Validation of

Building Energy Simulation Programs

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ABSTRACT

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Building energy simulation programs, which can predict the energy performance of existing or conceptual buildings, present a great potential to energy consultants for estimating the possible cost savings for a given energy conservation measure. However, consultants are often reluctant to use these programs since their reliability is questionable. This research proposes a procedure for the validation of energy simulation software which can be used by consultants to evaluate the software and detect errors in the program. First, two simulation programs (BESA-Design and MICRO-DOE 2.1, versions D and E) are subjected to an empirical validation, where the simulated energy performance of an existing commercial building is compared to the data recorded by the utility company. In addition, an inter-model comparison is performed where the results from these programs are compared with each other. In order to complement and enhance the results obtained by the empirical validation and the inter-model comparison, various verification techniques are designed and used to validate the MICRO-DOE2.1E program: (1) building response to a perturbation in the outdoor environment, (2) comparison of program algorithms with another modelling tool, (3) sensitivity analysis, and (4) simulations using simple models. These techniques emphasize the verification of heating, ventilating, and air-conditioning systems simulated by the program, while also considering the simulation of envelope heat transfer, heating and cooling loads, and indoor environmental conditions. In addition, the theory of decision models under uncertainty is used to select the most profitable energy conservation measures, given the possible errors which may occur in the evaluation of input variables. The MICRO-DOE program is chosen for this validation since it is viewed as a standard for building energy simulations and it is used in many applications in North America, including the National Energy Code of Canada.

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TABLE OF CONTENTS

PAGE

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1
INTRODUCTION

Various types of building energy simulation tools have been developed in the past twenty years with the goal to aid in the analysis of building energy consumption for both residential and commercial buildings. These tools have evolved considerably since their initial conception, mostly due to the constant developments in computer hardware. Today, several energy simulation programs are being marketed for use by designers and consultants to perform detailed building energy analyses either in the design or retrofit stage. With the present trend towards more energy efficient buildings and more specifically, with the proposed National Energy Code of Canada, the demand for these simulation tools is expected to increase dramatically in the near future.

Since the simulation results are used as the basis for important decisions during detailed building energy analyses, it is critical that the software be thoroughly tested in order to ensure its accuracy, as well as to instill confidence in the users. The verification performed by the software developer is not sufficient, and therefore, a third-party validation procedure is required.

Although research in this area has been documented for over 15 years, most of these studies were performed on test cells and small residential buildings, thereby focusing on the validation of the envelope heat transfer algorithms of the programs. Little attention was given to the use of these programs for the simulation of large commercial buildings nor to the verification of the heating, ventilating and air-conditioning (HVAC) equipment simulations. Furthermore, the attempts made to define a validation methodology have resulted in techniques which are very complex, time consuming and expensive.

The following sections summarize the major contributions to this type of research which have occurred since the early 1980's. Although several researchers worked in this area, the major contributions can be credited to the work of three distinct groups: (1) the Solar Energy Research Institute in the United States, (2) a group of institutions in the United Kingdom, and (3) a group from the Commission of European Communities.

1.1 Survey of the main approaches for the validation of energy simulation programs

The three main contributors to this field of research have attempted to develop a systematic and exhaustive procedure to define the accuracy of energy simulation programs. Although this objective has not yet been achieved, the procedures developed by these groups represent the most significant advancements in this field.

1.1.1 Validation techniques at the Solar Energy Research Institute (SERI) in the United States

One of the first reported validation studies was performed in the early 1980's by the Solar Energy Research Institute (SERI) in Golden, Colorado. In 1980 and 1981, the researchers at SERI performed two comparative studies in which they tested the ability of four building energy simulation programs (DOE-2.1, BLAST-3.0, DEROB-4.0, and SUNCAT-2.4) to accurately model a simple building. Since the results showed large disagreements between the predictions of the four programs, the need for a validation methodology was recognized and studies in this domain later ensued [1,2].

The comparative studies performed at SERI were limited, since there was no "correct" data with which the results could be compared. In 1981, an analytical verification technique was developed at SERI and was tested on SUNCAT-2.4, DOE-2.1 and DEROB III [2]. A simple building model was created and the heat transfer problems related to the building envelope were solved analytically, using numerical methods, as well as by the simulation software. In general, the results from the three programs were in good agreement with the analytical solutions. During the test, however, anomalies related to infiltration and perimeter heat losses were discovered in the DEROB program, which uses an iterative method, and these were subsequently corrected. Although this technique provided a reference for comparison purposes, it was restrictive since only very simple models could be tested.

In continuing their development of a validation methodology, the researchers at SERI participated in a study sponsored by the International Energy Agency and the U.S. Department of Energy [3]. In this study, a test house at the National Research Council in Ottawa was modeled by the team at SERI as well as by several European researchers using various simulation programs. The measurements taken at the test house gave a reference with which the simulations could be compared. At SERI, this study was used to compare three energy simulation programs: DOE-2.1A, BLAST-3.0, and SERIRES-1.0. These programs had previously shown large differences in annual heating and cooling energy predictions. To find the source of differences a detailed analysis procedure was developed which compared input and output data, weather data, as well as parametric sensitivity for each program. The results showed several differences in the input data and identified some errors in the source code. Once these errors were corrected, the three programs performed well, with differences within a reasonable range considering the algorithmic differences between the programs.

These studies conducted at SERI, culminated in the development of a validation procedure which integrated each of the individual studies. This procedure was not presented as an absolute validation methodology for simulation programs, but rather as a means of detecting errors in such programs. The proposed methodology consisted of the following steps [1]:

1. Analytical verification where the simulation results are compared with mathematical solutions for simple cases.
2. Empirical validation where the simulation results are compared with measured data from an existing building or test cell.

3. Comparative studies where the simulation results of various programs are compared.

Studies at SERI also highlighted the importance of parametric sensitivity studies, which define the impact of a given input variable on the results. This type of analysis allows the user to focus on the accuracy of those variables which are found to be the most sensitive in order to ensure accurate results. Although the importance of parametric sensitivity studies was discussed, it was not included as part of the validation procedure.

1.1.2 Developments in the United Kingdom

In the early 1980's, a group of institutions in the U.K. cooperated in a study on the validation of building energy simulation programs [4]. The purpose of the study was to establish a series of tests which could be used to show the accuracy of a program without being overshadowed by subjective input from the user or by lack of modelling details The tests included a variety of modelling tools, from large simulation programs, such as ESP, SERIRES, and TAS, to simpler methods such as CIBS admittance, RIBA calculator, and BREDEM.

In order to alleviate the errors in the inter-model comparisons caused by non-equivalent input and lack of building data, a very detailed building specification was prepared by a single user who ran it on all the programs. Large disagreements still occurred between the results of the various programs. The study concluded that better results would be obtained if a set of very simple buildings were used and the complexity increased slightly with each run, thereby facilitating the identification of the feature responsible for the disagreement in the results.

A set of analytical tests were designed which would supplement the analytical tests developed by SERI [2]. The SERI tests focused mainly on step changes in temperature across a single wall; whereas, the British expanded these tests to include sinusoidal as well as ramp variations in temperature. In addition, the British researchers selected a different range of building properties and a wider range of boundary conditions. The

British team also developed a rational approach used to interpret the significance of the errors detected using the analytical tests.

The British researchers found that empirical validation using a monitored building or test cell was the most significant validation technique since it determined the accuracy of the program as a whole [5]. They recognized the importance of this part of the validation process and devoted much of their time and resources to this task. Upon review of past work, they emphasized the importance of reliable data from the monitored building in order to minimize error. 'Blind' empirical tests were conducted, that is, the actual measurements were not considered for comparison purposes during analysis of the simulations [6]. Although the data sets chosen minimized errors, uncertainties still existed in the input, thereby affecting the results. Even with these uncertainties, the empirical testing was successful in detecting errors in the simulation programs.

The group of British researchers also showed the importance of understanding the theory and source code in order to explain the large differences in the results [4,6]. A standard form was prepared in order to assemble and organize the algorithms and assumptions used in the development of each program. Although some of the information obtained on these forms was often incomplete or incorrect, it was helpful in understanding the various aspects of each program.

Similar to the findings at SERI, the British group also identified the need to investigate the relationship between the input parameters and the simulation results through various methods of sensitivity analysis; however, a methodology for such tests was not defined [5].

1.1.3 Commission of the European Communities (CEC) concerted action PASSYS

The PASSYS project began in 1986 when the Commission of the European Communities formed a consortium of researchers from various European countries to develop a testing procedure which would improve the confidence in passive solar heating systems [7]. The project was separated into various subgroups, one of which, the MVD subgroup, was given the task of developing or refining a validation methodology for energy simulation programs. This subgroup reviewed and refined the methodologies developed by SERI and by the British team, and defined the following steps in the validation procedure:

-- theory and source code checking
-- analytical tests
-- inter-model comparison
-- sensitivity analysis
-- empirical validation
-- uncertainty evaluation
-- recommendations

The researchers of the PASSYS project, like the British team, put much emphasis on empirical validation which uses data from monitored buildings or test cells. They developed an empirical whole model validation methodology which was tested on several case studies [7,8]. Once again, the importance of accurate data sets from the measured building or test cell was highlighted since poor quality data could lead to inconclusive results. Although the validation methodology outlined by the PASSYS team was more detailed than those previously defined and it included the sensitivity analysis as part of the methodology, it did not describe a systematic approach which could be easily adopted by consultants. For example, the empirical validation technique described requires extensive monitoring of buildings or test cells which is not practical for a consultant or designer.

1.1.4 Other developments

Since the studies by SERI, the British team and the PASSYS group were first published in the early 1980's, several other researchers have contributed to this field. Most studies have focused on the application of one or several of the proposed validation techniques to (1) test cells, (2) residential buildings, or (3) commercial buildings. However, a validation methodology aimed at the consultant or average end-user of energy simulation software has never been developed.

In a recent study of four Australian thermal design tools, the contributions of SERI, the British team and the PASSYS group were acknowledged; however, the need for a thorough validation study was nonetheless established [9]. The study included a comparative test of the tools' abilities to simulate heat transmission through the building envelope and the subsequent changes in temperature. There was no testing of the simulation accuracy of mechanical systems or controls.

Another study proposed a method in which the performance of a building component could be simulated in a test cell, and a process of scaling and replication was developed which would represent the performance of the component in an actual building [10]. Although, the results may be accurate, this method can only be applied to individual components and, therefore, cannot show the accuracy of the simulation tool in modelling the building as a whole.

Ramdani and Candau [11] outlined three objectives of model validation: (1) determining whether there is an error in the model, (2) quantifying the error, and (3) identifying the source of the error. A method was proposed which uses mathematical models to fulfil these three objectives; however, it was only applied to a very simple test cell. The study also showed the importance of sensitivity analysis in determining the origin of modelling errors, unlike the SERI and British teams who used sensitivity analysis only to identify the input parameters which required a high degree of accuracy.

Strachan and Clarke [12] proposed that the validation problem may be solved by a complete validation facility which would contain both the physical and virtual elements required such as test cells, test components, data acquisition systems as well as the simulation programs and various validation tools. Although this may be a logical long-term solution, the study did not propose a validation methodology which could be adopted to ensure the proper testing of the simulation software.

Waltz [13] proposed that high levels of accuracy, say within 5% of the measured utility consumption, could be obtaineo by ensuring three key factors: (1) a complete understanding of the simulation tool, (2) a complete understanding of the building to be simulated, and (3) a careful analysis of the output data. Mainframe programs as well as complex and simple spreadsheet programs were tested for accuracy. Although an accuracy of within 5% of the measured utility consumption sounds acceptable, it cannot in itself show the validity of the program since the presence or absence of compensating errors cannot be ascertained.

1.2 Examples of studies using different validation techniques

The validation procedures previously described consist of a sequence of individual techniques which, together, are expected to validate a given energy simulation software. In a recent information paper [14], the British Research Establishment identified four possible sources of errors in thermal simulation programs: coding errors, errors in solution technique, inappropriate algorithms, and over-simplification. In addition, four validation techniques were defined which can be used to identify these errors: code checking, analytical tests, inter-model comparisons and empirical validation. These techniques were not presented as part of a validation procedure but as tests which could be applied to a given software in order to detect any possible errors. Furthermore, it reported that there still does not exist a methodology by which thermal simulation programs can be completely validated.

Each of these techniques has been applied, individually or in groups, by many researchers to determine the accuracy of simulation programs. The studies show the advantages of each validation technique as well as highlight the drawbacks. In the following sections, each technique is discussed separately along with the relevant studies which have been performed in order to evaluate the techniques on an individual basis, rather than in an overall procedure as was presented previously.

1.2.1 Inter-model comparisons

Inter-model comparisons have often been used in software validation, due to their relative simplicity in contrast with the monitored empirical validation which requires much more time and resources. In addition, the inter-model comparison technique also has the ability to model a wide range of buildings, from very simple to very complex. The building may not necessarily be realistic; a hypothetical example may be chosen in order to verify a specific algorithm. Furthermore, since the user defines the input, errors due to insufficient detail can be minimized. The only major drawback of this type of test is the absence of a reference with which the results can be compared for accuracy. Therefore, although the results of several programs may agree, no conclusion can be drawn as to the accuracy of these results.

In a comparative study of DOE-2, NBSLD, BLAST-2 and TWOZONE, the results from the four programs were in very good agreement when ordinary residential buildings were simulated [15]. However, discrepancies due to algorithmic differences between the programs became significant when large solar gains were introduced. Since the treatment of internal heat transfer was simplistic in all four programs and no measured data existed, the accuracy of the programs could not be determined. Furthermore, the modelling of convective heat transfer was similar in all four programs, although there were large differences when compared to a more detailed convection analysis which was being developed at the time. For example, in the more detailed analysis, it was assumed that the energy deposited by the sunlight was only distributed on one-fourth of the floor area whereas the four programs assume a uniform distribution over the entire floor. The detailed analysis resulted in an increase in the convective heat transfer from the floor to the air by more than a factor of two as compared to the result from a uniform distribution of sunlight energy over the entire floor area.

The discrepancies observed in the results of a comparative study can sometimes be attributed to assumptions or interpretations made by each user, unless the input is very well defined. In a study by the Passive Solar Modelling Group of the Commission of

European Communities, several models and calculating methods were used by researchers from different countries for the simulations of two test cells [16]. In the simulation of the first test cell, there was agreement between the results obtained by the six users of the Method 5000 program, a manual method developed in France. However, the results were not consistent among all programs tested. For the second cell, the results showed large disagreements, even among the users of the Method 5000 program.

In a comparative study of three building energy simulation programs (DOE-2.1, BLAST-2 and NBSLD), the annual heating and cooling loads were predicted for various climates [17]. The DOE-2.1 program was tested for two cases, one using ASHRAE standard weighting factors (SWF) and the other using custom weighting factors (CWF) calculated by the program. In general, the programs showed very good agreement for all climates and the discrepancies which did exist were easily explained. When monthly loads were compared, general agreement was found; however, some discrepancies were shown by predictions of DOE-2.1 (SWF), which consistently under-predicted the heating loads and over-predicted the cooling loads. The DOE-2.1 (SWF) simulation results also showed large disagreement in the design-day calculations, although these discrepancies were not seen in the results of the DOE-2.1 (CWF) simulations using the custom weighting factors. It was determined that the ASHRAE weighting factors depicted a more thermally massive building and that the custom weighting factors in the DOE-2.1 energy simulation program resulted in better agreement with the other two programs.

In an attempt to compare the results of various simulations with a base value, a previously validated or widely accepted computer program is often chosen to provide an accurate base case for the model. This allows for a reference with which the other simulations can be compared without the time or cost involved in an empirical validation. Furthermore, in this type of test, the restrictions present in an empirical validation do not exist, since any building can be simulated, in a wide range of complexities. However, the accuracy of the base case might still be questioned, since, even though the validated program is expected to give good results, they may not accurately reflect the building's performance. When Yuill and Wray [18] verified a simple building energy analysis computer program, named HOTCAN 3.0, they chose BLAST 3.0 as their standard of comparison. The verification consisted of several simulations emphasizing the calculation of internal and solar gains and on the calculation of admitted solar radiation through glazing, as well as the program's infiltration predictions. The verification was successful in detecting several errors in the simple program which would probably not have been found with a more global approach, such as comparing the simulated energy consumption with measured consumption from utility bills.

One validation study used inter-model comparison of three PC programs (BESA, TRAKLOAD, HAP) versus the BLAST program [19]. Due to the limitations of each program, differences in input data were unavoidable; however, these differences were taken into account when analyzing the results. The programs all exhibited similar trends in the simulation results and no particular error in the programs could be identified. Parametric sensitivity tests were also conducted during this study which will be discussed in a separate section. It was noted that the user-friendliness of the PC programs had an influence on the accuracy of the results, since they must use simpler methods and approximations to improve their speed and simplicity.

Zmeureanu et al. [20] used an inter-model comparison to demonstrate the ability of a thermal model, CBS-MASS, to accurately simulate an office building's energy performance as compared to the BLAST and TARP programs. The comparison showed good agreement in predicting the winter and summer thermal loads, with differences less than 7%. Although the predictions of the CBS-MASS program were not compared to actual measurements, the agreement between the results showed the program's ability to simulate a given model within the same accuracy as well known simulation programs.

An advantage of comparative studies is that very simple buildings, even unrealistic buildings, can be modelled for the purpose of comparison. The Solar Energy Research Institute conducted a study of four building energy simulation programs: DOE-2.1, BLAST-MRT, SUNCAT-2.4 and DEROB III [21]. A simple building model was chosen to ensure equivalent input for all four programs; however, due to the limitations of each program, several problems were encountered. These were first solved by simplifying the model further so that the program limitations were not a hindrance. Following this, sensitivity studies were performed to establish the possible range of errors and a value for the given parameter was chosen such that this error was minimized. The results showed an anomaly in the iterative calculations of the DEROB III program.

In an energy program validation study carried out by International Energy Agency, 23 programs were used to simulate two buildings, one hypothetical and highly simplified, the other a real building with available monitored data related to the building's energy performance [22]. The differences in the results were partly attributed to the different methods used by the programs to handle dynamic effects. The study concluded that the modelling of thermal storage and the interior heat balances were important factors which could significantly affect the final results.

1.2.2 Analytical testing

Unlike a comparative study, an analytical verification does not measure a program's ability to model a building, but rather, it verifies the accuracy of particular algorithms. The major disadvantage of this technique is that it is very limited in scope since only simple cases, for which mathematical solutions may be found, can be tested. Therefore, by itself, this technique could not be used to validate a given program, nevertheless, when used in conjunction with other studies, it becomes an important part of the validation procedure as defined by SERI, the British Research Establishment team and the PASSYS group.

In one study, analytical tests were used to verify the accuracy of the four programs tested (DOE-2.1, SUNCAT-2.4, BLAST-MRT, and DEROB III) [21]. The mathematical models predicted the change in interior temperature due to a step function change in the outdoor air temperature. The results of these tests supported the findings of the inter-model comparison, which indicated an inaccuracy in the DEROB program. This problem was subsequently corrected in a new version and the results showed excellent agreement with the analytical solution.

Zmeureanu et al. [20] used the analytical validation technique in conjunction with inter-model comparison to validate a thermal model. The results of the analytical testing, including the impact of factors such as air infiltration, thermal mass and solar radiation, showed good agreement between the mathematical results and the computer predictions, thereby quantifying the program's accuracy in modelling these basic heat transfer mechanisms.

In a verification study initiated by Energy, Mines and Resources Canada [23], the BLAST 3.0 building energy simulation program was tested in two phases. The first consisted of an analytical verification using a steady-state analysis during which the energy consumption for one day was simulated for two test houses and the results were compared with hand calculations. Although the results showed good agreement, with BLAST underestimating the consumption by 6.1% and 8.2% over the hand calculations, the BLAST program was tested further in the second phase using an empirical verification.

