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EFFECTIVE USE OF BUILDING ENERGY SIMULATION FOR ENHANCING BUILDING ENERGY CODES

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ABSTRACT

Building energy simulation is playing an increasingly important role in building energy codes. This paper investigates the important underlying issues affecting the use of building energy simulation for enhancing building energy codes. The background and development of building energy codes is described. The rationale and important issues of performance-based building energy codes are explained. The practical building design and essential simulation skills are presented. Finally, the key factors affecting the effectiveness and validity of the simulation approach are discussed.

INTRODUCTION

Building energy simulation is playing an increasingly important role in building design. A review of the relevant literature will show a healthy and growing application of building thermal and energy simulation tools to building design problems in many parts of the world (CIBSE, 1998; Clarke, 2001; Hui, 1998; Waltz, 2000; Wong, Lam, and Feriadi, 2000).

To promote energy conservation and control building design, many countries have developed or upgraded their building energy codes in the past decade (ASHRAE, 2001a; Hui, 2000; Janda and Busch, 1994). Very often, building energy simulation tools are being used for analysing the energy consumption in buildings so as to establish the basis for the building energy codes and their energy efficiency requirements. Moreover, in order to holistically consider the building's energy performance, building energy simulation is also taken as the evaluation method for determining code compliance under a performance-based approach (Briggs and Brambley, 1991; Hui, 2002).

An important trend for modern building energy codes is to move towards a greater use of building energy simulation and modelling techniques. This can help people understand the complex issues of building energy performance and improve the flexibility, clarity and effectiveness of the regulatory documents. However, as building energy simulation is a complicated process involving modelling and analytical skills, the building designers and practitioners often find it difficult to carry out the building energy analysis and comprehend the simulation results. Even the experienced energy modellers and government officials are sometimes puzzled by a wide range of simulation software and feel uncertain about the validity and accuracy of the energy calculations.

This paper investigates the important underlying issues affecting the effective use of building energy simulation for enhancing building energy codes. The background and development of building energy codes is described. The rationale and important issues of performance-based approach to building energy codes are explained. The practical building design and essential simulation skills are presented. Finally, the key factors affecting the effectiveness and validity of the simulation approach are discussed.

BUILDING ENERGY CODES

Building energy codes are implemented in many countries to provide a degree of control over building design and to encourage energy efficient design and operation of buildings (Hui, 2000; Janda and Busch, 1994). Traditionally, building energy codes are prescriptive in nature as they specify for each building component the minimum requirements to satisfy the code, such as minimum insulation levels and equipment efficiencies. Prescriptive requirements are simple to use and follow, but they tend to limit design freedom and might be a barrier to innovation, new building technologies and creative design techniques. Also, they are not able to consider the interactions between different building systems and the measures that would optimise their combined performance. In order to minimise these drawbacks, alternative code compliance paths are needed.

Figure 1 shows the major elements and compliance paths for modern building energy codes. These elements include building envelope, lighting, heating, ventilating and air-conditioning (HVAC), electrical power, lifts & escalators and service water heating. The basic/mandatory requirements on the top are fundamental issues that must be satisfied all the time. After that, there are three options for code compliance and the designer or building owner may decide which one to adopt.

(a) Prescriptive requirements: they are the "deem-to-satisfy" conditions.

(b) System/component performance: It is a partial-performance path and can allow "trade-offs" in some design parameters within the component or sub-system.

(c) Energy budget/cost: It is a full-performance path and will usually require detailed energy calculations based on simulation methods.

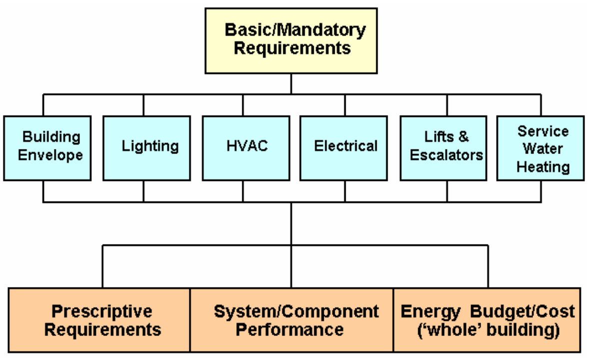

Figure 1. Major elements and compliance options for building energy codes

When formulating the requirements in building energy codes, building energy simulation is often employed to generate data and information for determining the compliance criteria and/or equations. For example, the system/component performance methods that some countries have adopted are developed based on analysis of simulation results and multiple regression techniques (Crawley, 1995; Hui, 1997; Wilcox, 1991). It is believed that the outcome of the building energy simulation will affect the properties and effectiveness of the building energy codes. However, the effect is not straightforward and the relationship is often clouded by a number of factors such as modelling assumptions and experience with the simulation software.

