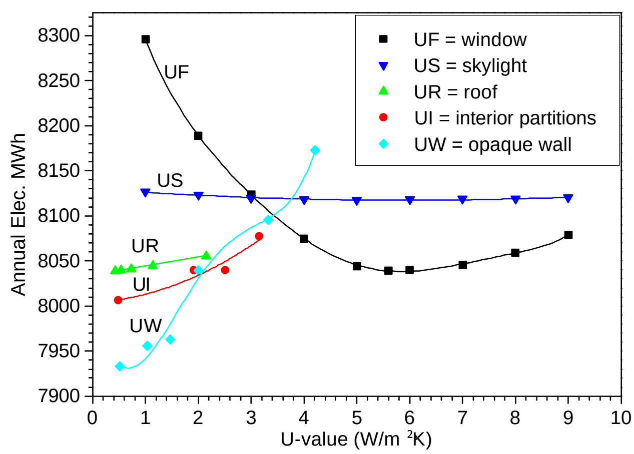

Figure 6.12 *Effects of U-values of Building Structure on Annual Electricity MWh*

Some interesting results can be observed from Figures 6.10 to 6.12. First, it can be from Figure 6.10 that the annual MWh decreases exponentially with the increase in projection ratio of the external shading devices (overhangs, side-fins and egg-crates). External shading up to a projection ratio of about 1.5 is an effective measure for energy-conserving design. Second, the regression straight lines in Figure 6.11 indicates that variables for the design of the window system have significant influence on annual building energy consumption. Third, the correlation with the U-values of building structure as shown in Figure 6.12 are varying for different building components (for example, the annual MWh increases with increase in U-value of opaque wall but decreases with the U-value of windows). The results imply that care should be taken to select a combination of envelope design which will optimise the energy performance of the building envelope.

Sensitivity on peak design loads

The simulation output of interest are the peak building electrical load and the peak cooling and heating loads in kW. Peak design loads determine the maximum demands and hence the equipment sizes and capacities required for the systems. Initial costs and operating strategies will be affected by the maximum demands, even though the annual building energy consumption remains unchanged. Table 6.10 gives the sensitivity coefficients calculated for the peak electricity kW. The figures should be treated with cautions since the determination of equipment and plant sizes often has to consider factors other than maximum demands (for example, standby capacities, safety margins and nominal ratings of equipment have to be considered). If the objective of a study is more on the initial costs of the systems, then the peak design loads should be a priority area for analysis.

Table 6.10 Sensitivity Coefficients for Peak Electricity kW

Abb.	Input parameter [2]	Sensitivity coefficients for peak electricity kW [1]			Coefficient of determ. (R^2) for linear regression
		Form (1) (kW per input unit)	Form (2 a) (% OP per % IP)	Form (3 b) (% OP per % IP)	
	1. Building Load				
SC	Shading coeff. of windows	1210	0.112	0.132	0.993
WR	Window-to-wall ratio	812	0.082	0.094	0.995
AT	Space air temperature (°C)	-32.4	-0.190	-0.187	0.982
EQ	Equipment load (W/m²)	63.6	0.220	0.218	0.998
LL	Lighting load (W/m²)	62.7	0.289	0.232	0.999
OC	Occupancy density (psn/m²)	7114	0.328	0.445	1.000
	2. HVAC System				
OA	Outdoor air flow (l/s/psn)	146	0.236	0.297	0.994
TS	Therm. cooling setpoint (°C)	-98.3	-0.580	-0.551	0.932
FE	Inverse of fan efficiency [2]	367	0.154	0.247	1.000
FS	Fan static pressure (Pa)	0.491	0.155	0.185	1.000
	3. HVAC Refrigeration Plant				
CH	Chw. supply temp. (°C)	-19.1	-0.029	-0.029	0.830
CP	Chiller COP (kW/TR)	1878	0.519	0.503	0.997

Notes: 1. Please refer to Table 6.5 for definition of the different forms of sensitivity coefficient.

2. The inverse of fan efficiency FE was used for determining the sensitivity coefficients and performing linear regression.

Figure 6.13 shows the sensitivity of peak electricity kW and annual electricity MWh against the change in floor weight. It can be seen that the two curves are similar. Both of them decrease with increase in the weight of the floor slab because of the effect of thermal mass. Unlike the annual MWh energy, peak loads are affected by the coincidence of block loads. When the hourly distributions of load components are examined, it is found that not all the load components peak and coincide at the same time. Most of them tend to peak in the summer months and the peak times are often dictated by the external weather conditions.