1.2.3 Empirical validation

Empirical validation is often seen as the best method to validate a program, since the model predictions can be compared with actual measurements, while also testing buildings of varied complexity, be it a test cell, residential or commercial building. The importance of accurate data sets, as well as detailed input data, has been greatly emphasized in many empirical validation studies including those conducted by the British team and the PASSYS group. However, this method of testing can be expensive and time consuming. Often the simulation results are only compared with energy consumption data from the utility companies since it is more easily accessible. In most cases, problems may be encountered during simulation since it is often impossible to precisely simulate a given building due to program limitations.

There are several differences between the simulation of test rooms, residential buildings and commercial buildings. Test rooms are not influenced by occupancy levels or by human factors such as opening windows or adjusting thermostats and therefore, are often used in empirical studies. Residential buildings are simpler than commercial buildings since they usually do not require the need to analyze complex HVAC systems. In addition, the energy loads in residential buildings are envelope dominated, unlike the case for most commercial buildings whose heating and cooling loads are greatly affected by internal loads, HVAC system dynamics and control systems [24]. Therefore, in general, a residential building simulation is more a test of a program's accuracy in modelling envelope heat transfer mechanisms, whereas a simulation of a commercial building would emphasize the accuracy of a program's envelope and HVAC system simulation. Since the simulation of residential buildings is less complex than that of commercial buildings, many studies exist in this area. A validation using a commercial building demands many more parameters since mechanical systems are present. Following are examples of studies which have been performed on test cells, residential houses and commercial buildings.

Zmeureanu et al. [20] noted some disadvantages of empirical testing, including the effect of the user-defined input on the simulation. Since many variables must be approximated by the user, particularly when the monitored data are not available, the desired results, such as a close prediction of the utility bills data, can be achieved rather easily after several iterations. In addition, since the empirical validation is a test of the impact of all the independent variables acting together, the results of the simulation could agree with the actual measurements even though compensating errors could be present in the program.

The second phase of the verification of the BLAST 3.0 program for houses, initiated by Energy, Mines and Resources Canada [23], consisted of an empirical validation where the results of the annual simulation were compared to monitored data for two houses, a standard house and an energy-efficient house. Monitored hourly space temperatures, hourly energy consumption, and peak demand were compared with the simulation results. Although the hourly temperatures showed good agreement, the comparison of the hourly energy consumption showed some discrepancies, particularly for the energy-efficient house. The daily energy consumptions showed good agreement for the standard house and larger errors, as high as 29%, for the energy-efficient house. However, the simulated monthly and annual energy consumptions were in better agreement with the monitored data, with errors under 15%.

An example of the effect of approximations in input data is observed in an empirical validation study performed at the Los Alamos Scientific Laboratory (LASL) to validate the DEROB/PASOLE system [25]. Seven test cells were monitored, each with different passive solar systems, then simulated using the DEROB/PASOLE program, and the results were compared. In general, the simulation temperatures were very close to the actual room temperatures; however, few discrepancies were found. Some of the discrepancies were attributed to the approximations in input data which were necessary due to the program limitations. For example, one test cell consisted of four water-filled cylinders aligned in front of the cell window, whereas in the simulated cell, the water was held within a single rectangular container having a volume equal to the total volume of the cylinders.

An empirical validation of the BLAST simulation program was conducted by the Passive Solar Analysis and Design Group at the Lawrence Berkeley Laboratory [26]. This study consisted of two parts, the first was the simulation of a small test cell and the second was a simulation of a thermally massive building in a severe summer climate inside a test chamber at the National Bureau of Standards. The results suggested an overestimation of the effectiveness of thermal storage. Other discrepancies in the results were attributed to uncertainties in input data, which was subsequently verified by several sensitivity studies. The results for the second simulation generally agreed with the measured values; however, some discrepancies were noted and attributed to errors or ambiguities in the model description or limitations of the program.

In an empirical validation study of several residential buildings by Sorrell et al. [24], general agreement was found among the simulation results of the programs EMPS-2.1B, DOE-2.1B and TARP 84. However, a disagreement was discovered between the measured winter attic temperatures and the predictions of the EMPS-2.1B program. After analysis, this was attributed to an error in the re-radiation algorithm which was corrected in the latest version of the EMPS program. All three programs underestimated the total energy consumption during the winter simulation. This was believed to be caused by the high insulation level of the house, thereby, creating a lower heat loss and increasing the percentage difference. In the summer case, the programs almost consistently overestimated the energy use with the largest deviations seen in the DOE-2.1B program for the high mass building. It was found that in general, the results of the simulations agreed with each other more than with the actual measurements which led to the conclusion that the disagreements were caused by insufficient input data for the building as well as inaccuracies in the models themselves.

May and Spielvogel [27] simulated a medium-sized office building using a proprietary hour-by-hour building energy simulation program for five specific cases: (1) the original design with a solar system, (2) the original design without a solar system, (3) the building as-operated, (4) the building with modifications to the actual operation, (5) an alternative building design. The as-operated simulations were required since there existed many differences between the assumptions made during the design and the actual operation of the building. The results of these simulations were compared with each other as well as with measured data. When the energy consumption was divided into three categories (lights and miscellaneous, operating energy, and fan energy and fuel), the results showed relatively good agreement with differences not exceeding 12%. However, the monthly variations of boiler input, heat pump input and chiller input showed some large discrepancies between the as-operated simulation and the actual measured data.

In an empirical validation study of an hourly microcomputer building energy analysis program, 36 commercial buildings were simulated and the results were compared with the actual energy consumption taken from the utility bills [28]. The results showed that the program was successful in simulating the energy consumptions since the errors in most cases were under 10% of the actual data. However, it was noted that it sometimes took several runs of revising the input data before the predictions were close to the actual values. Furthermore, the 36 buildings did not test all the different systems which could be modelled by the program and several program features remained untested. Although the results for this test were fairly accurate, the iterations needed to achieve acceptable results show that this validation technique can only show the program's ability to simulate the building's energy consumption. Whether or not it accurately simulates all the processes in the building cannot be verified.

Goldberg [29] compared five residential building energy simulation programs using the monitored energy consumption of two residential houses. The validation methodology consisted of two phases: the first being the comparison of the heating and cooling energy consumption and the second being a comparison of transient performance. Since the two houses tested were occupied, many occupant-related parameters had to be accounted for such as the net envelope mass flux, which relates to forced and natural ventilation as well as infiltration. By modifying the value of this parameter, a discrepancy was found in one of the programs which showed a lack of sensitivity. This was an indication of an error in the source code. Another parametric test was run to examine the effect of earth contact. Of the five programs, only SERIRES accurately simulated the earth-sheltered house and therefore would perform well for houses with significant below-grade components.

One empirical study of DOE-2.1B for a commercial building proved to be unsuccessful [30]. During the modelling of the office building, problems were encountered due to the inability of DOE-2.1B to model the common return air plenum as well as the economizer option on the heat pumps. This affected the results significantly; however, when comparing the total energy use on an annual or monthly basis, the predictions and the actual measurements were in good agreement. The predictions of monthly peak demands were not as accurate, overestimating the peak demand and incorrectly showing a peak in winter when in actual data the peak occurred in the summer. Although the system could not be modelled correctly due to the limitations of the program, the large discrepancies observed in the heating and cooling load predictions were surprising. The study further emphasized the importance of accurate inputs regarding occupancy schedules, lighting levels and equipment use in order to ensure valid results.

Diamond and Hunn [31] compared the simulation results of seven commercial buildings to metered data in a verification project of the energy simulation software DOE-2. The simulation results on an annual basis showed relatively good agreement with the metered data with a standard deviation for the set of seven buildings of 7.9%, and a maximum standard deviation of 12%. The monthly energy consumption showed standard deviations as high as 24%. When the energy consumption was divided into electricity and gas/fuel oil, the standard deviation for the monthly results reached as high as 35%. These discrepancies were attributed to compensating errors, errors in schedules, differences in actual and monitored weather data, and anomalies in the utility data.

1.2.4 Sensitivity analyses

Sensitivity tests are performed in order to quantify the impact of a single input variable on the overall results. By analyzing the results for a large range of input values, the necessity for more accurate information related to particular input data can be determined. In addition, sensitivity analyses can also be performed in order to detect discrepancies in the program. Although this type of test has not been defined as a validation technique, it has been reported as an important part of the validation procedure [1,7].

In the comparative study of three PC programs and BLAST [19], sensitivity tests were conducted on the following parameters: window area, air infiltration, thermostat setting, minimum air fraction, chiller and boiler size, and automatic sizing option. The sensitivity studies of the window area revealed some inadequacies in two of the three PC programs. In general, the trends from the PC programs were sometimes similar to those from BLAST. However, no significant trends were discovered since for certain parameters one program showed similar results as those from BLAST, while for another parameter, the results showed large discrepancies.

When the Passive Solar Analysis and Design Group at the Lawrence Berkeley Laboratory performed an empirical validation of BLAST, several sensitivity studies were also performed [26]. Among the parameters studied were air infiltration, solar radiation characteristics, internal surface convection coefficients, solar absorptivity, total incident solar radiation, thermal resistance of the exterior envelope, and properties of the thermal storage mass. The air infiltration level and the direct/diffuse split of the incident solar radiation were found to be the parameters which showed the most sensitivity. These two parameters were also judged to be among the most uncertain to be defined, which explained the differences between results.

Corson showed how sensitivity studies can determine the impact of input errors on final results, while also demonstrating the accuracy of the simulation programs [32]. The study further showed the importance of user interpretations on the results and suggested further training and adoption of conventions to reduce these types of errors.

1.3 Conclusions

The studies presented in this chapter used inter-model comparison, analytical verification, empirical validation and sensitivity analysis to test several energy simulation programs (Table 1.1). However, it has been shown that no particular validation technique can in itself sufficiently test a building energy simulation program. It is, therefore, important to integrate these techniques into a general validation procedure which does not necessarily require great amounts of time and resources that may not be readily available.

In his publication on the assessment of building performance by computer simulation [33], Clarke indicated a need for the accreditation of energy analysis programs. He proposed that validation methodologies should be an essential part of this accreditation process.

Many research studies in this field have concentrated on evaluating individual program algorithms without accounting for source code errors in transferring data within the program or the errors introduced by the user in approximating the input data. In order to detect these types of errors, the response of the program as a whole must be analyzed.

Previous validation studies have mostly focused on simple buildings or test cells without addressing the complexity involved in simulating an existing commercial building. There is clearly a lack of a systematic validation methodology which could be used by designers and consultants to ensure the accuracy of their predictions and increase their confidence in the simulation results.

Table 1.1 Summary of building energy simulation programs which have been subjected to validation

Author(s) *	Year	Programs studied
SERI	1981	DOE-2.1A, BLAST 3.0, DEROB-3, DEROB-4, SUNCAT-2.4
SERI	1985	DOE-2.1A, BLAST 3.0, SERIRES-1.0
SERI	1988	DOE-2.1C, BLAST 3.0, SERIRES
Group from United Kingdom	1985	ESP, SERIRES, TAS, CIBS admittance, RIBA calculator, BREDEM
Group from United Kingdom	1988	ESP, HTB2, SERIRES, DEROB-IUA
Group from United Kingdom	1989	NBSLD, WALTON, CIBSE, ESP, DEROB, DAVIES
CEC PASSYS project	1991	ESP
Ahmad, Szokalay	1993	TEMPER, CHEETAH, ARCHIPAK, QUICK
Gadgil, et al.	1980	DOE-2, NBSLD, BLAST-2, TWO-ZONE
Littler	1983	ESP, SUNCODE, SPIEL, CASAMO, SUNPAS, METHOD 5000, LOS ALAMOS III
Carroll	1989	DOE-2.1, BLAST-2, NBSLD
Yuill, Wray	1987	BLAST-3.0, HOTCAN-3.0
Zaheer-Uddin, et al.	1989	BESA, TRAKLOAD, HAP, BLAST
Zmeureanu, et al.	1987	CBS-MASS, BLAST-3.0, TARP
G.K. Yuill and associates, ltd.	1983	BLAST-3.0
Sorrell, et al.	1985	EMPS-2.1B, DOE 2.1B, TARP 84
Arumi-Noe	1979	DEROB/PASOLE
Bauman, et al.	1981	BLAST
Alezera, Hovander	1985	ADM-2
Goldberg	1985	HOTCAN-2.0, SERIRES-1.0, EEDO-1.0, 3D Scribe, CALPAS3-3.11
Heidell, Taylor	1985	DOE-2.1B
Diamond, Hunn	1981	DOE-2.1A
Corson	1992	DOE-2.1C, ADM-2, SEA-6, TRAKLOAD 3.1, VCACS-9,10

* NOTE: The studies are listed in order of appearance in the thesis.

1.4 Objectives and scope of the study

Although a particular software could not be tested for every possible case, a procedure could be followed by any energy simulation software user to determine program errors as well as define the limitations of the program. Consequently, the use of the validation techniques will also improve the user's understanding of the program output as well as his confidence in the results.

This study proposes a simple but systematic approach consisting of an empirical validation and an inter-model comparison, followed by various verification techniques: (1) building response to a given perturbation in the outdoor environment, (2) comparison of specific program algorithms with the HVAC2-TOOLKIT, (3) sensitivity analysis, and (4) simulations using simple models. This methodology is applied in order to evaluate the building energy simulation software MICRO-DOE2.1E using data from an existing commercial building. In addition, the theory of decision analysis under uncertainty is used in order to ensure the selection of the most profitable energy conservation measure.

CHAPTER 2
STARTING POINT: EMPIRICAL VALIDATION OF THE BESA-DESIGN COMPUTER PROGRAM

In the validation studies previously described, much emphasis was placed on empirical validations and inter-model comparisons. Consequently, these techniques are included in this study to demonstrate their limitations for software validation and the need for a more global validation methodology.

The starting point of this study evolves from my participation in a research contract for Hydro-Quebec for the evaluation of the BESA-Design energy simulation program. The objective of the contract was to evaluate the ability of the BESA program to accurately simulate the energy consumption of an existing commercial building, as well as its ability to predict the impact of several energy conservation measures. An empirical validation was carried out in parallel by three users in order to identify the impact of user interpretation on the results. The study used data from a large commercial building in the Montreal area and was successful in detecting several program errors.

This chapter presents the empirical validation of the BESA-Design program, beginning with the description of the commercial building which was the subject of the simulation. The measured utility data is used for the empirical validation since this is common practice for energy consultants. This chapter also presents the type of information which is usually available to a consultant for an energy analysis, as well as the additional calculations, assumptions and estimates of data required for the development of the input file.

2.1 Building description

The building used for this study is a large commercial building constructed in 1972. The total floor area of approximately 10 410 m² includes seven floors of offices and an underground garage in addition to the ground floor, consisting of the lobby, a restaurant, and a bank, as shown in Figure 2.1. The data for the building is obtained in part from a study performed by ADS Consultants [34] and completed by on-site visits and meetings with the building manager. Electricity is the only source of energy in this building.

2.1.1 Exterior envelope

The building envelope consists of prefabricated concrete panels and tinted glazing on all floors of the office tower. The ground floor also contains brick finishing on some facades. The windows of the tower, which are double-paned and bronze tinted, cover the entire length of each facade and are tilted downwards at an angle of approximately 10°. The floor-to-floor height of the office tower is 3.60 m, including a 0.90 m plenum as shown in Figure 2.2. The height of the lobby is 4.55 m including a 0.90 m plenum, whereas the height of the garage is 3.00 m with no plenum.

2.1.2 Lighting and equipment

The lighting consists mainly of recessed, non-ventilated fixtures with two or four fluorescent tubes. At the time of the visit, the implementation of an energy conservation measure was in the process which consisted of replacing the 40 W tubes with more economical 34 W tubes. This change was approximately 75% completed at that time. There are also incandescent spotlights in the lobby and the interior core of each floor, with bulbs of either 100 W or 75 W. The garage lighting consists of suspended fixtures with fluorescent tubes. The total installed lighting power was estimated for each floor during the site visit and, from this, the lighting power density is calculated for each thermal zone as a floor-area weighted average. These values are as follows:

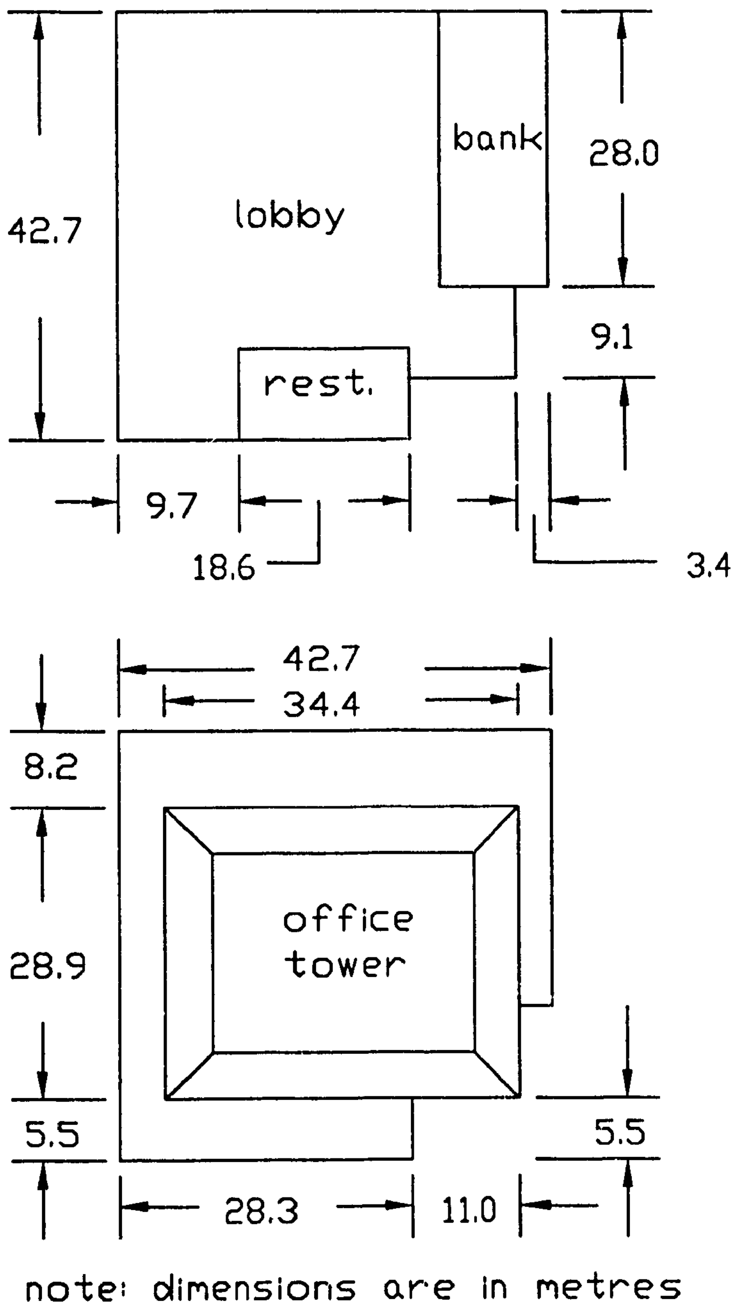

Figure 2.1 Plan of the building used in the study

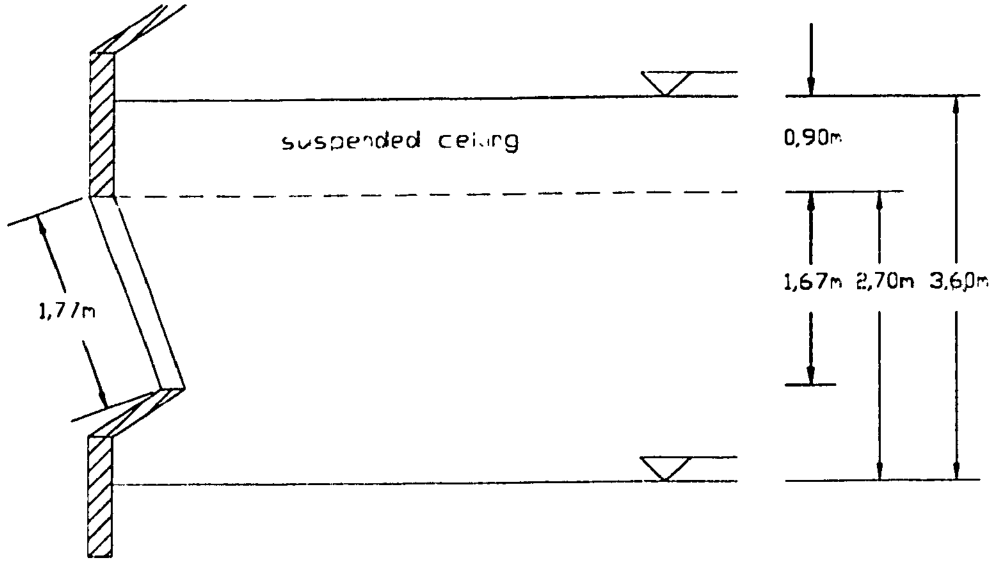

Figure 2.2 Elevation of a typical floor of the office tower

-- 3.2 W/m² in the lobby and hallways of the ground floor

-- 18.3 W/m² in the restaurant and bank

-- 25.8 W/m² on the first floor

-- 8.6 W/m² in the perimeter zones of floors 2 to 6

-- 10.8 W/m² in the interior zones of floors 2 to 6

-- 16.1 W/m² on the seventh floor

-- 1.1 W/m² in the garage

A similar technique is used for the evaluation of the equipment power density, which is mostly attributed to personal computers. The following values are obtained:

-- 7.0 W/m² on the first floor

-- 1.2 W/m² on floors 2 to 6

-- 1.0 W/m² on the seventh floor

The lighting intensity was measured at desk level throughout the building and is equal to 500-600 lux in the offices of floors two to seven, 900-950 lux for the offices of the first floor, and 100-150 lux for the interior hallways. All interior lighting and equipment are controlled manually. The exterior lighting, however, is controlled by photo-electric cells and has a total installed power of 5.4 kW.