PERFORMANCE-BASED APPROACH

To consider and evaluate the 'whole' building energy performance, some countries have designed and implemented a performance path using an energy budget/cost method. For example, in ASHRAE Standard 90.1, an energy cost budget method is being used to evaluate the building's energy performance. Compliance is established by calculating the energy consumption/cost for the proposed building and ensuring that it does not exceed an energy budget or target (ASHRAE, 2000).

In Canada, a similar approach called building energy performance method is being used for both commercial and residential buildings (CCBFC, 1999a & b). The calculation is based on computer-based building energy simulation and must be carried out using software that conforms to specifications set out by the authority.

In California, a list of approved computer programs have been specified by the energy commission (see "http://www.energy.ca.gov/title24/" for details) and they are the only programs that should be used under the energy budget methods of compliance for the Title 24 energy standards (CEC, 2001a). Approval manuals and procedures have been established to determine which software is acceptable for use in the performance compliance path (CEC, 2001b & c).

In recent years, the performance approach is being considered by countries in Asia and other parts of the world (ABCB, 1999; Chou, 2001; Hui, 2002; Wong, Lam, and Feriadi, 2000). Some of them are developing the so-called 'performance-based building energy codes' or incorporating the performance path and requirements in their existing codes. The main assessment procedure is to compare annual energy use of the proposed building to a similar prototype or reference building. Compliance with the code is achieved if the annual energy consumption for the proposed building is less than or equal to the annual energy consumption for the reference building. Figure 2 shows the compliance procedure for the performance-based building energy code being developed in Hong Kong.

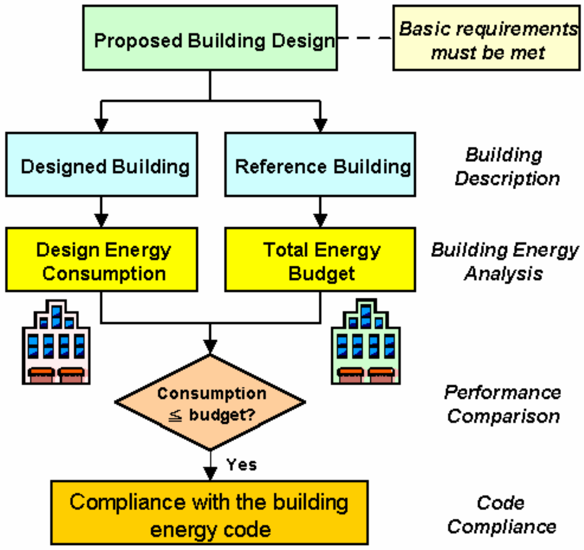

Figure 2. Compliance procedure for performance-based building energy code

IMPORTANT ISSUES TO CONSIDER

The performance-based code sets a maximum allowable energy consumption level without specification of the methods, materials, processes to be employed to achieve it. The onus will be on the designer to present a design solution together with appropriate predictive evidence of its energy behaviour. To ensure a fair and consistent comparison, it is necessary to specify the simulation and analysis process in a systematic way. The simulation tool, calculation procedure and modelling assumptions must be clearly defined to avoid cheating and manipulation of results.

However, as with any computer modelling, the process specification is not straightforward. It is often hindered by the large variety of building energy software, different ways of abstracting the problem into the model and the judgement required for choosing appropriate assumptions. To come up with a reasonable outcome, a critical examination of the building energy simulation is urgently needed.

(a) *Simulation software*

The building energy simulation software available in the market ranges from the simple and approximate to the detailed and sophisticated. Selecting a program for a particular job requires matching the tool to the task. Usually, building designers will select a specific software based on their own experience and familiarity, the type of features to model, the required level of detail, the contract requirements and any regulatory guidance.

At present, program users must rely on the documentation and verification provided by the software developers or large independent bodies, since they do not have enough resources to carry out extensive validations. Even if the program is regarded as verified at some acceptable level, questions may still arise concerning the validity of results obtained by users who are not familiar with the limitations of the program.

Should the Authority certify or otherwise approve the use of certain computer programs for doing the building energy calculation? This question will need to be considered from a practical perspective.