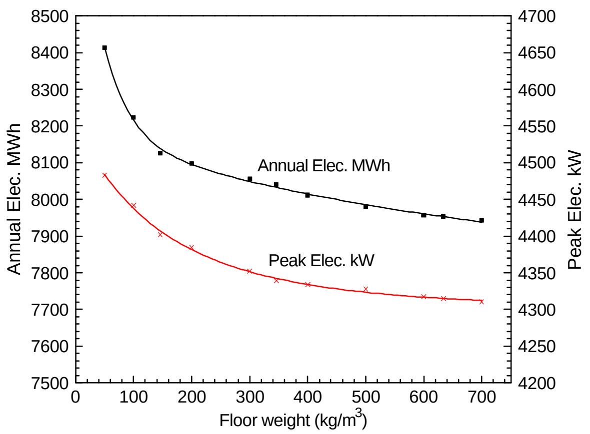

Figure 6.13 *Sensitivity of Annual Electricity MWh and Peak Electricity kW for Floor Weight*

Analysis of load profiles

The simulation outputs of interest are the monthly profiles of building electricity MWh, which provide information on the seasonal behaviour and partload performance of the building system. Figures 6.14 to 6.16 shows the monthly profiles of electricity MWh for shading coefficient (SC), outdoor air flow rate (OA) and chiller coefficient of performance (CP), respectively.

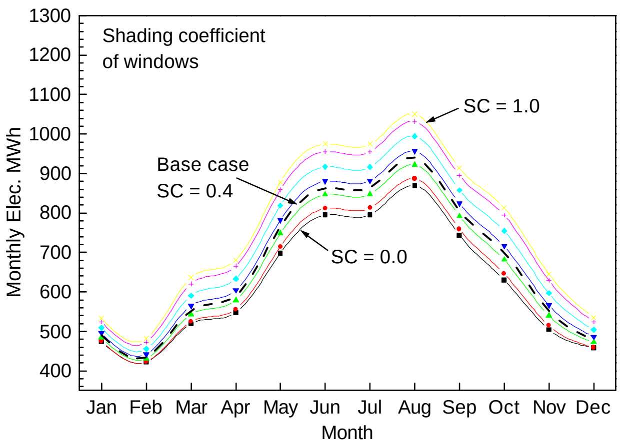

Figure 6.14 *Monthly Profiles of Electricity MWh for Shading Coefficient*

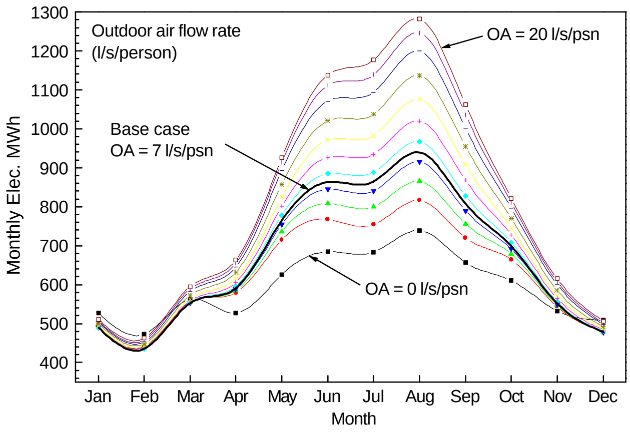

Figure 6.15 *Monthly Profiles of Electricity MWh for Outdoor Air Flow Rate*

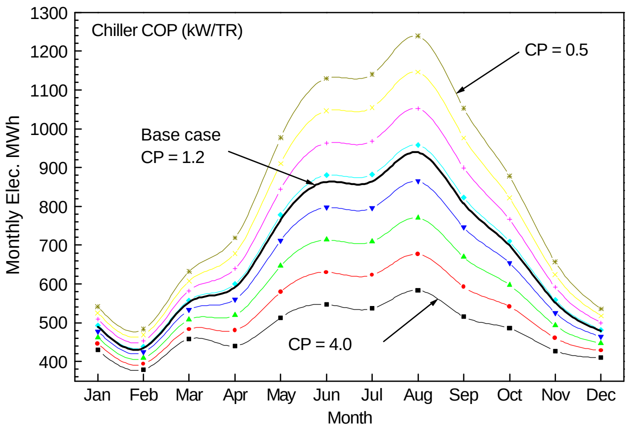

Figure 6.16 *Monthly Profiles of Electricity MWh for Chiller Coefficient of Performance*

It can be seen that some parameters affect the MWh profiles almost evenly throughout the whole year (such as SC); some parameters affect the profiles differently at different months (for example, changes in OA and CP are more influential in summer months than in winter months since they mainly affect the cooling energy use the hot summer). The sensitivity may vary throughout the year and there are potentials for improving the partload performance by controlling the parameters at different time of the year.

6.5 Regression Analysis

The principle of regression analysis applied to building energy performance studies is explained. Regression models and energy prediction equations for Hong Kong are developed and evaluated.

6.5.1 Methodology

Regression analysis is a statistical technique used to relate variables. The basic objective is to build a regression model relating a dependent variable to independent variables.

Regression-based techniques

Regression techniques are often used for studying the effects of various parameters on building energy performance (Sullivan, *et al.,* 1985; Sullivan and Nozaki, 1984) and for developing simplified equations for building energy standard (Wilcox, 1991). Usually, by varying the input variables, a large number of simulations are generated to derive algebraic expressions relating building performance to design parameters (Chou, Chang and Wong, 1993). To help assess and select the variables, techniques like sensitivity analysis and graphical diagnostic are often useful before the actual regression process. The selected parameters should make physical sense as well as being useful predictors.