Other electric motors found in the building are included as miscellaneous equipment. These motors consist of two elevators, an air compressor, an exhaust fan, two french drain pumps and a garage door opener.

2.1.3 Occupancy

The number of people in the building and the occupancy schedules are obtained from a previous study [34]. The maximum occupancy is approximately 35 people in the restaurant and 40 people in the bank. There are no persons in the lobby or garage. The maximum occupancy density for the office tower is estimated as 25.8 m^2/person on the first and seventh floors and 30.7 m^2/person on floors two to six.

2.1.4 Heating and cooling systems

Heating for the entire building, except the garage, is provided by perimeter electric baseboard heaters, with a total installed power of 48.4 kW per floor. The thermostats which control the baseboard radiators are usually set to approximately 20-21°C in the winter, although they can be adjusted by any occupant. The garage is equipped with two fan radiator heaters which keep the temperature at approximately 18-19°C. The heating operation is estimated to last between October 1 and April 30.

The HVAC system for the office tower and the ground floor offices consists of a central VAV system with a total air flow capacity of approximately 38 200 L/s, which can maintain the room temperature at approximately 23-24°C, except on very hot days when the temperature can surpass this setpoint. The supply fan has an electric motor power of 93.3 kW, ensures a static pressure of approximately 650 Pa and is equipped with inlet vanes to control the supply air flow. The return fan has an air flow capacity of 34 900 L/s and a 56.0 kW motor.

The cooling is provided by a direct-expansion cooling coil linked to four air-cooled condensers, model number RAUA 500-2 MB manufactured by TRANE. Each condenser is equipped with two compressors of 92.4 kW of cooling capacity each, resulting in eight stages of cooling. The supply air temperature is controlled in terms of the outdoor temperature: 14°C when the outdoor temperature is greater than or equal to 9°C, and 16°C when the outdoor temperature is less than or equal to -20°C. A linear variation of the supply temperature is assumed when the outdoor temperature varies between -20°C and 9°C.

The amount of outdoor air in the system is controlled by two parameters, the first is the supply air temperature and the second is the carbon dioxide level in the main return air duct. The priority is given to the air temperature, which sometimes leads to high levels of carbon dioxide in the return air, especially in the winter. In addition, a dry-bulb temperature economizer is present which regulates the amount of outdoor air brought into the system as a function of the outdoor air temperature. The minimum amount of outdoor air is estimated at 5% when the dampers are fully closed, due to air leakage.

A 90 kW electric humidifier maintains a humidity of approximately 25% in the winter. There is no heating capability in this central system nor any reheat terminals since all heating loads are satisfied by the baseboard radiators. The system operates from 7:30 am to 11:00 pm Monday to Friday. The availability of the cooling system is estimated to be between April 15 and October 15. A central exhaust system for the washrooms, with a 3 300 L/s fan and a 1.5 kW electric motor, is also present and operates between 7:00 am and 8:00 pm Monday to Friday.

The restaurant and the bank are each equipped with a rooftop HVAC unit. The unit serving the restaurant is a CARRIER model 50 C LJ 007 which operates at constant volume and does not have a heating capacity. The cooling capacity is approximately 26.7 kW of refrigeration available year-round, but only needed during the warm season. The system is also equipped with an enthalpy economizer which varies the amount of outdoor air brought into the system between 10% and 100%. The heating is supplied by perimeter baseboard heaters with a capacity of approximately 4.0 kW.

The unit serving the bank is a WESTINGHOUSE model 1R08A60271 equipped with a 52.7 kW cooling capacity and 24.5 kW heating capacity. It is a constant-volume system which operates with a fixed percentage of outdoor air of 15%. The system operates between 8:00 am and 5:00 pm Monday to Friday. Although the cooling is available year-round, it is not used in the winter.

The garage is equipped with two exhaust fans operating in series and controlled by a carbon monoxide sensor. The first fan has an air flow capacity of 3 780 L/s and a 1.12 kW motor. The second fan, which only operates when the capacity of the first one is insufficient, has a capacity of 2 830 L/s and a 0.75 kW motor. The fans operate mostly during periods of heavy traffic, in the morning and late afternoon. The make-up air is taken from the return air of the central system as well as the air infiltration through the garage door.

2.1.5 Service hot water system

Each floor of the office tower contains a 45.5 L hot water tank with a 3.0 kW heater. In addition, there is a 227 L tank on the fifth floor and a 152 L tank for the ground floor. The hot water supply temperature is set at 46.1°C.

2.2 Empirical validation of BESA-Design

The building is modelled using the building energy simulation software BESA-Design. The following sections present the additional calculations and the assumptions required for the development of the input file, as well as the results of simulations. Several problems encountered during the simulations and the errors which were discovered, are presented. Finally, the ability of the BESA program to predict energy savings by simulating the impact of certain energy conservation measures is evaluated and discussed.

2.2.1 Development of the input file

Since the program limits the total number of thermal zones which can be simulated to 25, the building is divided into 19 thermal zones, as shown in Figure 2.3 and described as follows:

-- zones 1 to 5 for the seventh floor (one central zone and four perimeter zones)
-- zones 6 to 10 for the intermediate floors 2 to 6
-- zones 11 to 15 for the first floor
-- zone 16 for the lobby and ground floor offices
-- zone 17 for the restaurant
-- zone 18 for the bank
-- zone 19 for the garage

The following assumptions and additional calculations are made in order to define input data, as they are required by the program:

1. The percent of the heat transfer across the exterior wall which is assigned to the plenum is estimated as the ratio of the plenum wall area to the net wall surface area. It is calculated as follows:

   plenum wall area = plenum height * length of wall

   plenum wall area = 0.9 * length of wall

   net wall area = (wall height - window height) * length of wall

   net wall area = (3.6 - 1.67) * length of wall = 1.93 * length of wall

   $$\text{percent load to plenum} = \frac{(0.9 * \text{length})}{(1.93 * \text{length})} * 100 = 46\%$$

2. The properties of the glazing system are obtained from a manufacturer's catalog [35] after a visual inspection of the existing window. In the input file for the blind simulation, a glazing system having similar properties as those obtained from the manufacturer's catalog is chosen from the available library. In later input files, the properties of the glazing system from the library are overridden by directly specifying

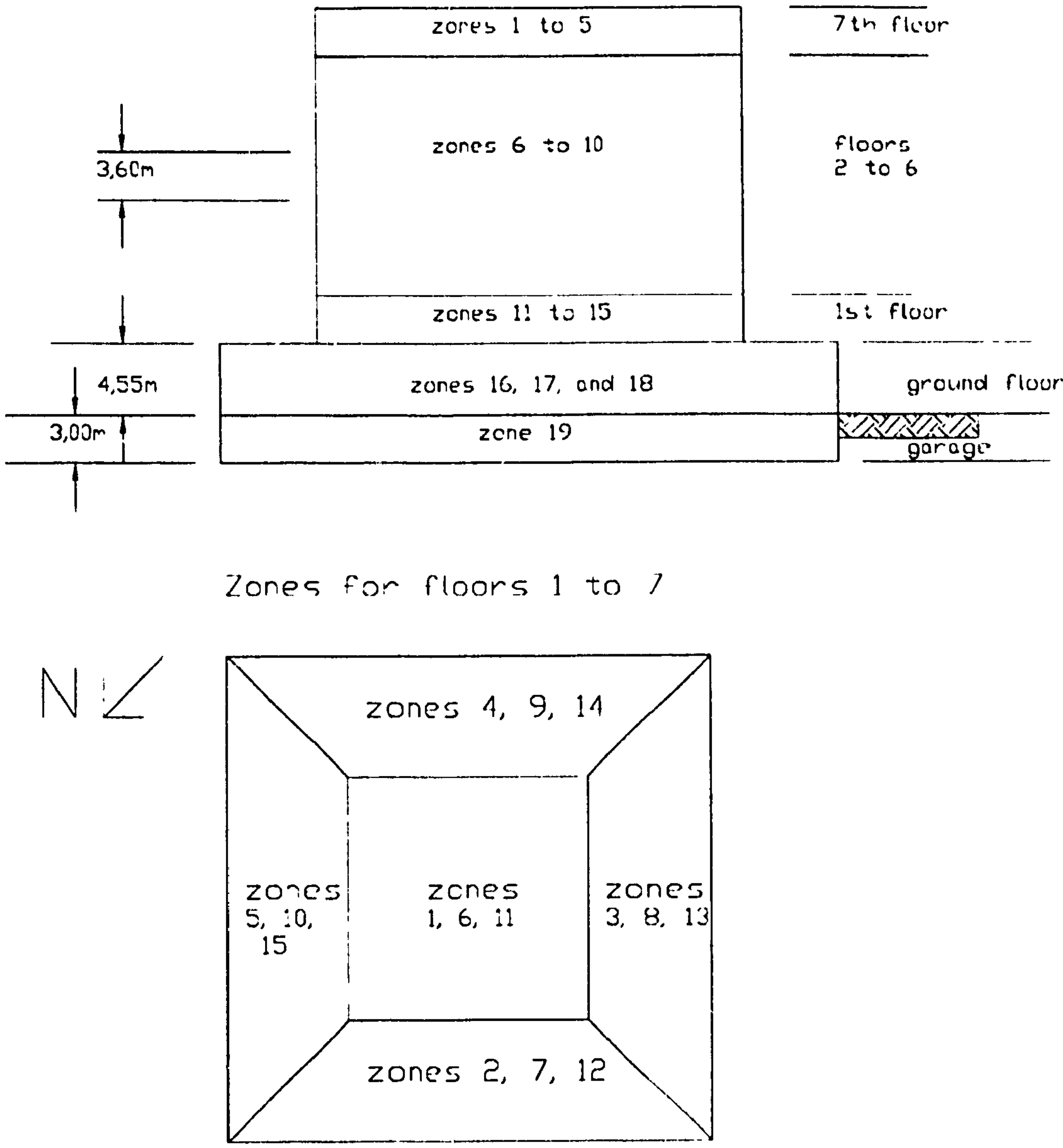

Figure 2.3 Thermal zones of the building model

the shading coefficient of the glazing. The thermal resistance is equal to 0.30 m^2·°C/W in the daytime and 0.36 m^2·°C/W at night, as defined by the manufacturer's catalog.

3. In order to estimate the heat loss through the underground walls, the 1989 ASHRAE Handbook of Fundamentals is consulted [36]. Table 3 of Chapter 25 in the handbook

shows that for a maximum depth of 2.1 m and a cement wall with a thermal resistance of 1.47 $m^2 \cdot °C/W$, the coefficient of heat loss is 2.52 $W/m^2 \cdot °C$. The input data required by the BESA program is then obtained by multiplying this coefficient with the design temperature difference across the wall, that is the difference between the average room air temperature (19.0°C) and the outdoor winter design air temperature (-23°C):

$$2.52\ W/m^2 \cdot °C * [(19.0°C - (-23.0°C)] = 105.8\ W/m^2$$

4. To estimate the heat loss through the underground floor slab, it has been recommended to use the floor perimeter rather than the floor surface area in order to avoid overestimating the heat loss [37]. Using Table 5 of Chapter 25 of the ASHRAE Handbook [36], the heat loss factor for the underground floor slab is estimated at 0.83 $W/m^2 \cdot °C$.

5. The lighting ballast factor is estimated at 1.18.

6. The heat loss from the lighting fixtures to plenum is estimated to be 53% [38].

7. The ground reflectivity is chosen as 0.2.

8. The heat gain from persons is split equally into sensible and latent heat gains.

9. The setpoint temperature of the central system as well as that of the two rooftop units is defined such that the heating starts when the room temperature is equal to 21°C and it uses the maximum capacity when the room temperature is equal to 20°C. The cooling starts when the room temperature reaches 23°C and uses the maximum capacity when the room temperature is 24°C (Figure 2.4).

10. The garage system is defined such that the heating starts when the room temperature is equal to 19°C and it uses the maximum capacity when the room temperature is equal to 18°C. The cooling setpoint is defined as 94°C (the maximum value accepted

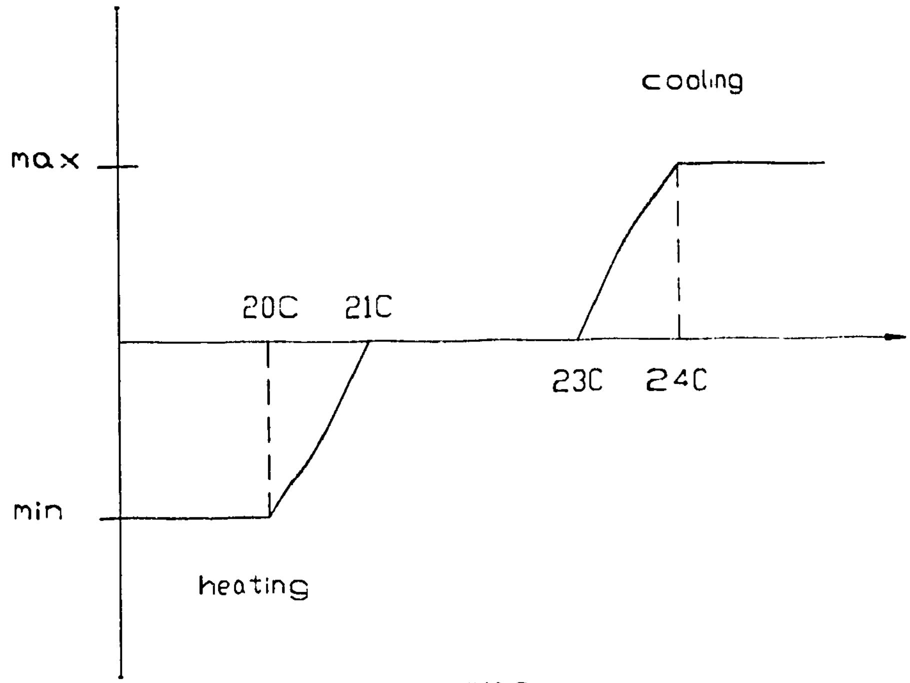

Figure 2.4 Temperature setpoints of the HVAC systems

by the program) since no cooling is available, and therefore, the temperature can increase in this space.

11. The estimation of air infiltration rates is very difficult since there have been various contradictory reports and recommendations concerning the average expected values [37, 39, 40, 41]. Therefore, the values estimated in the report by ADS [34] are maintained as follows:

-- 0.24 ach for perimeter zones of floors one to seven
-- 0.2 ach for the restaurant on the ground floor
-- 0.5 ach for the bank on the ground floor
-- 0.2 ach for the garage
-- 0.0 ach for all interior zones

There is one exception: in the lobby where a positive pressure is maintained during system operation, the infiltration rate is set to zero instead of 0.5 ach as estimated in the ADS report.

12. In defining the outdoor reset temperatures, a value of 0°C is used instead of the actual -20°C due to the limitations of the BESA program.

13. In the BESA-Design program, the supply, return and exhaust fan schedules are defined by only one schedule. Therefore, it is assumed that the exhaust fans follow the schedule of the supply and return fans.

14. The coefficient of performance for the central VAV system is calculated based on data from the TRANE catalogue [42]. For the condenser, a dry-bulb temperature of 29.4°C and a wet-bulb temperature of 22.2°C are used as rated conditions. For the evaporator, 23.9°C dry bulb and 19.4°C wet bulb are used. For these conditions, the chiller's refrigeration capacity is 184.8 kW with an electric input power of 59.8 kW which results in a coefficient of performance of 3.09.

15. Each condensing unit has six fans of 1.35 kW each (a total of 8.1 kW for each condensing unit). Since, the software requires the fan power for the cooling tower at 25, 50, 75 and 100% of full capacity as input data, these values are defined linearly from 8.1 kW at 25%, when only one condensing unit is operating, to 32.4 kW at 100%, when all four units are at full load.

16. The control of the amount of outdoor air brought into the system in terms of the CO_2 concentration in the return air duct cannot be simulated by the program. Therefore, the economizer is assumed to solely control the amount of outdoor air in the system. This assumption only affects the results when the outdoor temperature is above 21°C. At this temperature, the economizer sets the amount of outdoor air to a minimum; however, the CO_2 sensor could actually require a higher percentage of outdoor air. This would lead to an underestimation of the cooling energy required during the hot weather.

17. The default performance curves at part-load provided by the software are used since no other data is available from the manufacturers of the equipment.

18. It is impossible to define a HVAC system with no heating capacity such as is the case for this building; therefore, the minimum value of 3.4 kW which is allowed by the program is used.

19. It is not possible to introduce a schedule of operation starting mid-month. Therefore, the cooling schedule is originally defined from May 1 to September 30.

20. The data for the Carrier rooftop unit is obtained from the manufacturer's catalog [43]. The cooling capacity is 26.8 kW with an electric input of 7.69 kW for the compressor and 0.37 kW for the condenser fan, giving a coefficient of performance of 3.32.

21. The supply air flow rate for the Carrier unit is also defined from the manufacturer's catalog as 1 133 L/s, with a supply fan power of 0.35 kW and a static pressure of 24.9 Pa. Defining the heating capacity proves difficult since by setting the system heating capacity to zero and introducing the baseboard heaters, the room temperature is below the setpoint value. To correct this problem, the rooftop unit is given a heating capacity equal to the baseboard heaters, and the zonal heating capacity is set to its minimum value of 3.4 kW.

22. Catalogues are unavailable for the Westinghouse unit of the bank, since the unit is over 25 years old and the model was discontinued 15 years ago. The properties of a similar unit, with a cooling capacity of 52.8 kW, are defined as presented in the Carrier catalog. The electric power required for the compressor is estimated as 15.2 kW, and 0.75 kW for the condenser fan which results in a coefficient of performance of 3.3. However, to account for the age of the unit and the operating conditions, the coefficient of performance is reduced from 3.3 to 2.8.

23. The garage heaters are simulated as Heating Only with Radiation System. In order to simulate these heaters, a fictitious boiler is used in the central system with an efficiency of 100%.

24. Since the control of the exhaust fans by CO sensors cannot be simulated, information

from the building manager is used to estimate the number of hours per day the fans operate. The system is simulated using one fan with a 1.1 kW motor, operating 3 hours per day (9:00-10:00; 12:00-13:00; 17:00-18:00).