If there are not any approved programs, the proliferation of unapproved program will necessitate the review of all program algorithms each time a plan review is performed. Pre-certification of programs and user instructions will reduce plan check work. However, the effort and resources required to assess and certify the various simulation programs are not insignificant, as shown in California Title 24.

When the Authority considers a specific program acceptable for the code compliance, it is often more effective and convenient if the accuracy and performance of the programs can be compared to a "reference program" (such as DOE-2) which is widely accepted and extensively tested.

(b) *Reference building*

Definition of the reference building is often a controversial matter in the performance-based code. Basically, the reference building is a variant of the proposed design building but with all the prescriptive requirements satisfied. Usually, the reference building and the proposed building have the same energy sources, geometry, floor area, exterior design conditions, occupancy, thermal data, etc. The only difference is that the reference building is designed with its envelope, building elements and energy-consuming systems conforming to the prescriptive requirements for these building components or elements.

The reference building is intended to assure neutrality with respect to choices of architectural design, HVAC system, etc. To make the analysis reasonable, there is a need to ensure "fair" comparison between the design building and reference building. The procedure commonly adopted is to set up first the simulation input of the design building and then modify it to form the reference building that will meet exactly the requirements as laid down in the prescriptive requirements.

For those input parameters which have not been specified in the prescriptive requirements, it might be necessary to define the modelling assumptions according to sound professional judgements.

(c) *Modelling assumptions*

These modelling assumptions might include operating schedules, internal loads, etc. and are provided to ensure that common conditions were being used across the analyses of different buildings. When deciding on the modeling assumptions, it is very difficult if not impossible to cover every possible range of functions and every combination of design parameters. As different building energy software might have different input requirements and formats, it is also necessary to consider the compatibility of the assumptions.

Even though every effort has been taken to spell out the requirements and assumptions, it is expected that some situations will require special considerations. For the sake of regulatory control, it is reasonable to suggest that no trade-offs shall be given to those issues which cannot be clearly defined or spelt out. That means, the issue shall be set out and modelled in exactly the same way for the design building and reference building, when doing the energy calculations.

The building energy simulation relies on the users to make reasonable assumptions for the factors affecting energy use. Since this is a comparative analysis and the design and reference buildings use similar assumptions, the building energy consumption is expected to be reasonable predictions under this background.

PRACTICAL BUILDING DESIGN

The increase in computing speed and memory is allowing more sophisticated and complex tools to be used in building design. For example, full hourly energy analysis (8,760 hours in a year) and detailed dynamic thermal models can now easily be used in building energy simulation programs running on personal or laptop computers. Nevertheless, detailed building energy simulation programs, although powerful and sophisticated, are seldom used by practising building designers like architects and building services engineers. Many building designers are reluctant to use the simulation software because of the lack of confidence in the simulation results and the time and effort needed to learn how to use them.

The accelerating MHz (Mega Hetz) of the modern computers would not change people's altitude towards the use of simulation tools in design practice, partly due to the weak knowledge base of practitioners in this aspect and also due to the polarisation of focus between design and simulation (Hui, 1998). As building design is a creative process based on iteration, the architectural and engineering designs will move back and forth to synthesize the design solution within given constraints. This will make simulation data and process difficult to define and conduct. For instance, during early design stages, architectural ideas and concepts are ill-structured and not well-defined. The data and information required for building simulation are either not available or only approximated. This will create an obstacle to the use of detailed simulation tools that require full building description.

In actual situation, the building design is a teamwork and the team of people with the right skills and experience must be assembled at the start to meet the project design priorities. At present, many smaller firms would not find it practical to have on staff an energy specialist who can maintain current knowledge of building energy simulation. If a building energy analysis is needed, such as to meet the performance-based requirement or upon the client's request, then another energy consultant will be employed to carry out the task. To achieve timely design feedback and effective decision making, good communication and collaboration between different design professionals and consultants is necessary.

SIMULATION SKILLS

Figure 3 indicates the key concerns of building energy simulation. Human judgement and experience is a critical factor in building energy simulation and analysis because the program user is the one who determines how the information are put together to define the problem and analyse the building. Given the same problem, the end results are a function of both the program and the user. As the software knows no context, a critical mind is needed to design the analysis, interpret the results and determine the consequences. The design and modelling skills of the program user play an important role in the quality and adequacy of the results produced from the simulation models.