With the understanding developed from the previous sensitivity analysis, regression procedure is conducted first for ingle-parameter’ study to identify the principal form of relationships. Important input parameters are then taken to detailed analysis using the multiple linear regression method to develop simple prediction equations for parameters in the groups of uilding load’, VAC system’ and VAC refrigeration plant’, respectively. Analysis for the parameters affecting building envelope design is highlighted for explaining and assessing the OTTV method commonly found in building energy standards (see also Section 3.3).

A general form of energy prediction equation is proposed which include parameters across from different groups. ross-parameter' models are then developed. To test the effectiveness of the models and to assess the relative importance of the parameters, test cases using randomised input are generated. A method is also proposed which uses randomised inputs to generate data for developing regression models. This can reduce the number of simulations required for generating the data for regressing a large number of variables.

Statistical tools

The regression procedure for single-parameter study is performed using the statistical analysis functions of a microcomputer spreadsheet program (Microsoft Excel), and the multiple regression procedure is performed on a statistical package (Norusis, 1993a) [*]. Non-linear regression technique is used for developing prediction equations for cross-parameter models which involve multiplying of different groups of variables. Basically, the statistical methods use the least square approach to find out the best fit to the data (Milton and Arnold, 1990) and the oodness of fit' of the model is measured by the coefficient of determination (R^2) (Norusis, 1993a). R^2 is equal to unity if a perfect fit is found. The tandard error', which is the standard deviation of the residuals of the regression model, is also often used to draw statistical inference about the model performance.

6.5.2 Regression models

The annual building energy consumption (MWh) and the peak electricity kW are used as the objective function for the regression analysis.

Single-parameter analysis

The analysis is basically a further step to the sensitivity study to quantify the correlation (if any) found for the input parameters. Simple linear and quadratic regressions are applied to study the simulation results from the

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[*] The SPSS (Statistical Package for Social Sciences) software version 6.0 running on Microsoft Windows is used (Norusis, 1993a & b).

sensitivity analysis which involves only changes to one single parameter at a time.

Table 6.11 gives a summary of the relationships found for the DOE-2 simulation. The regression coefficients and the R^2 values are shown for those parameters which correlate well with the energy consumption MWh (by either a linear or a quadratic relationship or both). The results suggest that many parameters of building load are, to a good approximation, linearly related to the annual consumption whereas many parameters of HVAC system and plant can be fitted by quadratic equations. This can be explained from the algorithms and equations used by the different subprograms of the simulation tool (Lam and Hui, 1993).

Multiple regression models

The twelve significant parameters identified in the sensitivity analysis (see Section 6.4.3) require greater care to study their effects on building energy performance. Six parameters in building load, four parameters in HVAC system and two parameters in HVAC refrigeration plant are taken in the detailed analysis using multiple regression method. Table 6.12 gives the perturbation values of the parameters used for the simulations. Values for the annual MWh and peak kW are extracted from the simulation results and submitted to the statistical package for multiple regression procedure.

Table 6.11 Summary of Regression Relationships for Annual MWh

Abb	Parameter	Unit	Linear regression $y = m x + c$			Quadratic regression $y = A + B x + C x^2$			
			c	m	R^2	A	B	C	R^2
					1. Building Load				
AR	Absorptance of roof	–	8037	12	0.999	–	–	–	–
AW	Absorptance of wall	–	7874	249	0.999	–	–	–	–
SC	Shading coeff.	–	7410	1674	0.998	–	–	–	–
UF	U-value of window	$W/m^2 K$	–	–	–	8421	-102	6.2	0.999
UR	U-value of roof	$W/m^2 K$	8039	10	0.996	–	–	–	–
UW	U-value of wall	$W/m^2 K$	7928	48	0.944	–	–	–	–
WR	Wind.-to-wall ratio	–	7678	855	0.994	–	–	–	–
FH	Floor-to-floor height	m	7480	168	0.998	–	–	–	–
PZ	Perimeter zone depth	m	–	–	–	8208	-6.1	5.3	0.938
AT	Space air temp.	oC	8597	-22	0.999	–	–	–	–
EQ	Equipment load	W/m^2	5975	138	1.000	–	–	–	–
IF	Infiltration	ACH	8078	-65	0.987	–	–	–	–
LL	Lighting load	W/m^2	4606	172	1.000	–	–	–	–
OC	Occup. density	psn/m^2	6383	6123	1.000	–	–	–	–
					2. HVAC System				
OA	Outdoor air flow	l/s/psn	7473	83	0.994	–	–	–	–
QR	Min. cfm ratio	–	–	–	–	7874	293	952	1.000
TR	Throttling range	oC	–	–	–	8072	-2.6	3.9	0.987
TS	Therm. setpt. cooling	oC	–	–	–	23235	-958	14.3	0.996
					3. HVAC Refrigeration Plant				
FE	Inv. of fan efficiency	–	6825	672	1.000	–	–	–	–
FS	Fan static pressure	Pa	6812	0.9	1.000	–	–	–	–
CH	Chw. supply temp.	oC	–	–	–	10495	-577	31.5	1.000
CR	Chw. thrott. range	oC	8071	-18	0.995	8075	-25	2.3	1.000
DT	Chw. design delta	oC	–	–	–	8628	159	9.6	1.000
PE	Chw. pump mot. eff.	–	8266	-245	0.997	8478	-733	279	1.000
PH	Chw. pump head	Pa	7776	13	1.000	–	–	–	–
PI	Chw. pump imp. eff.	–	–	–	–	8615	-1122	494	1.000
CP	Chiller COP	kW/TR	5145	2417	1.000	–	–	–	–
NC	Number of chillers	nos.	7941	679	0.969	8717	-184	11.3	0.975