2.2.2 Problems detected in the program

Many problems were apparent in the initial version of the program, such as the screen freezing when particular schedule menus were used and the program crashing followed by the display of an error message. In addition, the program showed some errors in the results of the hourly simulations. The software can run simulations using either hourly weather data or typical day data, which simulates the weather conditions for one typical day each month. In the original version of the BESA program, the results of the hourly simulations showed zero energy consumption for cooling although the typical day simulation indicated some reasonable results. Hence, the hourly simulation underestimates the peak demand in the summer months, as presented in Figure 2.5.

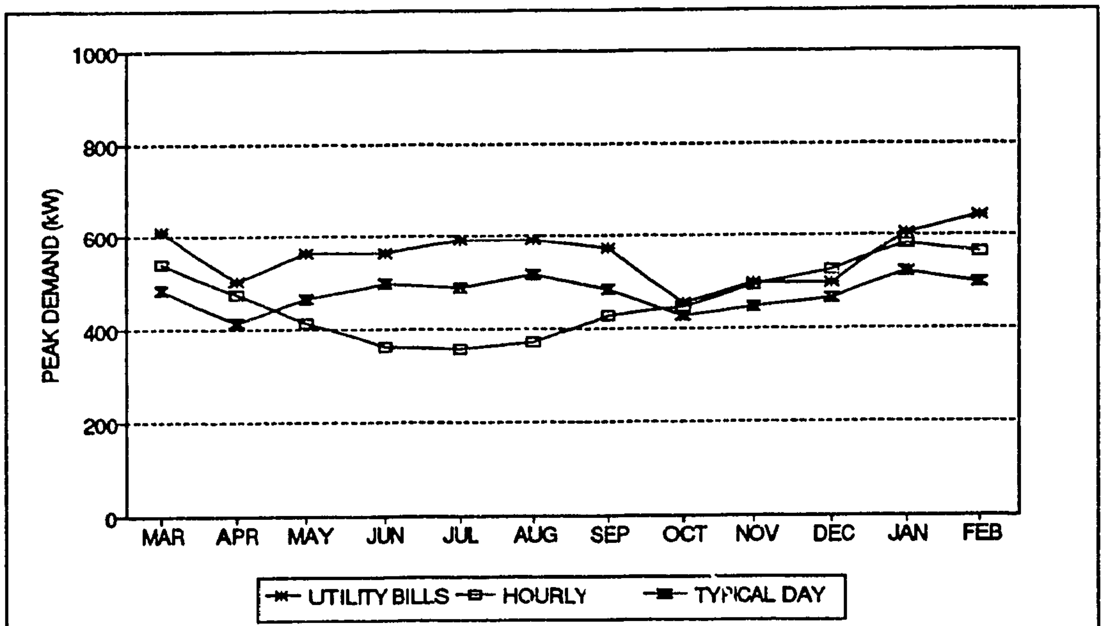

Figure 2.5 Comparison of the monthly peak electric demand from the utility bills and the peak demand predicted by the hourly and typical day simulations

Other problems encountered in the BESA program include differences between the printed report of input data and the actual values which were introduced in the program, such as the value of the solar transmission coefficient for glazing. Also, the temperatures for the restaurant and the bank on the ground floor were out of range. In addition, the results from the simulations also showed energy consumption for the chillers when they were not in use.

2.2.3 Blind simulation

The first simulation is performed without knowledge of data from the utility bills, and is named the "blind" simulation. Since this is a qualitative evaluation and the results are not compared to actual values, the results are verified in terms of expected values and also compared to previously published data for similar buildings. Once this is completed, the utility bills are consulted and modifications are made to the input file to calibrate the model so that the simulation results closely estimate the measured utility consumption.

The results of the blind simulation are analyzed in terms of the cooling and heating loads, as well as the maximum and minimum temperatures for each zone. In addition, the predicted annual energy consumption is compared to some published values for similar buildings. Since some errors are identified in the hourly simulation results, only the typical day simulation results are used for this analysis. However, in later versions of the BESA program this problem was corrected; therefore, for the simulations performed using these versions, the results from the hourly simulations are used since they are expected to be more accurate than the typical day simulation results in terms of annual energy consumption. Examples of some observations made during this analysis are presented below:

1. The annual energy consumption is compared to some published data which shows that the average energy consumption for office buildings in Montreal for 1988 was 455 kWh/m^2/yr and some energy efficient buildings consume approximately 200 to 250 kWh/m^2/yr [44]. The total energy consumption predicted by the BESA program is 306.8 kWh/m^2/yr which is consistent with the published data.

2. The maximum sensible cooling load for zone 8, a south-west perimeter zone, is 4 218 W while the total sensible cooling load for zone 6, an interior zone, is 4 998 W. Although the interior zone has no cooling load contribution from infiltration, exterior walls or windows, the high cooling load is expected due to the contribution from lighting (which is approximately eight times greater than for the perimeter zone), as well as the higher loads due to equipment and occupancy. The breakdown of the peak sensible cooling load for the perimeter zone 8 (Figure 2.6) shows the large contribution of the solar radiation on the peak cooling load, as is expected for a south-west perimeter zone with a large glazing area (46%).

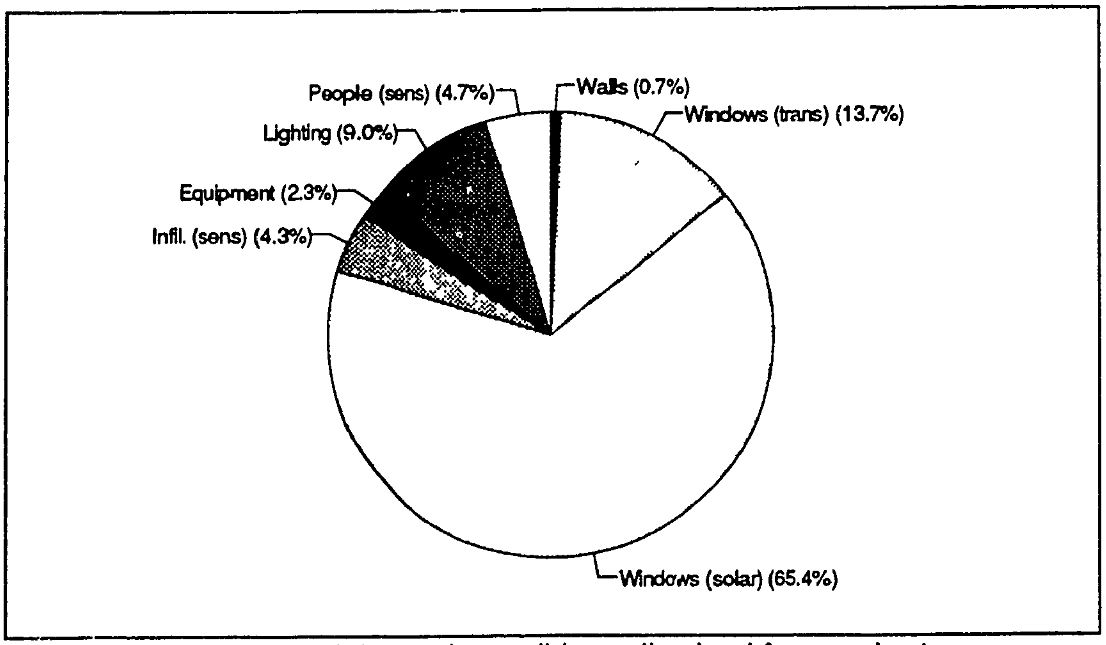

Figure 2.6 Breakdown of the peak sensible cooling load for a perimeter zone

3. The maximum sensible heating load for zone 8 is 6 488 W on January 1 and there is no heating load for the interior zone, as expected due to the high internal heat gains. The maximum sensible heat load is broken up into heat transfer through walls (626 W) and windows (4 567 W) as well as sensible heat loss due to infiltration (1295 W) as shown in Figure 2.7.

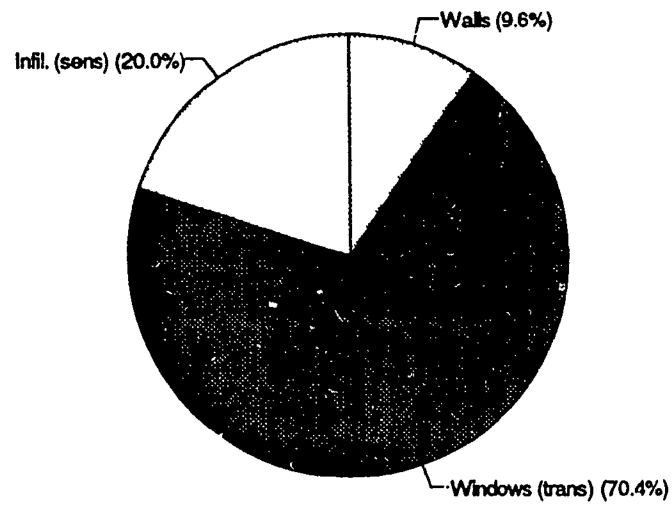

Figure 2.7 Breakdown of the sensible heating load for a perimeter zone

4. The predicted range of air temperature for each zone is assumed to be an important indicator of the accuracy of the simulation. The restaurant is the only zone which is problematic, with temperatures as low as 10.6°C. It seems as though the thermostat only controls the baseboard heaters in the secondary zones of the system and the main system controls the master zones. Since this system consists of only one zone, the thermostat control is not activated. Consequently, a heating coil is introduced in the HVAC system in replacement of the baseboard heaters. The temperatures for all other zones in the building range from 20.6°C to 23.9°C when the system is on, and 21.1°C to 22.8°C when the system is off. The garage shows a minimum temperature of 18.3°C.

In the context of the study undertaken for Hydro-Quebec, three users independently performed the blind simulation using the BESA program in order to evaluate the impact of user interpretation on the results. A large difference was found between the annual energy consumption estimated by the three users: (A) 306.8 kWh/m^2 (the simulation performed by the author), (B) 298.6 kWh/m^2, (C) 193.0 kWh/m^2 [45]. The differences between the three input files included approximations made in glazing properties, operating schedules for lights and equipment, occupancy schedules, air infiltration rates and efficiency of motors. The large differences observed in the blind simulation results of the three users emphasize the importance of user interpretation and approximations made in defining input data.

The blind simulation proved to be effective in detecting certain inadequacies of the building model, particularly in the analysis of the predicted zone air temperatures. The analysis of the required cooling energy revealed an error in the hourly simulation, as previously described. The simulation results also showed that the program was successful in predicting the annual energy consumption when it was compared to previously published values of similar buildings.

2.2.4 Calibration of the computer model

In the second step of this evaluation, the utility bills of the building, from January 1, 1992 to June 6, 1993, are made available. However, the billing periods do not correspond to a specific month, but rather they cover periods anywhere from 24 to 41 days. In order to evaluate the energy consumption for each month, a technique suggested by Hydro-Quebec is used to normalize the energy consumption [46]: the energy consumption for a particular billing period is multiplied by the number of days of that month recorded in that billing period and then divided by the total number of days in the billing period. The contributions for a particular month from various billing periods are then added to give the total consumption for that month. An example of this calculation is presented below:

a. First utility bill from May 29 to June 25, 1992:

Number of days in the billing period = 27

Number of days energy was consumed in June = 25

Energy consumption for the billing period = 178 000 kWh

Corrected consumption, $= \frac{25 \text{ days}}{27 \text{ days}} \times 178\,000 \text{ kWh} = 165\,555 \text{ kWh}$

b. Second utility bill from June 25 to July 29, 1992:

Number of days in the billing period = 34

Number of days energy was consumed in June = 5

Energy consumption for the billing period = 234 600 kWh

$$\text{Corrected consumption}_2 = \frac{5 \text{ days}}{34 \text{ days}} \times 234\,600 \text{ kWh} = 34\,500 \text{ kWh}$$

The normalized consumption for the month of June is the total of the contributions from the two billing periods:

165 555 + 34 500 = 200 055 kWh

The peak demand for a particular month is taken as the maximum demand recorded during the billing periods covering that month. For example, the first and second billing periods described above recorded peak demands of 564.0 and 540.0 kW, respectively. The peak demand for June 1992 is then normalized to the maximum of these two values, 564.0 kW.

The normalized values are shown in Table 2.1. The utility bills show an annual energy consumption of 2 559 655 kWh or 245.9 kWh/m², an annual peak demand of 645 kW or 62.0 kW/m², and an annual energy cost of $ 158 477.65 or $ 15.23/m²/yr. Since changes were made to the operating conditions of the building in the spring of 1992, the twelve months chosen for comparison with the simulation values are taken as March 1, 1992 to February 28, 1993.

First, the monthly energy consumption predicted by the blind simulation is compared with the data from the utility bills as shown in Figure 2.8. The energy consumption is overestimated for every month, in particular December, January and February, although the overall shape of the graph follows the data from the utility bills. The differences range from +9.3% in November to +37.4% in January. The comparison of the monthly peak demand can be seen in Figure 2.9, where there are much larger overestimations, ranging from 3.4% in April to 56.8% in January.

Table 2.1 Normalized monthly consumption, peak demand and energy costs from utility bills

Month	Consumption (kWh)	Peak demand (kW)	Costs ($)
March 1992	233 867	612	13 402
April 1992	160 839	504	10 405
May 1992	177 044	564	12 443
June 1992	200 055	564	13 137
July 1992	213 857	591	13 548
August 1992	211 043	591	14 019
September 1992	191 000	576	12 894
October 1992	189 207	456	12 057
November 1992	203 647	498	12 278
December 1992	228 644	498	13 364
January 1993	285 552	606	15 856
February 1993	264 900	645	15 023

The base model is modified several times in order to calibrate the model, that is, to reach a good agreement between the predictions and the monitored data: differences less than 15% on a monthly basis and 10% on a yearly basis are deemed acceptable, as required by Hydro-Quebec. The modifications of parameters concern those with uncertain values, such as efficiency of the supply fan and motor, setback temperatures, weight of space furnishings and various schedules. In addition, throughout the project, several errors were detected in the program and the software designer was notified immediately. Subsequently, a total number of eleven new versions of the program were used, resulting in numerous simulations. The results from the following simulations are compared in this section:

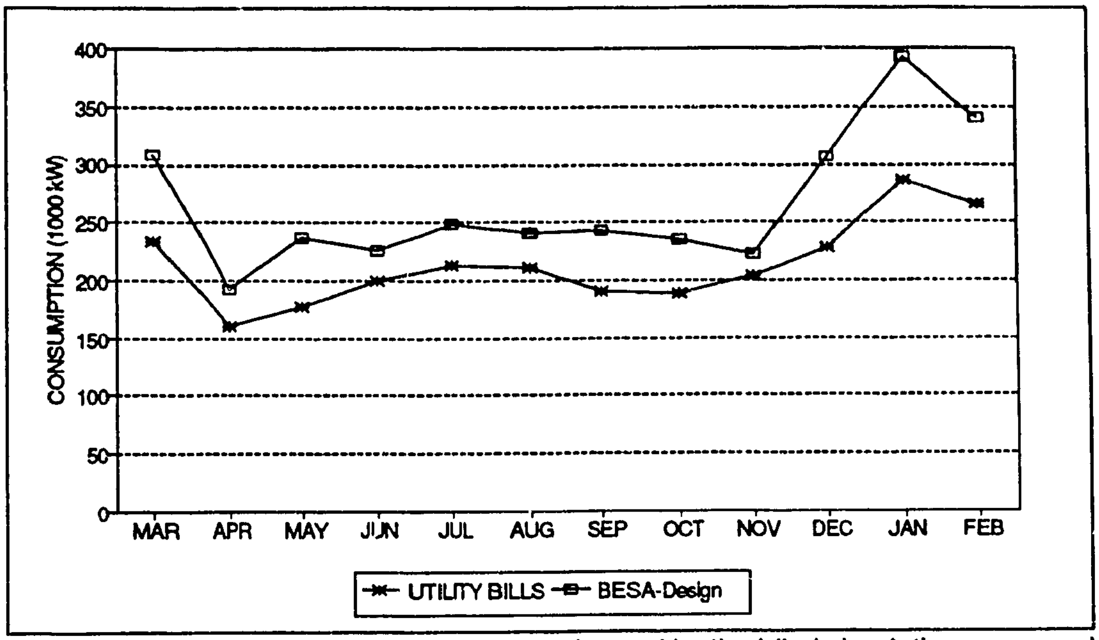

Figure 2.8 Monthly energy consumption estimated by the blind simulation compared to the normalized utility bills

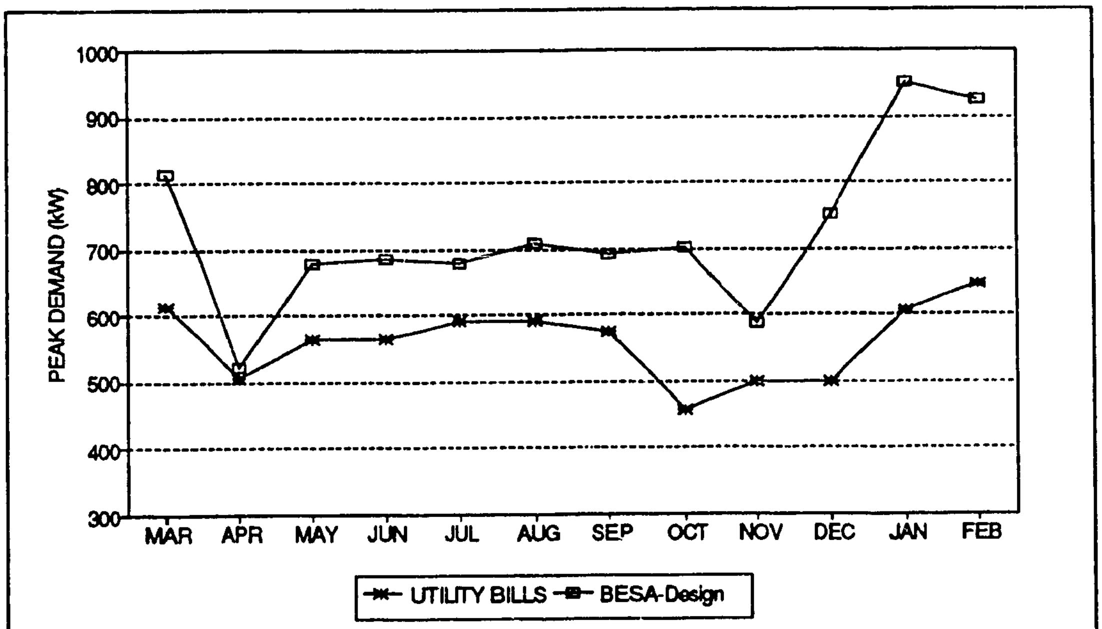

Figure 2.9 Monthly peak demand estimated by the blind simulation compared to the normalized utility bills

1. Blind; where the initial input file was used.

2. Run 1; where a blind simulation was performed with a new version of the program which required that all input data be reentered.

3. Run 2; where the input file for the blind simulation was modified to calibrate the model with the utility bills.

4. Run 3; where the same input file as Run 2 was used with the new version of the program received August 23, 1993.

5. Run 4; where the same input file as Run 2 was used with the new version of the program received September 8, 1993.

6. Run 5; where the model was calibrated using the latest version of the program.

The annual energy consumption predicted by each simulation is shown in Figure 2.10 for simulations using (1) typical day (TD), and (2) hourly weather file (H). For the blind simulation, only the typical day results are presented due to the problems detected with the hourly simulation results. The graph shows that the annual energy consumption from the hourly and typical day simulations for each case are very close; however, the program versions used in Run 3 and Run 4 greatly underestimate the consumption, although the latest version, Run 5, shows good agreement.

Figure 2.11 presents the annual peak demand for each simulation using typical day and hourly weather data. Unlike Figure 2.10 which showed similar results for the annual energy consumption predicted by the typical day and hourly simulations, the peak demand predicted by the typical day simulations are consistently lower than the peak demand predicted by hourly simulations.