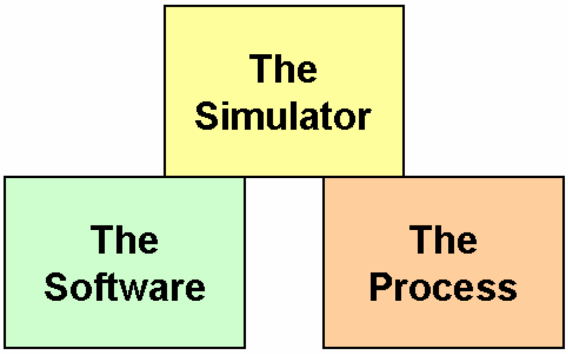

Figure 3. Key concerns of building energy simulation

To conduct the analysis properly and effectively, the aims of the study and the intended use and possible limitations of the simulation tool must be fully understood. The level of technical knowledge needed to correctly use the simulation tools are often high so that mis-applications and mis-interpretations are not uncommon in building energy studies. In the past (and still with some simulation tools at present), the user interface is the weakest part of a building energy simulation program. With increasing popularity of graphical user interface (GUI) and windows-based approach, the problem with user friendliness has been partly resolved.

However, although some percentages of the possible mistakes have been eliminated, there are still many opportunities for an unwary user to make significant errors when performing the simulation, for example in problem definition and key assumptions. Therefore, proper guidance and quality control are essential for ensuring meaningful results and reasonable judgement. Some guidelines and manuals have been published in recent years to provide assistance to building energy 'simulators'. Examples are CIBSE

(1998), Kaplan and Caner (1992) and SEDA (2001a, b & c). Specific guidance on energy budget/cost calculation can also be found in the user guides of relevant energy standards such as ASHRAE (2000) and CEC (2001a).

KEY FACTORS

There are three main factors affecting the effective use of building energy simulation tools in building design, namely: complexity, accuracy and validity.

(a) *Complexity*

Building energy simulation requires a large amount of detail for input and will produce a lot of data in its output. It often takes so much time and effort to become familiar and competent with just one simulation program. Given the variety of available software and procedures, new simulation users still confront a steep learning curve and this will discourage the use of the simulation in the building designer's office. If the simulation tools demand a lot from their users, then the naive user was as likely to be misled as helped. The inherent complexity of the simulation model often distances the user from a clear appreciation of the underlying issues and physical processes. When the users become overwhelmed by specific aspects, they tend to lose sight of the overall objective and interrelationships within the procedure.

There is no easy way out when dealing with a complex simulation model. But some enhancements in the import/transfer of building geometric data from architectural drafting program and the intuitive/cognitive design of program interfaces will be helpful. Also, when the situation allows, for example, during early design stages, a less complicated simulation program can be used as the first evaluation tool to establish the information and data needed for early design decisions (ideally, the data could be extended later for use in detailed simulation programs). To make this feasible under the building energy codes, building energy software with different levels of sophistication shall be allowed and the developing nature of simulation process shall be considered in the framework of the codes.

(b) *Accuracy*

A controversial issue with building energy simulation is the program's ability to deliver accurate results. Because of the complex and lengthy computational procedures, step-by-step verification of simulation results is generally impractical. Thus, in most cases the program accuracy has to be taken on trust (Wright, Bloomfield and Wiltshire, 1992). In many other 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 is irrelevant (Wiltshire and Wright, 1988).

When comparing different simulation programs, the results 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. In addition, the discrepancies between the actual and predicted energy consumption, and between the predictions from different programs, are often found very large in validation studies. It should be noted that the accuracy level changes as a function of the quality of design information supplied 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.

Fortunately, in the performance-based building energy codes mentioned before (see Figure 2), only a comparative study is needed for determining code compliance (designed building versus reference building). To a certain extent, absolute accuracy of each calculation is not very critical. As long as the background and assumptions of the two buildings are consistent and the same simulation tool and process are being used, the outcome would be reasonable and acceptable. What is more important will be the assessment of particular trade-off options being proposed in the designed building. For example, is it reasonable to enhance the lighting system in order to compensate for a less energy-efficient building envelope? Accurate evaluation of such a proposal is important to ensure that the result will enhance overall performance.

(c) *A matter of validation*

In building energy simulation, the meaning of program validation and verification must be considered in context. Bloomfield (1989) pointed out 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. In fact, all building simulation models are simplifications of reality and there is no such thing as a completely validated building energy simulation program (ASHRAE, 2001b).