Table 6.12 Perturbation Values for Multiple Regression Analysis

Building load:	SC	WR	AT (°C)	EQ (W/m²)	LL (W/m²)	OC (psn/m²)
(3^6 = 729 runs)	0.1	0.1	21	0	0	1
	0.55	0.5	25.5	15	15	5.5
	1.0	0.9	30	30	30	10
HVAC system:	OA (l/s/psn)	TS (°C)	FE	FS (Pa)		
(4^4 = 256 runs)	2	21	0.1	0		
	8	24	0.4	1000		
	14	27	0.7	2000		
	20	30	1.0	3000		
HVAC refrig. plant:	CH (°C)	CP (kW/TR)				
(4^2 = 16 runs)	4	0.5				
	6	1.0				
	8	1.5				
	10	2.0				

Note:
1. SC = shading coefficient of windows; WR = window-to-wall ratio; AT = space air temperate; EQ = equipment load; LL = lighting load; OC = occupant density (in person/m²)
2. OA = outdoor air flow; TS = cooling thermostat setpoint; Inv. FE = fan efficiency; FS = supply fan static
3. CH = chilled water supply temperature; CP = chiller coefficient of performance

In order to get a better regression fit, it is sometimes necessary to transform the parameter (such as inverse) and add new variables into the equation by combining two parameters (i.e. a product term of two parameters) *. Several different forms of regression models have been tested by adding the product term one by one, and the cceptable’ models are finally selected based on interpretability, parsimony and ease of use. Table 6.13 gives a summary of the final selected regression equations for the three groups of parameters.

* The new variables, if any, are entered into the regression equation using the ‘stepwise selection’ method (Norusis, 1993a).

Table 6.13 Summary of Multiple Regression Models

For parameters of building load (SC, WR, AT, EQ, LL, OC)

MWh = 1414 + 4407 SC x WR - 27 AT + 142 EQ + 182 LL + 7414 OC

R^2 = 0.9915 Standard Error = 402 MWh

Peak kW = 1317 + 3788 SC x WR - 24 AT + 76 EQ + 79 LL + 5909 OC

R^2 = 0.9844 Standard Error = 402 kW

For parameters of HVAC system (OA, TS, FE, FS)

MWh = 5188 + 542 OA + 2858 FE + 4 FS + 0.0000427 FS x FS + 4.62 TS x TS - 18 OA x TS - 113 TS x FE - 0.23 TS x FS + 0.731 FS x FE

R^2 = 0.9674 Standard Error = 1172 kW

Peak kW = 3547 + 233 OA + 1206 FE + 1.47 FS + 0.000197 FS x FS + 1.89 TS x TS - 6.84 OA x TS - 47.1 TS x FE - 0.0908 TS x FS + 0.357 FS x FE

R^2 = 0.9708 Standard Error = 536 kW

For parameters of HVAC refrigeration plant (CH, CP)

MWh = 6222 - 120 CH + 2811 CP R^2 = 0.9897 Standard Error = 181 MWh

Peak kW = 2713 - 76 CH + 2348 CP R^2 = 0.9935 Standard Error = 119 kW

Note:
1. SC = shading coefficient of windows; WR = window-to-wall ratio; AT = space air temperate; EQ = equipment load; LL = lighting load; OC = occupant density (in person/m^2)
2. OA = outdoor air flow; TS = cooling thermostat setpoint; Inv. FE = fan efficiency; FS = supply fan static
3. CH = chilled water supply temperature; CP = chiller coefficient of performance

For parameters of building load, i.e. SC, WR, AT, EQ, LL and OC, it is found that the term C x WR’ has significant influence, as the R^2 values will be improved much by its entering into the equation. The R^2 values calculated for MWh and peak kW are 0.9915 and 0.9844, respectively, and this indicates a good fit for the model. The regression coefficients of the terms OC and C x WR’ show that they are the most important for determining the load and energy performance. For parameters of HVAC system, i.e. OA, TS, FE and FS, more product terms are needed to get a satisfactory fit for the regression equation and the fan efficiency (FE) is the most essential parameter. For parameters of HVAC refrigeration plant, the form of equation is quite simple, as there are only two parameters selected (other parameters are either qualitative or not correlated linearly).