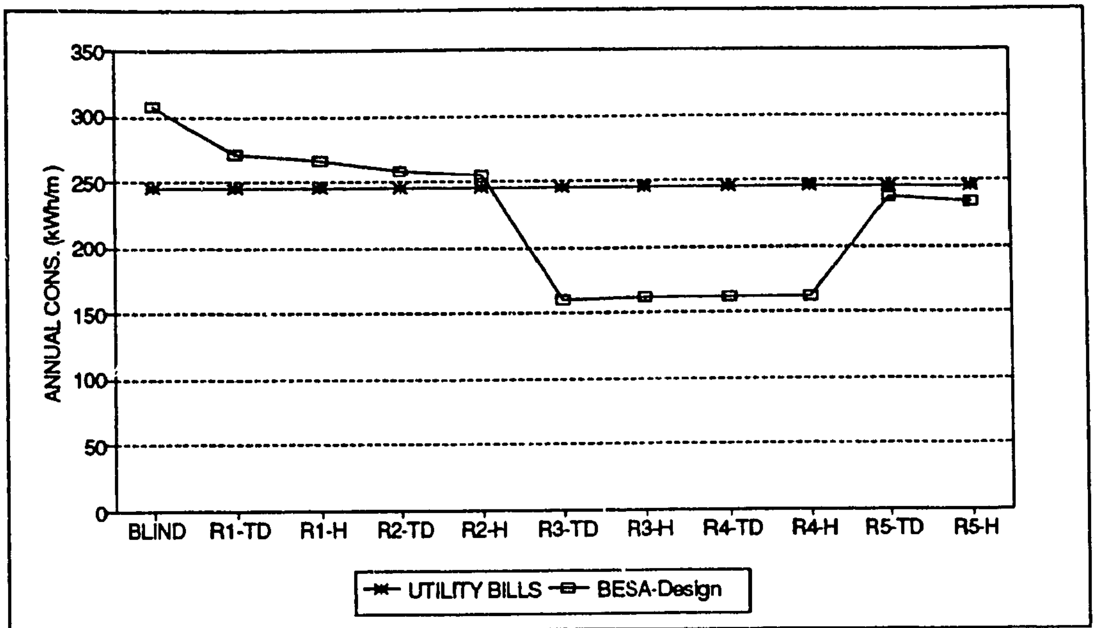

Figure 2.10 Annual energy consumption obtained from the utility bills and from various simulations using the BESA-Design program

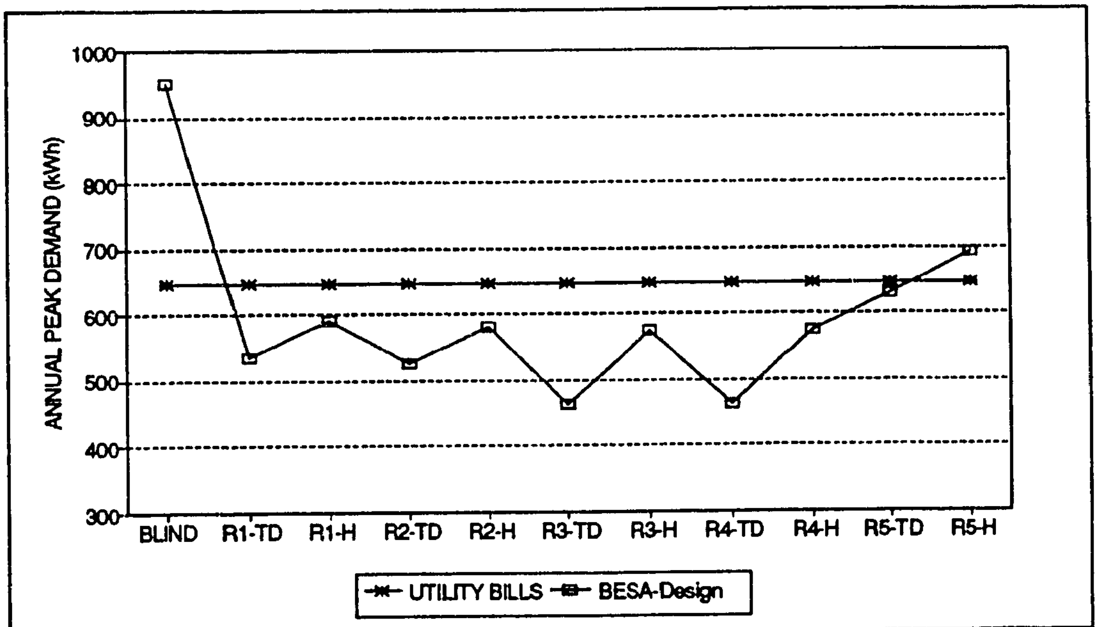

Figure 2.11 Annual peak electric demand obtained from the utility bills and predicted by various BESA-Design program simulations

Figure 2.12 shows the monthly variation of energy consumption predicted by the various simulations using hourly weather data. The results of Run 5 are the closest estimate of the monthly energy consumption, since it is the final calibrated model. Run 3 and Run 4 show the effect of the new versions on the simulation results, namely the large underestimate of the energy consumption.

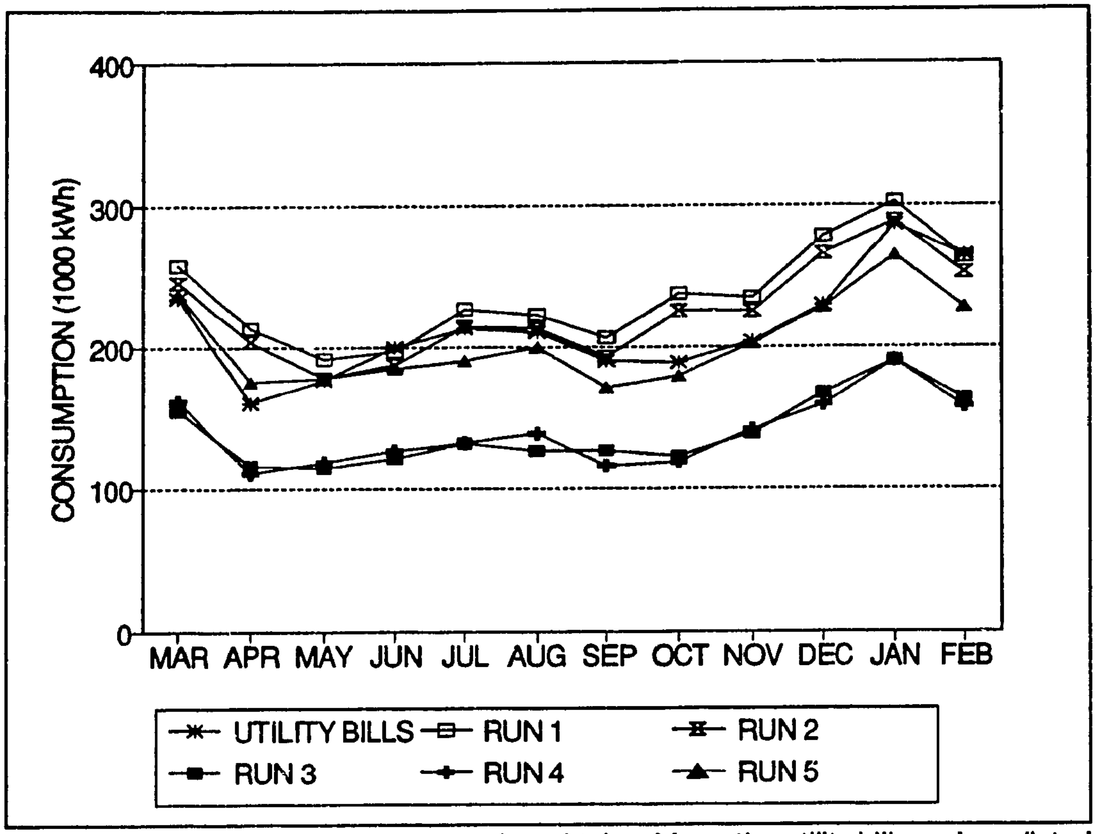

Figure 2.12 Monthly energy consumption obtained from the utility bills and predicted by various BESA-Design program simulations

Monthly variation of peak demand, as predicted by the various simulations, is presented in Figure 2.13. The peak demand predicted by Run 2, which is a calibrated model, shows large differences in the summer months; however, the results from the newer versions do not follow this trend. The results of Run 5 are the best estimates of the normalized values from the utility bills.

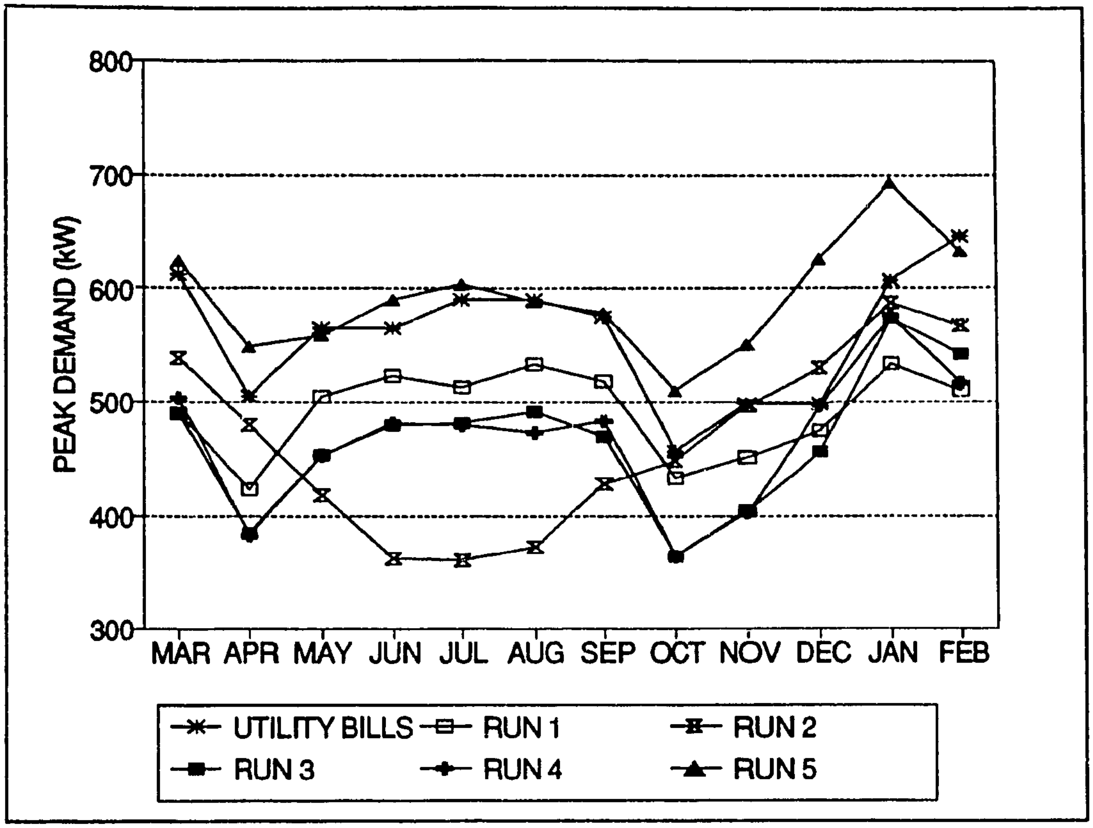

Figure 2.13 Monthly peak electric demand obtained from the utility bills and predicted by various BESA-Design program simulations

Table 2.2 presents the annual energy consumption, peak demand and annual energy cost predicted by the final simulation. The differences between the simulation results and the utility bills are within the requested limits, as defined by Hydro-Quebec. It is interesting to note that although the hourly simulation is expected to be more precise, the results from the typical day simulation are closer to the data from the utility bills. It should be emphasized that the program does not have the capability to accurately simulate the rate structure of the utility company, since it is not able to evaluate the penalties imposed if the subscribed electric demand is exceeded.

Table 2.2. Annual consumption, peak demand, and cost obtained from the final simulation, Run 5

	Normalized Value	Hourly		Typical day	
		Final result	Diff. (%)	Final result	Diff. (%)
Consumption ($kWh/m^2/yr$)	245.9	234.7	-4.5	236.4	-3.9
Peak Demand (kW)	645	692	7.3	629	-2.4
Cost ($\$/m^2/yr$)	15.23	15.62	2.6	14.99	-1.6

The development of the input file can be extremely time-consuming due to the numerous input values which are not readily available. The consultation of manufacturers' catalogues is required as well as the calculation and estimation of some parameters. These uncertainties in the input values are used to calibrate the simulated model to the data from the utility bills. However, due to the large amount of parameters which can be modified, many iterations are required in order to obtain the calibrated model. Consequently, the final model which is presented here is not a unique solution. In fact, in the study for Hydro-Quebec, the three users arrived at different calibrated models, while still remaining within acceptable differences for monthly energy consumption and peak demand, with the exception of user C who overestimated the peak demand from November to February (Figures 2.14 and 2.15) [45]. User-interpretation of input data can greatly affect the simulation results, as seen in the figures. Unfortunately, it is a problem which cannot be easily solved, especially with the reality of uncertain input data which faces all consultants and users of energy simulation software.

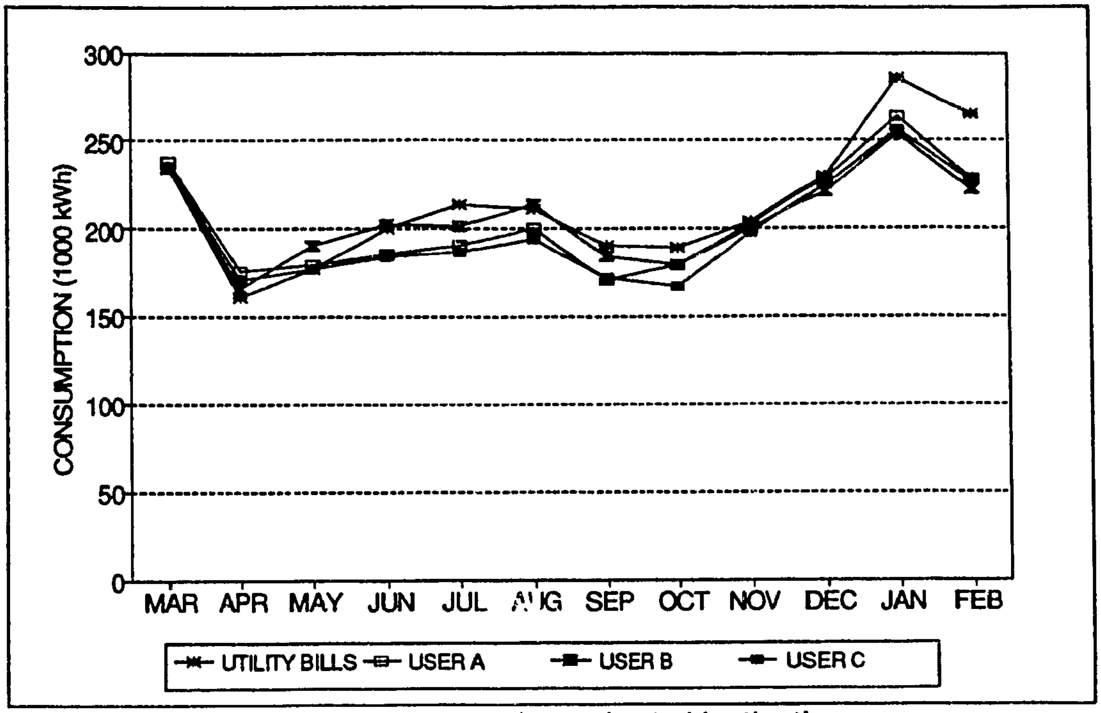

Figure 2.14 Monthly energy consumption estimated by the three users

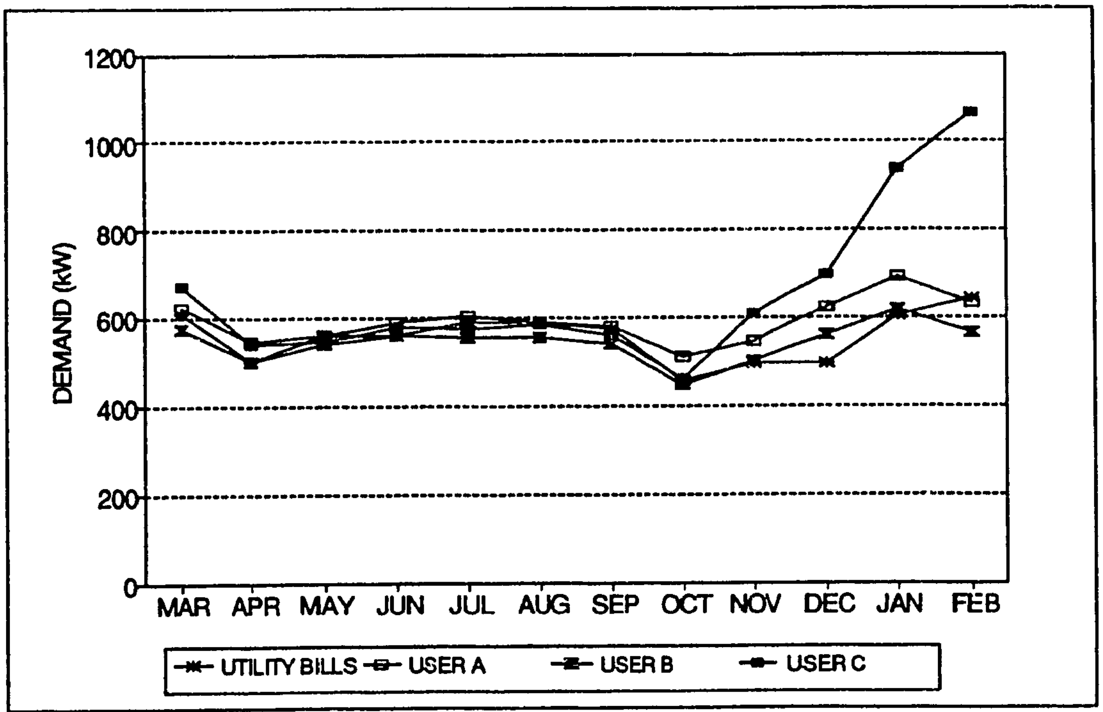

Figure 2.15 Monthly peak electric demand as estimated by the three users

2.2.5 Simulation of energy conservation measures

One of the important features of an energy simulation program is the ability to predict the energy savings realised after the implementation of a given energy conservation measure. The simulation of various energy conservation measures (ECMs) is performed using the final calibrated computer model, that is Run 5, as the base model of the large existing building. However, the scope of these measures is limited by the specific request of the building manager that they not include the purchase of new HVAC equipment nor any large initial investment. The following individual measures are simulated:

1. Insulation of the floor between the garage and the ground floor.
2. Insulation of the floor between the garage and the ground floor, while decreasing the garage temperature from 19°C to 15°C.
3. Night setback of indoor temperature from 20°C to 16°C in the winter by the installation of programmable thermostats.
4. Increase of the cooling setpoint from 23-24°C to 25-26°C.
5. Reduction of the lighting power density on the first floor from 25.8 W/m² to 22.0 W/m².
6. Reduction of the lighting power density on the first floor from 25.8 W/m² to 11.4 w/m² and use of task lighting of 1.4 W/m².
7. Turn off lights in the washrooms, stairwells and garage during unoccupied periods.
8. Installation of timers and motion detectors to ensure general lighting is off during unoccupied periods.
9. Installation of power management devices to turn off office equipment when it is not in use.

In addition, four groups of energy conservation measures, developed by combining some of the previous individual measures, are also evaluated:

I. Measures 4 and 5.
II. Measures 3, 7, 8, and 9.
III. Measures 3, 4, 5, 7, 8, and 9.
IV. Measures 4, 5, 7, 8, and 9.

Table 2.3 lists the cost savings and reduction in annual energy consumption obtained for each measure compared with the base model. Every measure simulated shows a reduction in energy consumption, and individual ECM 8 and group ECM II, show the highest reductions in their respective categories. On the other hand, an increase in annual energy cost is observed for ECM 3 due to the large increase in peak demand resulting from the night setback of indoor air temperature. The largest energy cost savings are predicted for ECM IV, and among the individual ECMs, ECM 6 shows the largest savings.