Nonetheless, although the validation process is time consuming and not definite, it is important to have validation procedures that address quality control of the building energy and environmental software (Bloomfield, 1999). In recent years, standard validation methods for energy software are just appearing (Ben-Nakhi and Aasemb, 2003). Some professional bodies have developed standard test methods for identifying and diagnosing differences in predictions for whole building energy simulation software that may possibly be caused by software errors. The most representative ones are:

- the International Energy Agency (IEA) building energy simulation test (BESTEST) diagnostic method (Judkoff and Neymark, 1995)
- ASHRAE standard method of test for building energy analysis computer programs (ASHRAE, 2001b)

Both of them are based on a similar concept. The philosophy is to generate a range of results from several programs that are generally accepted as representing the state-of-the-art in whole building energy simulation programs. 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. More importantly, it can give users confidence that the program can accurately predict the building's energy consumption and thermal behaviour. Of course, it can also make code enforcement officials feel more comfortable with enforcing the simulation requirements or accepting an energy software.

CONCLUSIONS

The move towards building energy simulation is driven by the ongoing development and revision of building energy codes as well as the environmental credentials to which some building owners aspire. Building performance is now a popular word for the vast majority of new projects. Being able to model a new building at various design stages can help clients achieve optimisation and meet the requirements laid down by local energy legislation. Further increase in the demand for building performance simulation is envisaged as new policies and regulations are coming up, such as the European Union (EU) directive on building energy performance. With increasing concern in this field, people are demanding more simulation and modelling to be done on buildings prior to construction, so as to understand better the design and performance relationships.

Building energy codes shall be flexible and adaptable to society needs and dynamic conditions such as technological advances and new energy efficient technologies. With the emergence of performance-based codes, building designers are encouraged to use simulation tools and take a more integrated approach to designing buildings and assessing their performance. Although the performance path in most existing building energy codes is still complicated and not easy to define, there is a trend that the obstacles preventing wider use of simulation in design practice could be overcome and the gap between design and simulation could be bridged.

The simulation methodology as laid down in the building energy codes is not only useful for the design control of new buildings, but could also be applied to evaluation of energy conservation opportunities in existing buildings. It is hoped that effective use of building energy simulation in building energy codes would pave the way towards collaborative and integrated environment "For Better Building Design", which is the main theme of this conference.

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REFERENCES

ABCB (Australian Building Codes Board), 1999. *International Survey of Building Energy Codes*, Australian Greenhouse Office, Canberra, Australia. (available at http://www.greenhouse.gov.au/)

ASHRAE, 2001a. *ANSI/ASHRAE/IESNA Standard 90.1-2001, Energy Standard for Buildings Except Low-rise Residential Buildings*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, Georgia.

ASHRAE, 2001b. *ANSI/ASHRAE Standard 140-2001, Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, Georgia.

ASHRAE, 2000. *Standard 90.1-1999 - Energy Standard for Buildings Except Low-Rise Residential Buildings, User's Manual*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, Georgia.

Ben-Nakhi, A. E. and Aasemb, E. O., 2003. Development and integration of a user friendly validation module within whole building dynamic simulation, *Energy Conversion and Management*, 44 (1): 53-64.

Bloomfield, D. P., 1999. An overview of validation methods for energy and environmental software, *ASHRAE Transactions*, 105 (Part 2): 685-693.

Bloomfield, D. P., 1989. Evaluation procedures for building thermal simulation programs, In *Proc. of the Building Simulation '89 Conference*, June 23-24, 1989, Vancouver, BC, Canada, pp. 217-222, International Building Performance Simulation Association.

Briggs, R. S. and Brambley, M. R., 1991. Whole-building energy targets: a methodology for future performance-based standards, In *Proc. of the Building Simulation '91 Conference*, August 20-22, 1991, Sophia-Antipolis, Nice, France, pp. 631-637, International Building Performance Simulation Association.

CCBFC (Canadian Commission on Building and Fire Codes), 1999a. *Performance Compliance for Buildings: Specifications for Calculation Procedures for Demonstrating Compliance to the Model National Energy Code for Buildings Using Whole Building Performance*, National Research Council of Canada, Ottawa.

CCBFC (Canadian Commission on Building and Fire Codes), 1999b. *Performance Compliance for Houses: Specifications for Calculation Procedures for Demonstrating Compliance to the Model National Energy Code for Houses 1997 Using Whole House Performance*, National Research Council of Canada, Ottawa.

CEC, 2001a. *2001 Energy Efficiency Standards for Residential and Nonresidential Buildings*, P400-01-024, California Energy Commission, California, August 2001 (Title 24, Part 6).