Analysis for building envelope parameters

Building envelope design is an important area for building energy standards and the overall thermal transfer value (OTTV) method is commonly used for its control in developing countries, such as Hong Kong and Singapore (see also Section 3.3). Deringer and Busch (1992) has explained the general methodology for developing OTTV equations in ASEAN. The process involves parametric studies using detailed simulation program and regression analysis of the parametric results for determining the OTTV parameters. Figure 6.17 gives an overview of the methodology. Care must be taken to understand not only the procedure, but also the implications and assumptions behind the OTTV equation.

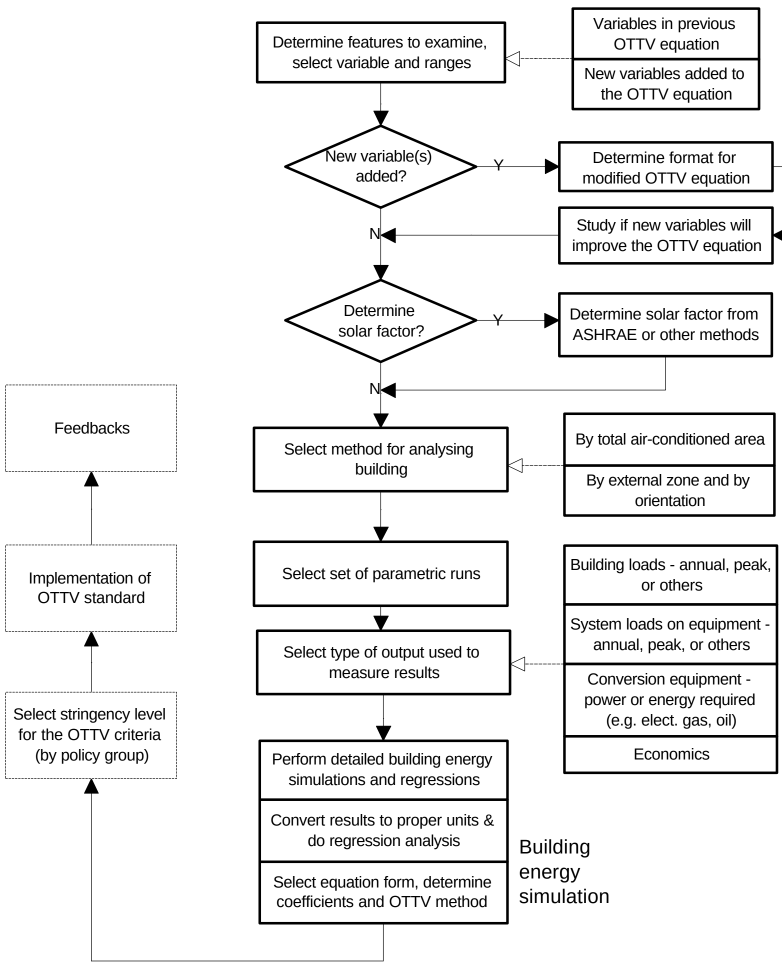

Figure 6.17 *Methodology of OTTV Analysis for Building Energy Standards*

An analysis has been performed using multiple regression to study the design parameters of building envelope and their properties in the OTTV formula. Four parameters (SC, WR, UF and UW), which are the key variables in common OTTV equations, are selected. Table 6.14 gives the perturbation values of the parameters used in the DOE-2 simulation for generating the regression data. Two sets of regression equations have been determined, one using only the four basic parameters and another using a formula similar to the OTTV equation.

Table 6.14 Perturbation Values for Multiple Regression Analysis for Building Envelope Parameters

	SC	WR	UF ($W/m^2 \cdot K$)	UW ($W/m^2 \cdot K$)
Building envelope parameter: (4^4 = 256 runs)	0.1	0.05	1	1.038
	0.4	0.35	4	2.005
	0.7	0.65	7	3.321
	1.0	0.95	10	4.208

Note: 1. SC = shading coefficient of windows; WR = window-to-wall ratio; UF = U-value of window glass; UW = U-value of opaque wall

Table 6.15 Summary of Multiple Regression Models for Building Envelope Parameters

For parameters of building envelope (i.e. SC, WR, UF, UW)
MWh = 6728 + 2517 SC + 2119 WR - 31 UF + 85 UW
R^2 = 0.7826 Standard Error = 593 MWh
Peak kW = 3327 + 2485 SC + 1982 WR - 61 UF + 60 UW
R^2 = 0.7569 Standard Error = 626 kW
For parameters of in the form of OTTV variables [2]
MWh = 7786 + 152 (1 - WR) x UW - 55 WR x UF + 5055 WR x SC
R^2 = 0.9798 Standard Error = 180 MWh
Peak kW = 4314 + 90 (1 - WR) x UW - 113 WR x UF + 5045 WR x SC
R^2 = 0.9638 Standard Error = 240 kW

Note: 1. SC = shading coefficient of windows; WR = window-to-wall ratio; UF = U-value of window glass; UW = U-value of opaque wall