Table 2.3 The predicted annual cost and consumption savings for each ECM using BESA-Design

Measure	Cost savings		Reduction of energy consumption	
	$	%	kWh	%
ECM 1	1 025.00	0.6	29 118	1.2
ECM 2	363.00	0.2	13 439	0.5
ECM 3	-3 171.00	-1.9	111 993	4.5
ECM 4	5 175.00	3.1	72 795	2.9
ECM 5	1 852.00	1.1	29 118	1.2
ECM 6	6 898.00	4.2	109 753	4.4
ECM 7	1 127.00	0.7	16 799	0.7
ECM 8	6 104.00	3.7	152 310	6.1
ECM 9	2 628.00	1.6	50 397	2.0
ECM I	7 064.00	4.3	16 798	0.7
ECM II	5 924.00	3.6	237 425	9.6
ECM III	9 450.00	5.8	212 787	8.6
ECM IV	9 498.00	5.8	109 701	4.4

When the energy conservation measures were simulated by the three users, for the study previously described, the results showed some disagreement [45]. The annual energy cost savings predicted by the three users varies significantly for each energy conservation measure, as shown in Table 2.4. Since the results from User C are not very reliable due to the high values of peak demand simulated in the base case, more emphasis is placed on the comparison of the results of User A (the author) and User B. It is interesting to note that although the estimated cost savings vary between the two users, the order in which the recommended measures are ranked, from highest to lowest cost savings, shows some similarities between the two cases. This calls into question the need for a very accurate base model for the simulation of energy conservation measures.

Table 2.4 Annual cost savings predicted by the three users for each energy conservation measure

Measure	Percent reduction in annual energy cost		
	User A	User B	User C
ECM 1	0.6	0.6	2.5
ECM 2	0.2	0.4	2.1
ECM 3	-1.9	-6.8	-28.7
ECM 4	3.1	5.0	5.7
ECM 5	1.1	0.4	1.6
ECM 6	4.2	3.5	4.4
ECM 7	0.7	3.8	1.7
ECM 8	3.7	3.3	7.3
ECM 9	1.6	2.9	6.6
ECM I	4.3	5.0	5.1
ECM II	3.6	6.2	12.5
ECM III	5.8	10.2	15.2
ECM IV	5.8	10.5	12.2

It must be kept in mind however, that the initial investment required for an ECM is vital in deciding which measure to implement. Owners and building managers use several economic models to estimate whether the investment will be profitable. Consequently, the accuracy of the estimate of the initial cost is essential to correctly predict the profitability of a given energy conservation measure. For this study, the indices used to weigh the profitability of each energy conservation measure are: (1) the payback period, and (2) the benefit-cost ratio. These indices were recommended by Hydro-Quebec to be used in evaluating the energy conservation measures for the contract previously described. The payback and benefit-cost ratio are calculated as follows:

$$\text{payback period (years)} = \frac{\text{initial investment}}{\text{annual savings}} \tag{2.1}$$

$$\text{benefit-cost ratio} = \frac{\text{savings per year} * (1+i)^n}{\text{initial investment}} \tag{2.2}$$

where i is the interest which was assumed to be 8%, and n is the amortization period assumed to be 20.

Several energy conservation measures do not require any initial investment, such as ECM 4, 5, 6, 7, and group ECM I. The initial investment required for the other measures is estimated by contractors from the Montreal area:

1. The cost of insulation is estimated for ECM 1 and 2 as:
   202.92 $/m^2 x 1681.5 m^2 = $341 212.

2. The cost of the thermostats for ECM 3 is equal to $164/thermostat.

3. The cost of the motion detectors for ECM 8 is estimated as:
   150 $/unit x 5 units/floor x 7 floors = $ 5 250.

4. The cost of power management devices for office equipment for ECM 9 is estimated as:

$$\frac{248\ \$/\text{unit} \times 133\ \text{computers}}{6\ \text{computers/unit}} = \$\ 5\ 500.$$

5. The cost of the motion detectors and equipment management devices for ECM II, III, and IV is calculated as:

$$\$\ 5\ 250 + \$\ 5\ 500 = \$10\ 750.$$

The payback period and benefit-cost ratio are calculated for those energy conservation measures requiring an initial investment and leading to cost savings, as listed in Table 2.5. The most profitable measure, according to these indices, is ECM IV with a payback of only 1.13 years and a benefit-cost ratio of 2.07.

Table 2.5 The payback period and benefit-cost ratio for some selected energy conservation measures simulated using BESA-Design

Measure	Payback period (years)	Benefit-cost ratio
ECM 1	>> 10	<< 1
ECM 2	>> 10	<< 1
ECM 8	0.86	2.72
ECM 9	2.1	1.12
ECM II	1.8	1.29
ECM III	1.14	2.06
ECM IV	1.13	2.07

2.3 Conclusions

The objective of this initial study was to evaluate the ability of the BESA-Design program to respond to the consultants' needs by testing the program's ability to simulate a large existing commercial building and estimate the impact of several energy conservation measures. During the evaluation process, several program errors were discovered which leads to the conclusion that the program requires further improvements before it can be used by consultants.

The comparison of the simulations performed independently by three users revealed the importance of user-interpretation in the development of the input file. Furthermore, the annual energy cost savings estimated for the simulated energy conservation measures, varied significantly between users, although a similar trend was found among the ranking of the recommended measures.

From a procedural viewpoint, the study shows that the empirical validation is able to detect certain anomalies in the program results as well as establish the limitations of the program. However, due to the uncertainty in input data and the effect of compensating errors, the empirical validation cannot adequately identify program errors. This conclusion leads to the need for a more systematic and detailed approach to the validation process, which is presented in the following chapters.

CHAPTER 3
VALIDATION OF THE MICRO-DOE 2.1 PROGRAM. PART 1 - EMPIRICAL VALIDATION AND INTER-MODEL COMPARISON

In his book on independent verification and validation of software programs, Robert Lewis emphasizes the need for third party validation of software [47]. Furthermore, he stresses that the party validating the software has a final responsibility to the customer of the software and not to the developer. Through research, many building energy simulation software have been subjected to validation techniques in order to define their level of accuracy. However, as discussed, the previous research has usually focused on the validation of heat transfer algorithms through the envelope with little attention given to the HVAC systems and large commercial buildings.

Contrary to the present practice of the validation of energy simulation software, Lewis places the role of independent verification and validation simultaneously with the software development. However, for the case of BESA-Design described previously, this approach proved to be inefficient and very time-consuming since 11 different versions of the software were used, requiring several calibrations. In the approach described by Lewis, each phase in the development of the software is subjected to a vigorous plan of verification and validation. More specifically, this process is seen in four stages: requirements verification, design verification, code verification and validation. The verification process is seen as a method of evaluating the program's algorithms and logical sequence, whereas the validation considers the software performance as a whole. The details of the validation process, however, are vague and do not clearly define what types of tests are needed to ensure validity. Consequently, although the need for verification and validation is emphasized, the process outlined in the book does not provide any immediate nor long-term solutions.

This study proposes a procedure to validate building energy simulation software. The procedure is aimed at energy consultants and users of energy simulation programs since it does not require long-term measurements or great investment. The first part includes two of the validation techniques previously described: the empirical validation and the inter-model comparison. The second part, which will be discussed in chapter 4, presents various verification techniques which are used to detect program errors.

This procedure is used to validate the MICRO-DOE 2.1 energy simulation program [48]. There are several reasons which led to the use of the MICRO-DOE program over BESA-Design: (1) the developer of the BESA program was not able to continue providing technical support or improving the program due to the lack of interest of the construction industry to use or accept the BESA-Design program; (2) the latest version of the MICRO-DOE 2.1 program, version E, was expected to be available in the near future; (3) the MICRO-DOE 2.1 program is seen by most users as a standard in building energy simulations. Therefore, all efforts in applying the global validation approach are directed towards the use of the MICRO-DOE 2.1E program by an energy consultant.

Since 1976-77, when the first version of the DOE program was released, several validation studies were performed on the program [1, 2, 3, 15, 16, 17, 21, 26, 31]. However, an energy consultant is still surprised, at first glance, by the results provided by the program. Only after additional simulations, where the impact of a given parameter is isolated and the complexity of the model is reduced, can the consultant understand the logic behind the results, and recover the confidence in the program. This study aims to add new information to the existing validation studies of the DOE program, and especially to the new version E.

3.1 Empirical validation of MICRO-DOE 2.1D

An empirical validation is first performed using the version D of the MICRO-DOE 2.1 program. During this process, the input file is developed, the model is calibrated, and finally, several energy conservation measures are simulated. The following section describes some assumptions and calculations required, in addition to those presented previously for the BESA-Design program.

3.1.1 Definition of the input file

The input file was developed using the initial assumptions for the building rather than the calibrated model of the BESA program. When the problems related to program limitations discovered in DOE are similar to those found in BESA, the same assumptions are made. These include the simulation of the carbon dioxide sensors for the control of outdoor air brought into the system, the carbon monoxide sensors for the garage exhaust fans and the HVAC schedule beginning at 8:00 am instead of the actual 7:30 am. On the other hand, some limitations present in BESA are not present in the DOE program, such as the cooling equipment operating from April 15 to October 15, which can easily be simulated in DOE.

The commercial building is separated into 24 thermal zones: 5 zones for plenums in addition to the 19 zones defined in BESA. The layout of zones 1 through 19 follow the same layout as previously described. The plenums defined as thermal zones are:

-- zone PLEN-7 for the plenum of the seventh floor
-- zone PLEN-1-6 for the plenums of floors 1-6
-- zone PLEN-LB, for the plenum of the lobby and the ground floor offices
-- zone PLEN-VH, for the plenum of the restaurant
-- zone PLEN-FD, for the plenum of the bank

The same information as in the case of the BESA-Design program is used directly to develop the input file. However, due to some program limitations and different methods of defining input data, some additional calculations are necessary:

1. One electric domestic hot water heater is simulated with a capacity equivalent to the total heating capacity of all hot water tanks in the building:

   $$9 \text{ tanks} * 3.0 \text{ kW/tank} = 27.0 \text{ kW}$$

2. One way to define the installed power for fans is to define Watts per unit of air flow rate or W/(L/s), therefore, the size of the washroom exhaust fan is defined as:

   $$\frac{(2 \text{ hp} * 746 \text{ W/hp})}{(3303.7 \text{ L/s} / 8 \text{ floors})} = 3.6 \text{ W/L/s per zone}$$

3. The size of all other fans are defined as follows:

   central supply fan: $\frac{125 \text{ hp} * 746 \text{ W/hp}}{38\ 230 \text{ L/s}} = 2.44 \text{ W/L/s}$

   central return fan: $\frac{75 \text{ hp} * 746 \text{ W/hp}}{34\ 920 \text{ L/s}} = 1.60 \text{ W/L/s}$

   restaurant fan: $\frac{0.75 \text{ hp} * 746 \text{ W/hp}}{1\ 130 \text{ L/s}} = 0.495 \text{ W/L/s}$

   bank fan: $\frac{1.5 \text{ hp} * 746 \text{ W/hp}}{2\ 265 \text{ L/s}} = 0.495 \text{ W/L/s}$

4. Although there are only four condenser units, each one is equipped with two compressors of 92.3 kW of cooling capacity each, which results in eight stages of refrigeration. Therefore, eight chillers are defined with a capacity of 92.3 kW each.

5. The installed power of the condenser fans must be defined as a ratio of the power used by these fans to the total cooling capacity of the chiller:

   $$\frac{6 \text{ fans/unit} * 1.35 \text{ kW/fan}}{2 \text{ compressors/unit} * 92.3 \text{ kW/compressor}} = 0.0438$$

6. The energy consumption for the exhaust fans of the garage is accounted for in miscellaneous equipment. It is assumed that one fan of 1.1 kW is operational between 12:00 pm and 1:00 pm and two fans totalling 1.9 kW are operational from

9:00 am to 10:00 am and 5:00 pm to 6:00 pm. (The BESA program allows only one fan to be simulated. It was assumed that one fan of 1.1 kW was operational three hours per day: 9:00 am to 10:00 am, 12:00 pm to 1:00 pm, 5:00 pm to 6:00 pm.)

7. The glass conductance as defined in the MICRO-DOE program does not take into account the resistance of the outdoor air film. Therefore, an average value for the outside film coefficient, 0.0294 $m^2 \cdot °C/W$ [49], is subtracted from the value obtained in the manufacturer's catalog [35] for the daytime U-value, 2.67 $W/m^2 \cdot °C$ (0.375 $m^2 \cdot °C/W$), and the glass conductance of the glazing, excluding the outside film coefficient is equal to 2.89 $W/m^2 \cdot °C$.

3.1.2 Calibration of the model

Since the measured utility consumption and peak demand are already known, this validation does not include a blind simulation, as previously presented for BESA, and proceeds directly to the calibration phase. During the calibration of the DOE-2.1D model, the values of input variables with large uncertainties are modified without considering the calibration modifications performed for the BESA program. Although the modifications made to the two programs may disagree, this procedure allows for an objective calibration of the DOE model without being influenced by the results of the BESA program. In other words, the two programs are calibrated independently.

The calibration of the first model is difficult since during some months the consumption and peak demand are underestimated while for other months, they are overestimated. In order to arrive at the final calibrated model, modifications are made to the value of the input parameters with large uncertainties, as enumerated below:

1. The domestic hot water use during the night and on weekends is increased from 10% of the maximum capacity to 15%.

2. The equipment use schedule is increased during the night from 5% of the maximum

capacity to 30% to account for equipment that is not turned off.

3. A different glazing is chosen from the manufacturer's catalog [35], thereby increasing the shading coefficient from 0.16 to 0.38 and increasing the glass conductance from 2.89 $W/m^2 \cdot °C$ to 3.63 $W/m^2 \cdot °C$.

4. The floor weight is increased from 24.4 kg/m^2 to 73.2 kg/m^2.

5. The wall absorptance for the concrete and brick walls is decreased from 0.85 to 0.65 to represent the recommended values published in the DOE user manual [48].

6. The infiltration rates are modified from the initial values given by the ADS report, which estimated 0.24 ach for the perimeter zones of the office tower, 0.5 ach for the lobby and bank, and 0.2 ach for the restaurant and garage. The new infiltration rates for the perimeter zones of the office tower are 0.3 ach when the HVAC system is off; for the lobby, restaurant and ground floor the infiltration is estimated at 0.25 ach when the system is off, and 0.25 ach continuously for the garage. No infiltration is assumed for the ground floor or office tower when the system is on.

7. The increase in temperature of the supply and return air in the ducts is increased for all systems from 1.1°C to 2.0°C.

8. The ballast factor of the fluorescent fixtures is increased from 1.18 to 1.2.

9. The heating schedule for the garage is lengthened from its initial estimate of October 15 through April 15 to September 15 through May 15 in order to reduce the number of hours the garage is underheated in September and May. The heating schedule in all other zones is similarly lengthened.

10. The cooling schedule is lengthened from its original estimate of April 15 to October 15 to April 1 to November 1 which is the schedule used in the BESA program.

11. The minimum humidity is decreased from its original estimate of 25% to 20%.

12. The miscellaneous equipment energy is increased by 60 kW for some equipment which had not been accounted for.

13. The cooling setpoint temperature is decreased from 24°C to 22.8°C.

The annual energy consumption, peak electric demand, and annual energy cost as predicted by the MICRO-DOE 2.1D program are compared to the data obtained from the utility bills in Table 3.1. The peak electric demand predicted by the DOE 2.1D program is higher than the value from the utility bills, by over 16%. However, this high peak demand appears only for one month in the simulation results. The simulation estimates of the annual energy consumption and cost are both within 10% of the normalized data.

Table 3.1. Annual energy consumption, peak demand, and energy cost estimated by the MICRO-DOE 2.1D program and compared to the normalized data

	Normalized value	MICRO-DOE 2.1D	
		Result	Diff. (%)
Consumption ($kWh/m^2/yr$)	245.9	228.5	-7.1
Peak Demand (kW)	645	749	16.1
Cost ($\$/m^2/yr$)	15.23	15.16	-0.5

The results of the calibrated model in terms of monthly energy consumption and peak demand are compared to the normalized data as shown in Figures 3.1 and 3.2. The consumption is underestimated for most months up to 14.0% in June, except April with an overestimate of 12.4%. The peak demand is mostly overestimated with a maximum of 23.6% in January and an underestimation of up to 12.9% in November. However, as seen in the figures, the overall shape of the consumption and demand curves follows the normalized data relatively well.

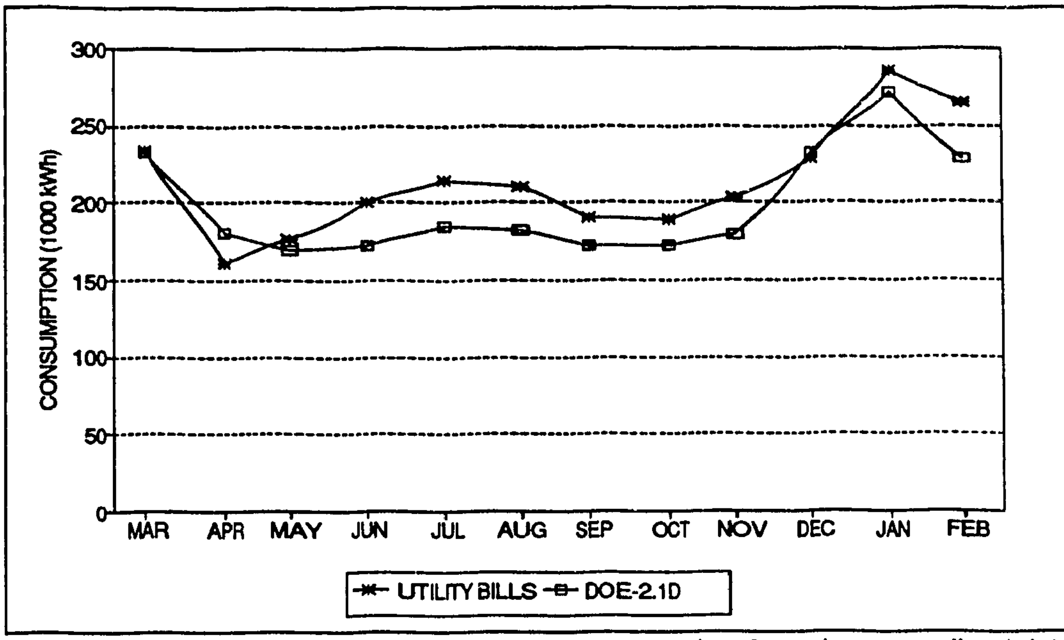

Figure 3.1 Comparison of monthly energy consumption from the normalized data and the MICRO-DOE2.1D program results

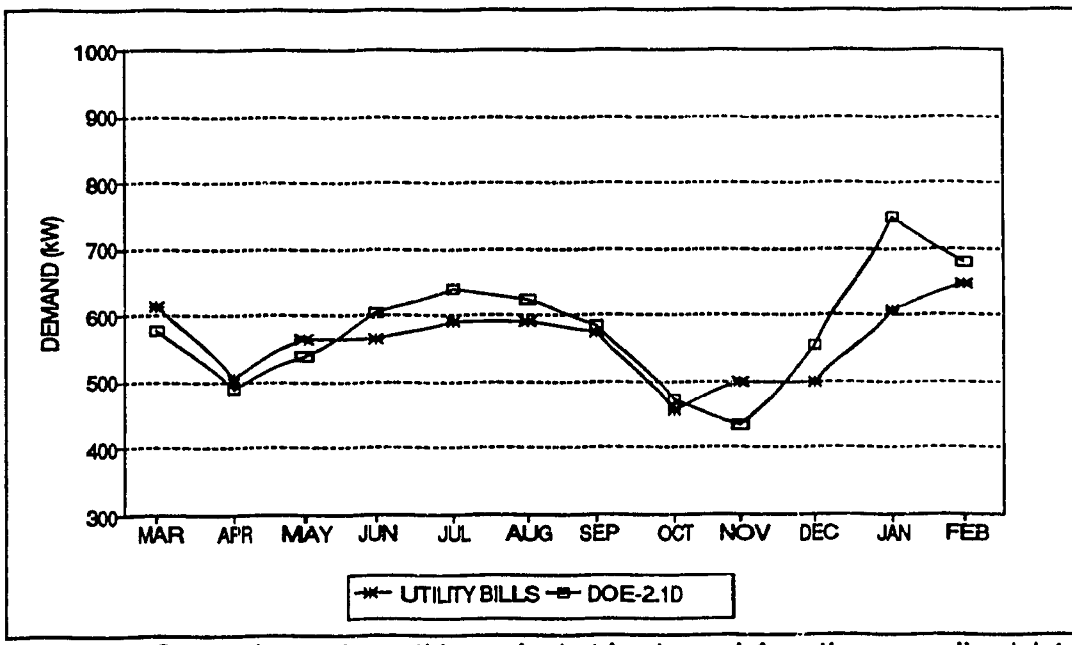

Figure 3.2 Comparison of monthly peak electric demand from the normalized data and the MICRO-DOE2.1D program results

Although the program cannot accurately simulate the method used by the utility company to calculate the penalties for exceeding the prescribed electric demand, the monthly energy costs are nonetheless well estimated by the program. The monthly energy costs from the utility bills are compared to the predicted costs as seen in Figure 3.3. The estimates follow the same pattern as the actual costs, with the largest difference of 13.3% occurring in April.