CEC, 2001b. *Alternative Calculation Method (ACM) Approval Manual for the 2001 Energy Efficiency Standards for Nonresidential Buildings*, P 400-01-011, California Energy Commission, California, April 2001.

CEC, 2001c. *Alternative Calculation Method (ACM) Approval Manual for the 2001 Energy Efficiency Standards for Residential Buildings*, P 400-01-012, California Energy Commission, California, April 2001.

Chou, S. K., 2001. Building Energy Standard (BEST) - an engineering tool for compliance of energy performance standards, papers presented at *the Seminar on Energy Efficiency in Building Design*, organised by the Building and Construction Authority of Singapore, 18 April 2001, Singapore. (available at http://www.bdg.nus.edu.sg/BuildingEnergy/)

CIBSE, 1998. *Building Energy and Environmental Modelling*, CIBSE Applications Manual AM11: 1998, Chartered Institution of Building Services Engineers, London.

Clarke, J. A., 2001. *Energy Simulation in Building Design*, 2nd ed., Butterworth-Heinemann, Oxford, U.K.

Crawley, D., 1995. Development of a database of building envelope simulations for evaluating building envelope retrofits, In *Proc. of the Building Simulation '95 Conference*, August 14-16, 1995, Madison, Wisconsin, pp. 467-474.

Hui, S. C. M., 2002. Using performance-based approach in building energy standards and codes, In *Proc. of the Chonqing-Hong Kong Joint Symposium 2002*, 8-10 July 2002, Chongqing, China, pp. A52-61. (available at http://arch.hku.hk/research/BEER/besc.htm)

Hui, S. C. M., 2000. Building energy efficiency standards in Hong Kong and mainland China, In *Proc. of the 2000 ACEEE Summer Study on Energy Efficiency in Buildings*, 20-25 August 2000, Pacific Grove, California.

Hui, S. C. M., 1998. Simulation based design tools for energy efficient buildings in Hong Kong, *Hong Kong Papers in Design and Development*, Vol. 1, 1998, pp. 40-46, Department of Architecture, University of Hong Kong, Hong Kong. (http://web.hku.hk/~cmhui/hkpdd/hkpdd-v1.htm)

Hui, S. C. M., 1997. A randomised approach to multiple regression analysis of building energy simulation, In *Proc. of the IBPSA Building Simulation '97 Conference*, 8-10 September 1997, Prague, Czech Republic, Volume II, pp. 133-140.

Janda, K. B. and Busch, J. F., 1994. Worldwide status of energy standards for buildings, *Energy*, 19 (1): 27-44.

Judkoff, R. and Neymark., J., 1995. *International Energy Agency Building Energy Simulation Test*

(BESTEST) and Diagnostic Method, National Renewable Energy Laboratory, Golden, Colorado.

Kaplan, M. and Caner, P., 1992. *Guidelines for Energy Simulation of Commercial Buildings*, Bonneville Power Administration, Portland, Oregon.

SEDA, 2001a. *Guidelines for Conducting an Energy Efficiency Design Review*, Australian Building Greenhouse Rating Scheme, Sustainable Energy Development Authority (SEDA), Grosvenor Place, NSW, Australia.

SEDA, 2001b. *Guidelines for the Use of Simulation in Commitment Agreements*, Australian Building Greenhouse Rating Scheme, Sustainable Energy Development Authority (SEDA), Grosvenor Place, NSW, Australia.

SEDA, 2001c. *Validation Protocol for the Use of Computer Simulations to Estimate Building Energy Performance*, Australian Building Greenhouse Rating Scheme, Sustainable Energy Development Authority (SEDA), Grosvenor Place, NSW, Australia.

Waltz, J. P., 2000. *Computerized Building Energy Simulation Handbook*, Fairmont Press, Lilburn, Georgia.

Wilcox, B. A., 1991. Development of the envelope load equation for ASHRAE Standard 90.1, *ASHRAE Transactions*, 97 (Part 2): 913-927.

Wiltshire, T. J. and Wright, A. J., 1988. Advances in building energy simulation in the U.K. - the science and engineering research council's programme, *Energy and Buildings*, 10 (1988): 175-183.

Wong, N. H., Lam, K. P. and Feriadi, H., 2000. The use of performance-based simulation tools for building design and evaluation - a Singapore perspective, *Building and Environment*, 35 (2000): 709-736.

Wright, A. J., Bloomfield, D. and Wiltshire, T. J., 1992. Building simulation and building representation: overview of current developments, *Building Services Engineering Research and Technology*, 13 (1): 1-11.