2. The regression is done using a transformation of variables, like this:

X = (1 - WWR) x UW Y = WWR x UF Z = WWR x SC

Table 6.15 shows the regression equations determined for the two cases. It can be seen that the goodness of fit for the equation using only the four basic parameters is not satisfactory (R^2 = 0.7826 and 0.7569 for MWh and peak kW, respectively). The major reason is the omission of the C x WR’ term in the equation. The regression equation using the OTTV formula is quite good for both MWh (R^2 = 0.9798) and peak kW (R^2 = 0.9638). This result implies that the OTTV formula has close (linear) relationships with building energy performance and the parameters on solar design of window (SC and WR) are most influential. The regression coefficients derived using the OTTV formula are similar to the coefficients TD_{eq}, DT and SF in the OTTV equation (see Section 3.3). By comparing the regression coefficients developed for different weather files (such as for different geographical locations), it is possible to assess for different climates the relative importance of the wall conduction, window glass conduction and window solar. For Hong Kong, the solar coefficient for the C x WR’ term is the most important as shown in Table 6.15.

6.5.3 Develop energy equations

If the regression equations are extended to include all the design parameters, a set of nergy equations’ can be developed to provide an effective means for analysing building energy performance and energy targets (Lam, 1992a; Cornell and Scanlon, 1975; Briggs and Brambley, 1991).

Forms of equation

If the parameters of oad’, ystem’ and lant’ are considered as three group functions, the general form of energy equation will be like this:

$$E = Function\ [\ (Load), (System), (Plant)\ ] \qquad (6.3)$$

where E = energy or load index, such as annual MWh and peak kW

Load = f (envelope, internal loads, etc.), such as f (SC,WR,AT,EQ,LL,OC)

System = g (system operations, controls, fans), such as g (OA,TS,FE,FS)

Plant = h (chilled water circuit, refrigeration plant), such as h (CH, CP)

The simplest formula for expressing the above function will involve adding of the group functions, like this:

$$E = constant + (Load) + (System) + (Plant) \quad (6.4)$$

where *constant* = regression constant in the equation

Another way of expression is to multiply all group functions, like this:

$$E = (Load) ◈ (System) ◈ (Plant) \quad (6.5)$$

These two forms are used to develop energy equations relating parameters coming from different groups. The dding’ expression (Equation (6.4)) can be established using multiple regression as in the previous section, but the ultiplying’ expression (Equation (6.5)) cannot. To tackle this problem, nonlinear regression is used to develop prediction equation for the latter. The nonlinear regression procedure in the statistical software solves the regression problem by iteration (Norusis, 1993b).

Cross-parameters models

Cross-parameter models involve variables coming from different group functions (i.e. load, system and plant). A simple model was derived to see the effects of using cross-parameters. Table 6.16 gives the perturbation values for the DOE-2 simulation to generate models for the most important parameter(s) in each group, i.e. SC, WR, OA and CP. Table 6.17 shows the cross-parameter regression equations developed for this case. It can be seen that the goodness of fit again is not very satisfactory when the C x WR’ term is not included (R^2 = 0.9156 and 0.9093 for MWh and peak kW, respectively). When this term is used, the R^2 for MWh is increased to 0.9586. The regression coefficients of the terms in Table 6.17 can be compared with the corresponding values from the previous individual group models in Table 6.13. It can be seen that the values for C x WR’ and CP do not differ very much when parameters from other groups are introduced. But those for OA are quite different since individual group models for OA involve other product terms.

Table 6.16 Perturbation Values for Multiple Regression Analysis for Cross Parameters

	SC	WR	OA (l/s/psn)	CP (kW/TR)
Cross parameter:	0.1	0.1	2	0.4
(3^4 = 81 runs)	0.55	0.4	11	1.2
	1.0	0.9	20	2.0

Note: 1. SC = shading coefficient of windows; WR = window-to-wall ratio; OA = outdoor air flow rate; CP = chiller coefficient of performance (COP)

Table 6.17 Summary of Multiple Regression Models for Cross Parameters

For cross parameters of all three groups (SC, WR, OA, CP)

MWh = 2377 + 2446 SC + 1786 WR + 92 OA + 3262 CP

R^2 = 0.9156 Standard Error = 777 MWh

Peak kW = -100 + 2053 SC + 1491 WR + 68 OA + 2900 CP

R^2 = 0.9093 Standard Error = 703 kW

For cross parameters of all three groups (SC, WR, OA, CP) using the SC ◈ WR term

MWh = 3722 + 4771 SC x WR + 92 OA + 3262 CP

R^2 = 0.9586 Standard Error = 544 MWh

Note: 1. SC = shading coefficient of windows; WR = window-to-wall ratio; OA = outdoor air flow; CP = chiller coefficient of performance (COP)

Testing models using randomised simulation input

To test the predictive power of the regression models, a method is proposed to generate datasets using andomised' input values for the parameters. The procedure for generating the randomised input and data involve the following steps:

- Select the parameters to be studied.
- Determine the range of variations of each parameter.
- Establish the values of the parameters in the simulation input file by a andom-number generator' (the values should be within the ranges).
- Establish as many random input files as necessary.
- Submit the input files to detailed simulation.