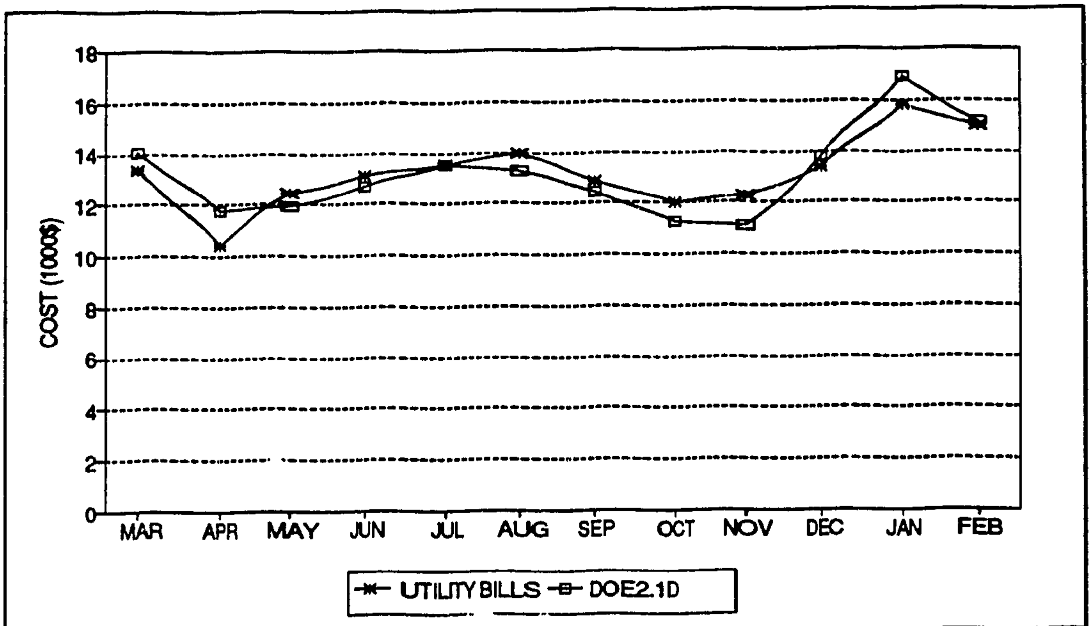

Figure 3.3 Comparison of monthly energy cost obtained from the utility bills and estimated by the MICRO-DOE2.1D program

3.1.3 Qualitative analysis of simulation results

In this section, a qualitative evaluation of computer predictions is presented. Since no measured data is available other than the energy consumption and peak demand from the utility bills, this section emphasizes the trends in the performance of the mechanical systems as predicted by the program.

The cooling loads of thermal zones (predicted in the LOADS block), the thermal loads of the cooling coils (from the SYSTEMS block), and the energy consumed by the central plant (from the PLANT block) are shown in Figure 3.4 on a monthly basis. The space cooling load is calculated based on internal heat gains, solar heat gains, difference between the outdoor and indoor air temperature, and building envelope characteristics. This value is then transferred to the SYSTEM block, which calculates the thermal load of the cooling coil based on entering and leaving air conditions and air flow rate. The system cooling load includes all energy used by fans, the load sent to the plant, as well as the loads on the cooling coils of the two unitary systems. The plant energy consumption includes fans, central chiller, air cooled condenser, as well as the energy consumption of the two unitary systems.

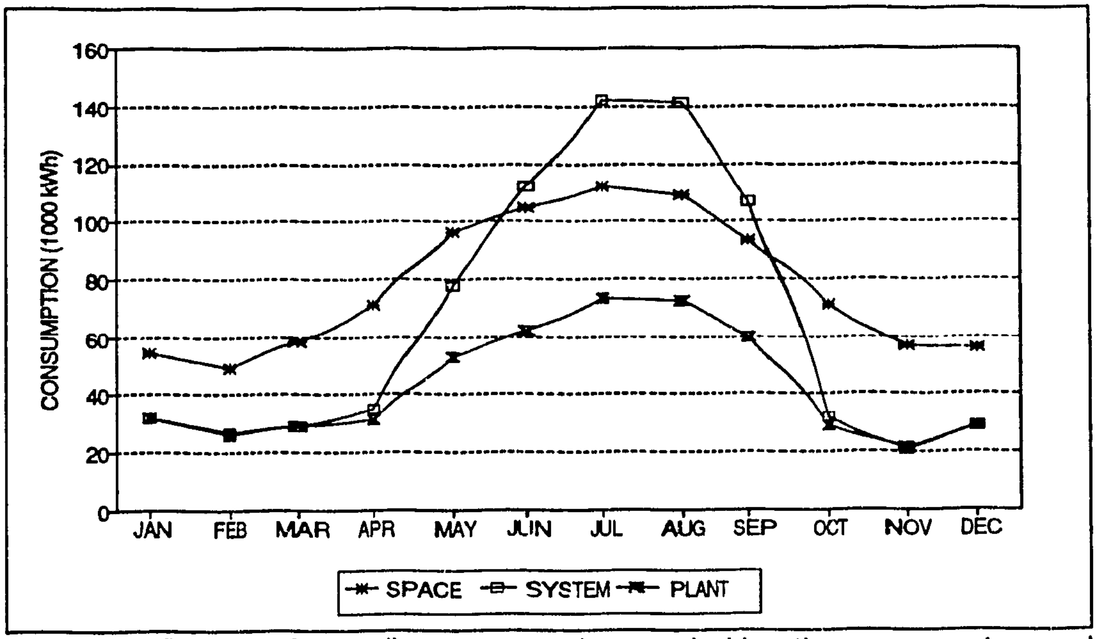

Figure 3.4 The monthly cooling consumption required by the space, system and plant simulated by the MICRO-DOE2.1D program

The cooling load of the space in the winter, as seen in the figure, is satisfied by increasing the percentage of outdoor air; therefore, the chillers do not operate. In the summer, the plant energy consumption is lower due to the coefficient of performance of the chillers. In other words, the energy consumption shown for the plant represents the energy input to the plant, whereas the cooling energy required by the system represents the refrigeration effect needed to satisfy the thermal loads. The shape of all three curves are as expected, although the absolute values could not be verified with actual data.

In Figures 3.5 and 3.6, the breakdown of monthly cooling energy required by the system and the plant, respectively, is presented. The system cooling energy is divided into its various components: fans for the central system (SYS-1), the two unitary systems (SYS-VH, SYS-FD), and the garage, as well as the load on the cooling coils of the three systems. Similarly, Figure 3.6 shows the breakdown of the monthly cooling energy for the plant into its components: fans, chiller, condenser, SYS-VH cooling coil and SYS-FD cooling coil. In both figures, the energy required by the central system fans is relatively constant throughout the year, and it is the largest contributor to the cooling energy in the winter.

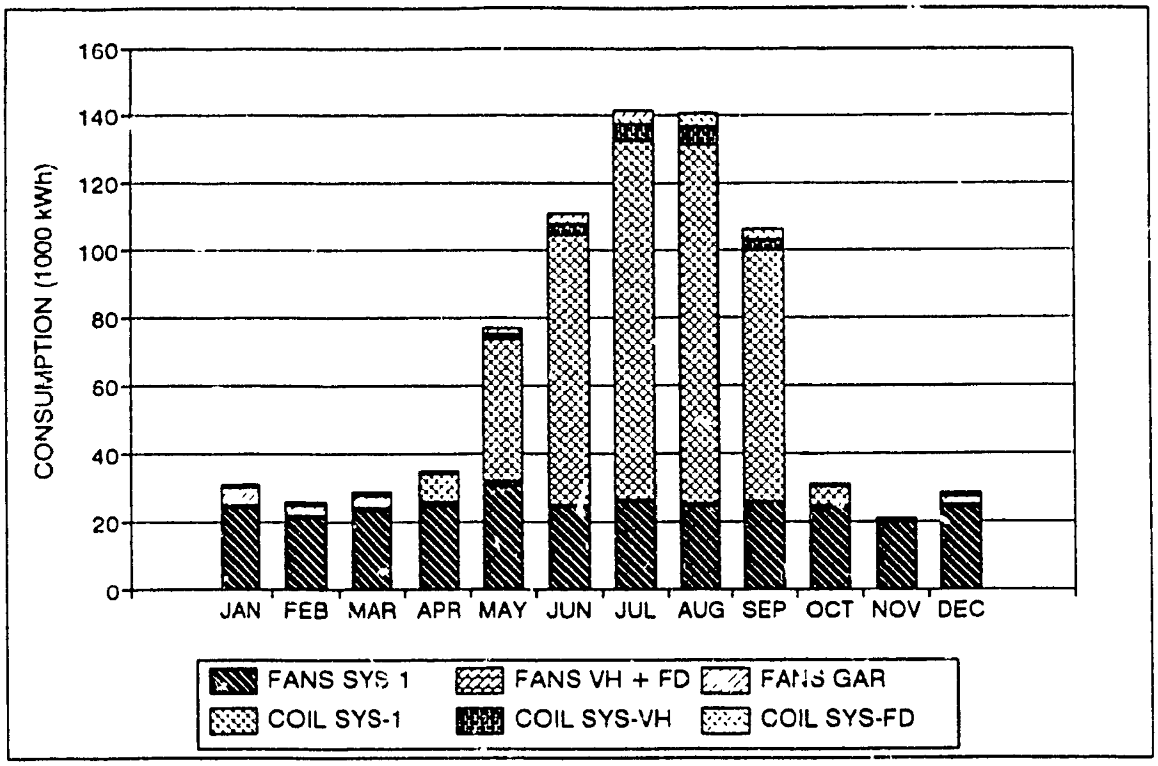

Figure 3.5 Breakdown of the monthly cooling consumption for the HVAC system, as predicted by the MICRO-DOE2.1D program

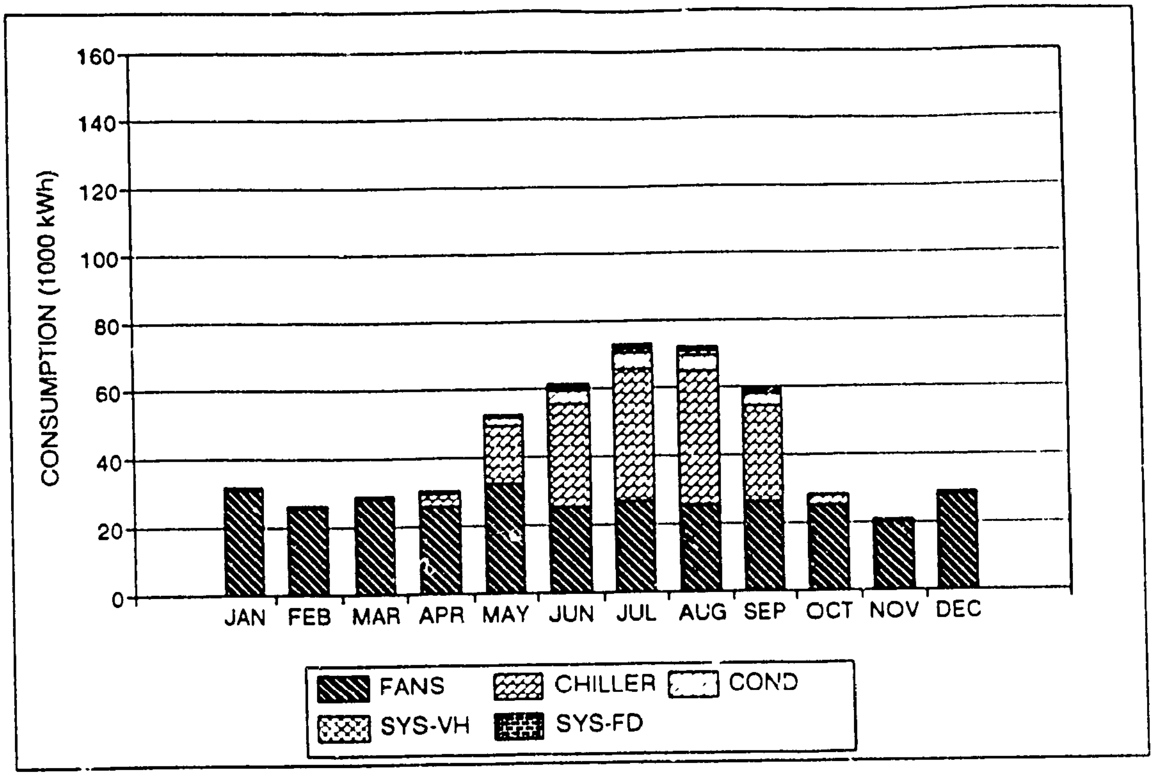

Figure 3.6 Breakdown of the monthly cooling consumption for the plant block, as simulated by the MICRO-DOE2.1D program

The peak system cooling demand is also analyzed in terms of its components, as well as the peak cooling demand for the plant. The trend is very similar to the component energy of Figures 3.5 and 3.6, in that the largest contributor to the cooling demand from the SYSTEM block is the central system cooling coil load, and the largest contributor for the PLANT block is the chiller. The contribution of the other components is minor.

Figures 3.7 and 3.8 present the monthly heating consumption and peak demand, respectively, for space, system and plant. The space heating energy and demand required in the summer are slightly higher than the system and plant, since heating is not available. The heating demand for the space is lower than the system or plant demand in the winter, due to the cold supply air which is accounted for in the system heating demand. However, the monthly space heating energy is very similar to the system and plant energy due to the 100% efficiency defined for the heating system simulated.

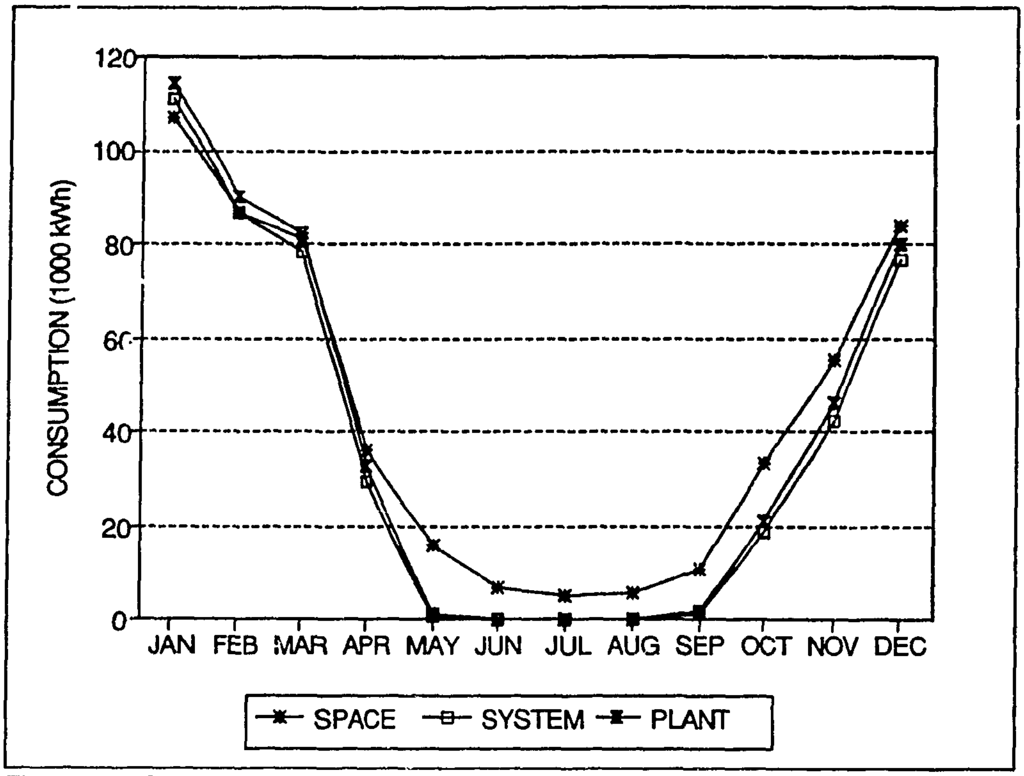

Figure 3.7 The monthly heating consumption required by the space, system and plant as simulated by the MICRO-DOE2.1D program

The total building energy consumption is divided among its end-uses as seen in Figure 3.9. The LIGHTS category includes the energy consumption from the lights as well as the miscellaneous equipment in BUILDING-RESOURCES-ELEC. This is due to a slight error in the program since the miscellaneous electric motors should be included in MISC. EQUIP. The figure shows that the lights, equipment and vertical transportation make up 53.8% of the total annual consumption, which is reasonable for an office building such as the one simulated. The cooling energy is less than the heating energy; however,

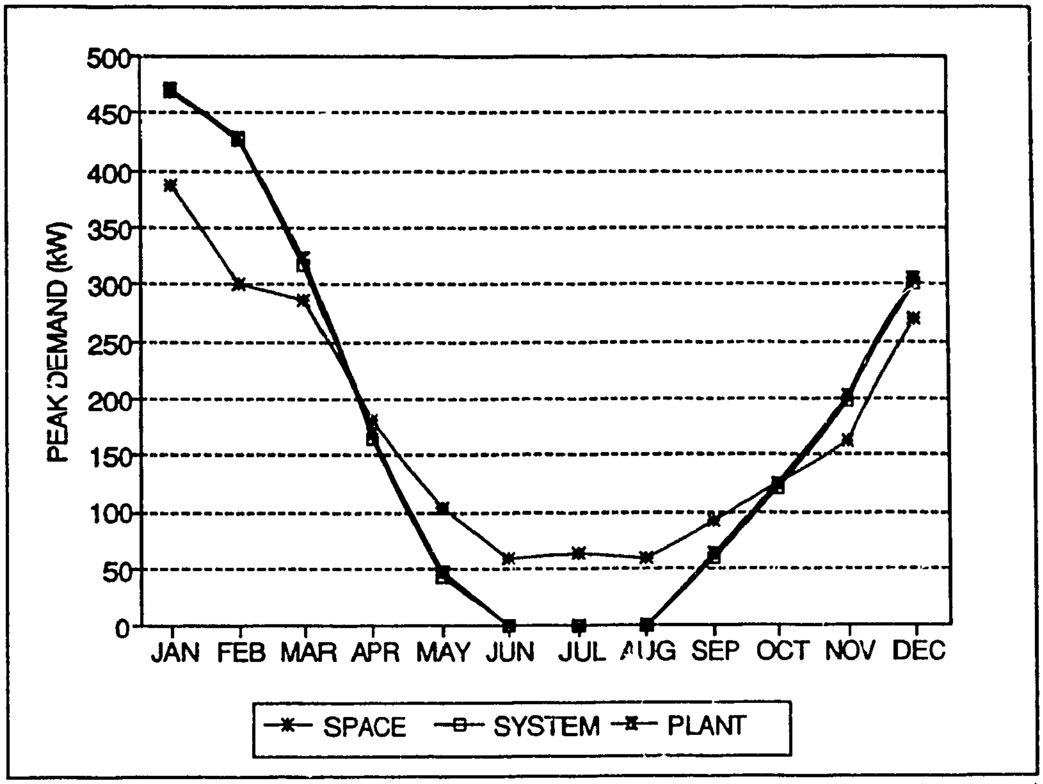

Figure 3.8 The monthly heating demand required for the space, system and plant as simulated by the MICRO-DOE2.1D program

considering that the monthly consumption for the summer months is underestimated between 9.0% and 14.2%, the cooling consumption presented in the figure may underestimate the actual consumption.