- Using the regression equation concerned, calculate the predicted outcomes (such as MWh and peak kW) of each input file.

- Obtain the simulation results and compare with the predicted values.

Some simple tests have been performed for the 12 parameters used earlier for building regression models:

- Building load (SC, WR, AT, EQ, LL, OC) – 20 random simulation runs

- HVAC system (OA, TS, FE, FS) – 20 random simulation runs

- HVAC refrigeration plant (CH, CP) – 20 random simulation runs

Twenty simulation runs were performed to generate the test data for the previous regression models. Figures 6.18 to 6.20 shows the comparisons of MWh predictions for the load, system and plant models, respectively. It can be seen that the models are quite good in predicting the 20 sets of randomised data.

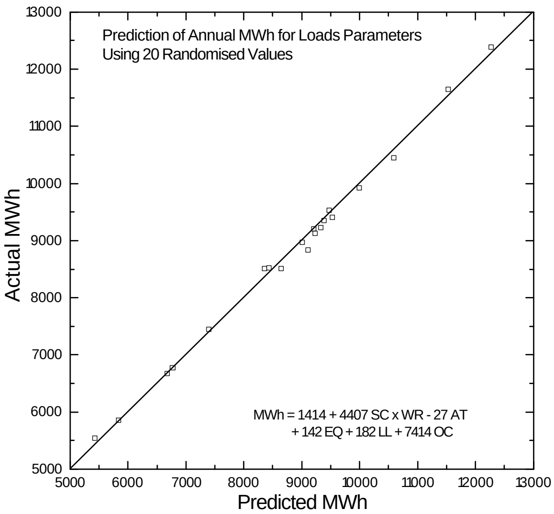

Figure 6.18 *Comparisons of MWh Predictions Using Randomised Simulation Inputs for Load Model*

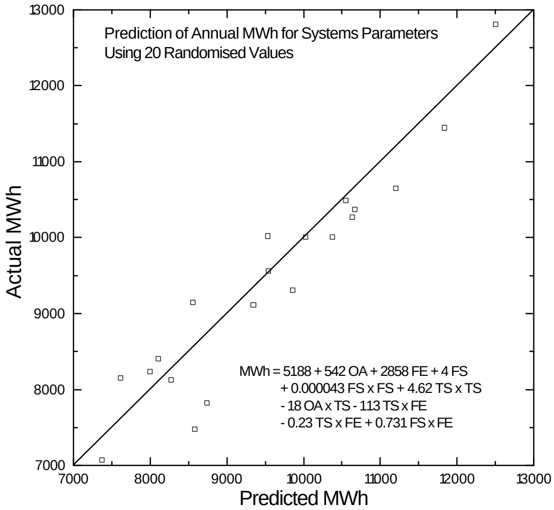

Figure 6.19 *Comparisons of MWh Predictions Using Randomised Simulation Inputs for System Model*

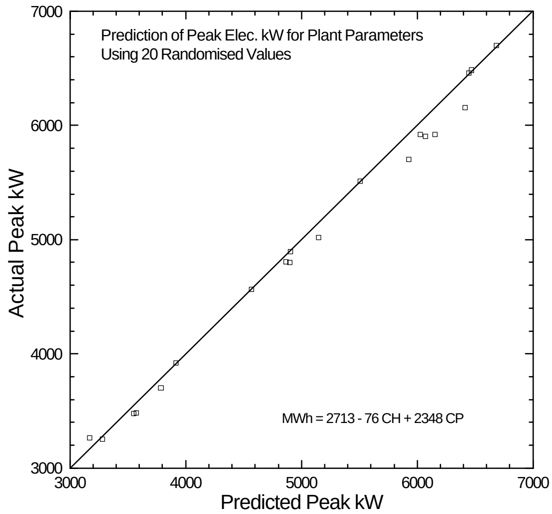

Figure 6.20 *Comparisons of MWh Predictions Using Randomised Simulation Inputs for Plant Model*

Generate regression models using randomised inputs

When the number of parameters is large, an enormous amount of simulations have to be done to generate data input for the regression analysis. The total number of simulations for all combinations of the perturbations of the input parameters may be unacceptably large. For example, if there are 12 parameters and each of them require 3 perturbation values, then the total number of simulation required for all combinations of them is equal to 3 to the 12th power (3^{12}), i.e. 531,441 simulations. To tackle this problem, a method using randomised simulation inputs for the parameters is proposed so that less simulations are needed to generate the dataset for regression analysis.

The process is very similar to the randomised testing carried out previously, but more simulation runs will be conducted to build the regression model. It is believed that the number of simulations required depends on the number and the properties of the parameters involved. Generally speaking, the more simulations are done (more cases), the more representative the regression model will be. However, it is difficult to determine the minimum number required for every situation, unless a feedback mechanism can be installed in the simulation cycle to check for the necessity of including more cases.

To develop a regression model for all the 12 parameters studied previously, the author has performed 100 simulations on DOE-2 to generate the MWh data which are taken to the linear and nonlinear regression analysis. The randomised simulation process has also been added as an option to the automated procedure of the supporting program UTODOE2’ (see Section 6.2.2). Table 6.18 gives the selected MWh models developed using both the dding’ and ultiplying’ forms of equations (see Equations (6.4) and (6.5)). It can be seen that the multiplying form can give a better fit (R^2 = 0.988) as compared with the adding form (R^2 = 0.9202). The former one is therefore recommended.

Table 6.18 Regression Models for Twelve Parameters

For 12 parameters of all three groups (SC, WR, AT, EQ, LL, OC, OA, TS, FE, FS, CH, CP)

Multiplying model:

MWh = (Load) x (System) x (Plant)

= (-1.38 - 7.3 SC x WR - 0.0151 AT - 0.167 EQ - 0.206 LL - 9.6 OC)
x (-340 - 73.7 OA -412 FE - 0.406 FS - 0.0000384 FS x FS - 0.644 TS x TS
+ 2.49 OA x TS + 16.7 TS x FE + 0.0215 TS x FS - 0.0872 FS x FE)
x (0.508 - 0.0109 CH + 0.311 CP)

R^2 = 0.9880

For 12 parameters of all three groups (SC, WR, AT, EQ, LL, OC, OA, TS, FE, FS, CH, CP)

Adding model:

MWh = constant + (Load) + (System) + (Plant)

= -4107 + (4757 SC x WR - 20.5 AT + 166 EQ + 223 LL + 9120 OC)
+ (-415 OA + 4315 FE + 6.79 FS + 0.000672 FS x FS + 2.26 TS x TS
+ 18.9 OA x TS - 193 TS x FE - 0.367 TS x FS + 1.09 FS x FE)
x (- 304 CH + 3891 CP)

R^2 = 0.9202

Note:
1. SC = shading coefficient of windows; WR = window-to-wall ratio; AT = space air temperate; EQ = equipment load; LL = lighting load; OC = occupant density (in person / m^2)
2. OA = outdoor air flow; TS = cooling thermostat setpoint; Inv. FE = fan efficiency; FS = supply fan static
3. CH = chilled water supply temperature; CP = chiller coefficient of performance

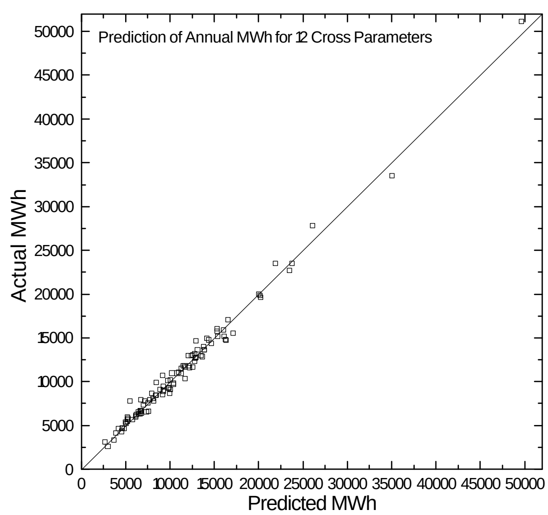

Figure 6.21 *Comparisons of MWh Regression Fit for the 12-parameter Model*

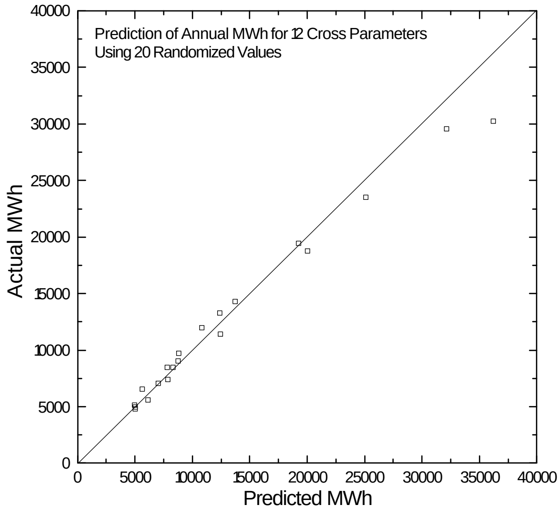

Figure 6.22 *Comparisons of MWh Predictions Using Randomised Simulation Inputs for the 12-parameter Model*

Figure 6.21 shows the regression fit of the selected 12-parameter model. The data points indicate the distributions of MWh in the original 100 dataset which are used to build the model. A randomised sample test has also been performed for the 12-parameter model using 20 randomised values. Figure 6.22 shows the performance of the model. It can be seen that the model can perform quite well for the test cases.

The regression analyses in this thesis demonstrate the benefits and potentials of an approach to expressing building energy performance in terms of a number of design variables which will be considered critical at the early design stage. What is suggested is a simplified and flexible method which offers the possibility of developing equations and criteria for energy performance that can extend beyond the common OTTV methods. It is believed that these techniques can be used to establish a form of energy target which can be integrated into building energy standards to help designers assess the true building energy performance effectively.