The qualitative analysis of the MICRO-DOE2.1D base model shows that the results obtained are reasonable in terms of the cooling and heating consumption and peak demand predicted for the space, system and plant. The breakdown of the annual energy consumption into its end-uses also shows reasonable results for the type of building simulated.

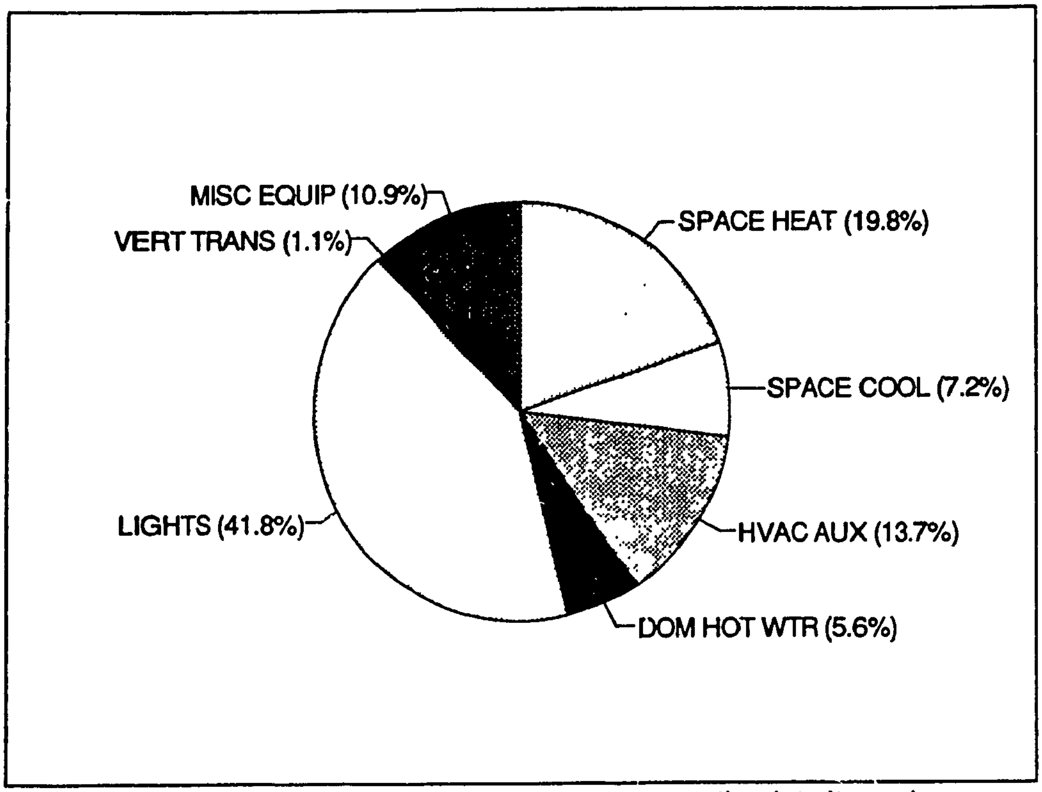

Figure 3.9 Breakdown of the annual energy consumption into its end-uses, as simulated by the MICRO-DOE2.1D program

3.1.4 Simulation of energy conservation measures

The energy conservation measures described in Chapter 2 for the BESA validation are also simulated using the MICRO-DOE2.1D program; the results are presented in Table 3.2. Measures 1 and 3, as well as group II, all show an increase in energy costs. The largest cost savings are obtained with individual measure ECM 6 and the group of measures ECM IV, with savings of $3 387.50 and $8 030.00, respectively. However, the predicted consumption savings are highest with individual measure ECM 8 and group ECM III. The energy cost savings predicted for each measure as simulated with the MICRO-DOE program are compared to the values predicted by the BESA program in section 3.3.2.

Table 3.2 The predicted annual cost and consumption savings for each ECM using MICRO-DOE2.1D

Measure	Cost savings		Reduction of energy consumption	
	$	%	kWh	%
ECM 1	-1 667.70	-1.03	-51 716	-2.13
ECM 2	806.80	0.50	9 510	0.39
ECM 3	-6 865.80	-4.24	73 701	3.03
ECM 4	2 972.70	1.84	60 801	2.50
ECM 5	1 747.30	1.08	32 211	1.33
ECM 6	3 687.50	2.28	64 884	2.67
ECM 7	105.80	0.07	6 877	0.28
ECM 8	1 280.30	0.79	85 083	3.50
ECM 9	525.00	0.32	33 496	1.38
ECM I	5 384.90	3.33	91 654	3.77
ECM II	-3 503.60	-2.16	163 077	6.71
ECM III	3 420.60	2 11	237 194	9.76
ECM IV	8 030.00	4.96	160 333	6.60

The payback period and benefit-cost ratio for the measures having a positive cost savings as well as requiring an initial investment are shown in Table 3.3. The measure with the best results (ie. the lowest payback period and highest benefit-cost ratio) is clearly ECM IV, with a payback period of 1.3 years and a benefit-cost ratio of 1.75. The measures ECM 4, 5, 6, and 7 are also recommended since they do not require any initial investment, and the simulation results show a positive energy savings.

Table 3.3 The payback period and benefit-cost ratio for some selected energy conservation measures simulated using DOE-2.1D

Measure	Payback period (years)	Benefit-cost ratio
ECM 2	>> 10	<< 1
ECM 8	4.1	0.57
ECM 9	10.5	0.22
ECM III	3.1	0.74
ECM IV	1.3	1.75

3.2 Empirical validation of MICRO-DOE2.1E

The empirical validation of the MICRO-DOE2.1E program is undertaken in a similar way as the validation of the previous version. However, some modifications to the input file are necessary, due to the new format required by the software.

3.2.1 Differences between MICRO-DOE program versions D and E

The new version (version E) of the MICRO-DOE simulation software is similar to the one previously described (version D); however, the consequences of the modifications made in the new version were estimated to decrease the heating loads by 10-20% and increase the cooling loads by 10-20% [50]. This section presents only those modifications made to the program which affect this study:

1. The user interface of the version E is slightly modified to facilitate movement between menus.

2. A batch mode is incorporated, so that an unlimited number of input files can run consecutively.

3. The energy consumption for the elevators is combined with the miscellaneous equipment.

4. The elements previously described in BUILDING-RESOURCES in the LOADS block, such as the miscellaneous equipment and the domestic hot water, are moved to PLANT-ASSIGNMENT in the SYSTEMS block.

5. The data required for defining the domestic hot water system is more detailed, such as the flow rate in gallons per minute, the tank size in gallons and the supply temperature.

6. Some major modifications were made to the ECONOMICS block in relation to the way the energy costs are defined.

7. The correlation between air film conductance and wind speed, the wind speed calculations, and the calculation of the infrared radiation loss from the building envelope to the sky were modified.

3.2.2 Simulation results

In order to compare the differences in results between the two versions of the MICRO-DOE 2.1 program, no additional calibration of the model is undertaken. Consequently, some simulation results are slightly out of the acceptable range when compared to the data from the utility bills.

The annual energy consumption, peak demand and annual energy cost as predicted by the MICRO-DOE 2.1E program is shown in Table 3.4. Although the annual consumption is underestimated by 12.1% as compared to the measured consumption, the estimated peak demand is within 3.7% of the measured value. In addition, the annual e: ergy cost is also well estimated, with a difference of only 4.3%.

Table 3.4. Annual consumption, peak demand, and cost estimated by the MICRO-DOE 2.1E program and compared to the data from the utility bills

	Normalized value	MICRO-DOE 2.1E	
		Result	Diff. (%)
Consumption (kWh/m²/yr)	245.9	216.2	-12.1
Peak Demand (kW)	645	669	3.7
Cost ($/m²/yr)	15.23	14.58	-4.3

Figures 3.10, 3.11, and 3.12 show the monthly energy consumption, peak demand and energy costs, respectively, obtained from the measured data and the simulation results. The comparisons show some values are out of range for a few months, especially the consumption values for November and February which are underestimated by 19.1 and 21.9% respectively. In addition, the peak demand is underestimated in March by 16.7%; however, it is overestimated in April by 16.8%. The monthly energy costs are relatively well simulated as seen in Figure 3.12, with the largest underestimation occurring in November by 14.6%, and the largest overestimation in April by 12.3%.

3.2.3 Qualitative analysis of simulation results

The monthly variation of the cooling energy consumption required by the space, system, and plant is very similar to the tre ıds seen in the results of the previous version (Figures 3.4, 3.5, and 3.6). Consequently the qualitative analysis leads to the same conclusions as discussed previously. The results from version E are generally slightly lower than those previously seen for version D; however, no significant differences are observed. These differences are presented in further detail in section 3.3.1.

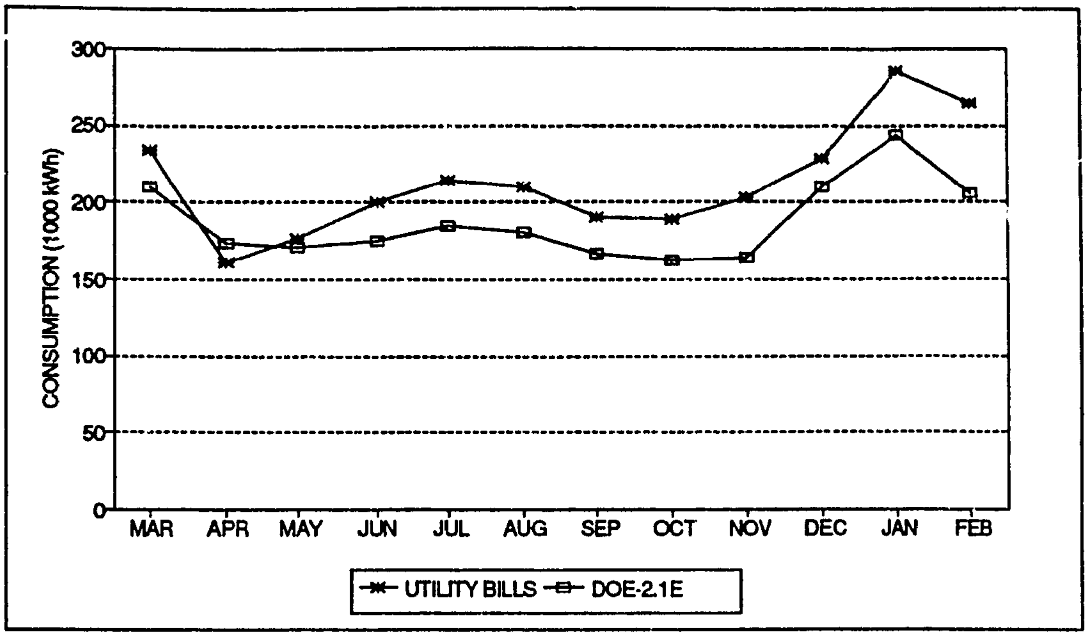

Figure 3.10 Monthly energy consumption predicted by the MICRO-DOE2.1E program compared to the utility bills

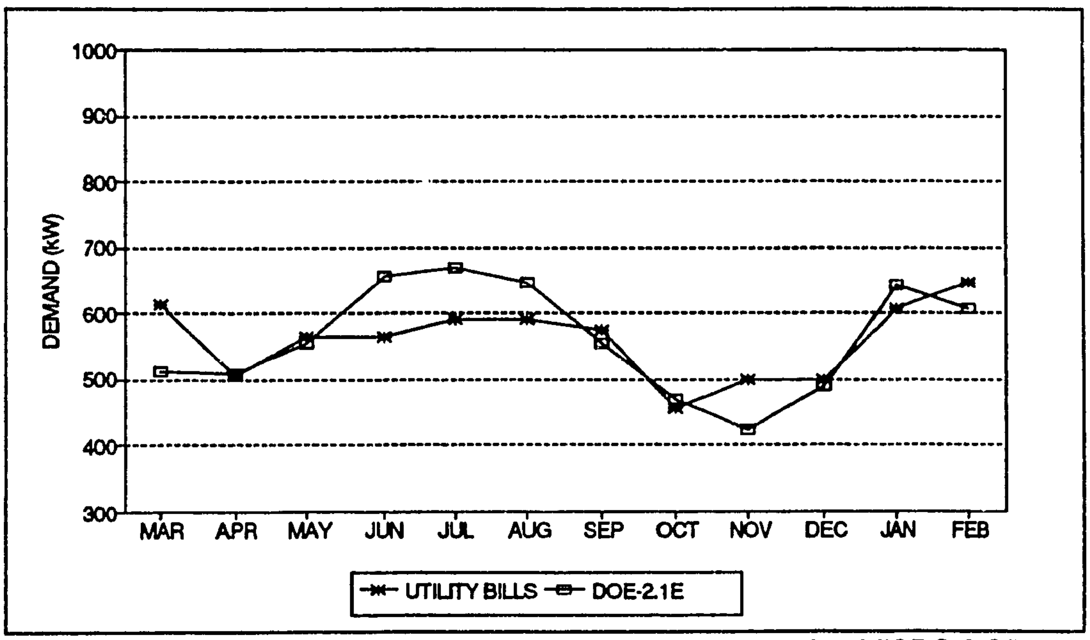

Figure 3.11 Monthly peak electric demand predicted by the MICRO-DOE2.1E program compared to the utility bills

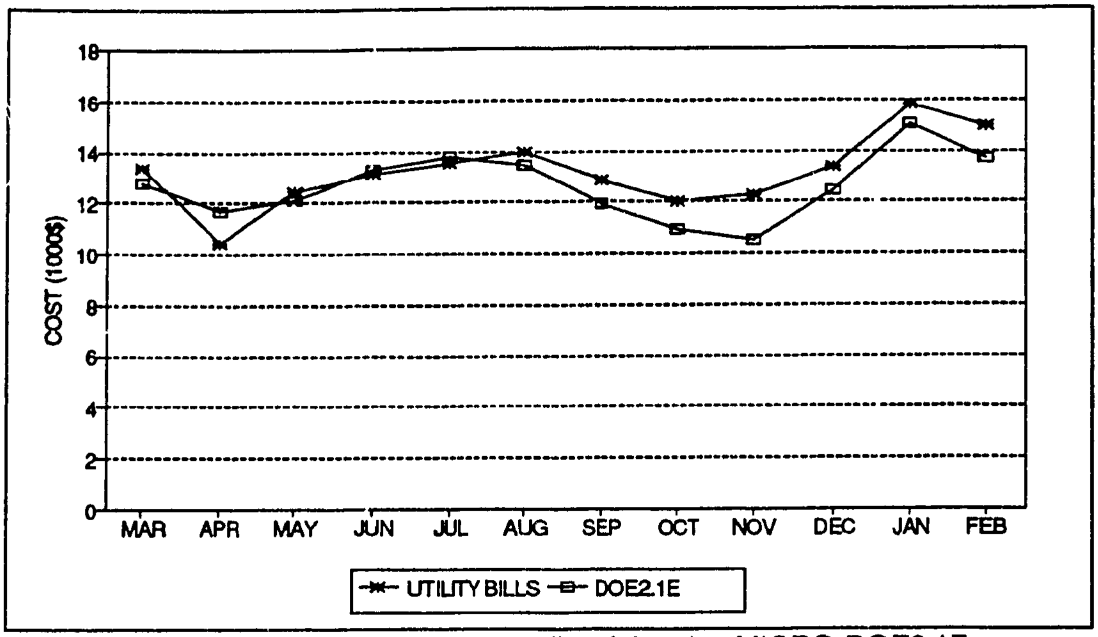

Figure 3.12 Monthly energy costs predicted by the MICRO-DOE2.1E program compared to the utility bills

The monthly variations of the heating energy consumption and peak demand also show very similar trends to those discussed for the results of the simulations using version D (Figures 3.7 and 3.8); however, the results for version E are significantly lower than those for version D. The comparisons of the heating energy consumption and peak demand estimated by the two versions are presented in section 3.3.1.

The total annual energy consumption is divided among its end-uses, as seen in Figure 3.13. The lights and equipment make up 56.9% of the total energy consumption, whereas the heating and cooling account for only 15.3% and 21.0% respectively. Of the cooling consumption, the fan energy is the largest consumer, as expected. The remainder of the annual energy, 6.8%, is accounted for by the domestic hot water system.

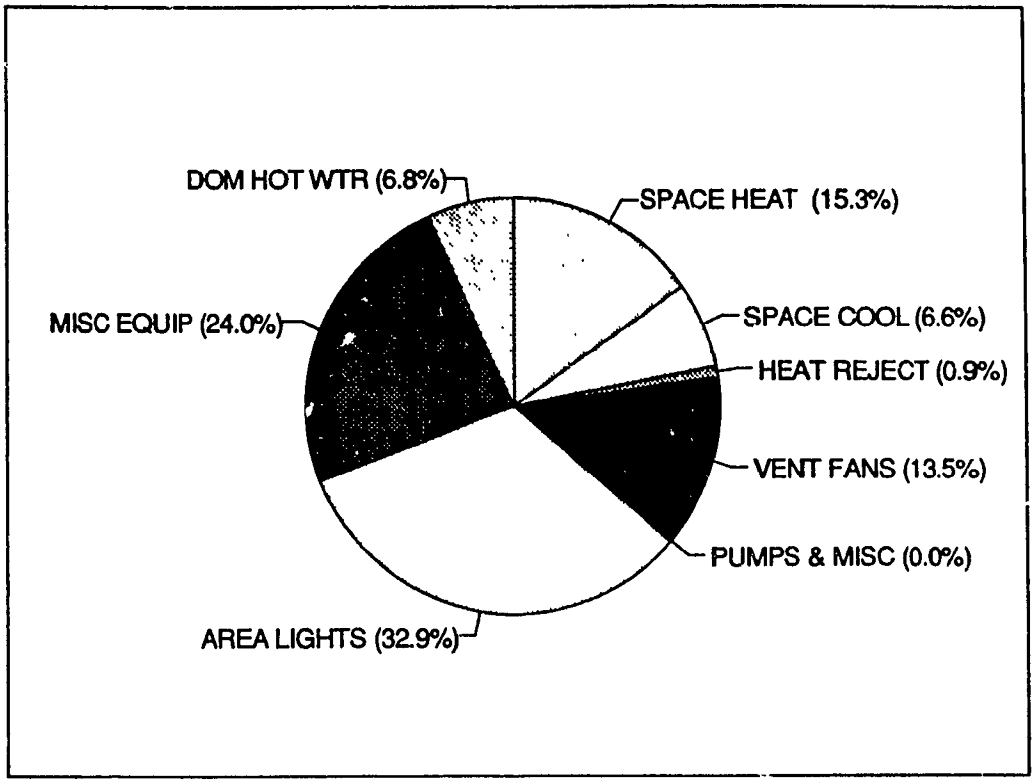

Figure 3.13 Breakdown of annual energy consumption into its end-uses, as simulated by the MICRO-DOE2.1E program

3.2.4 Simulation of energy conservation measures

The energy conservation measures are also simulated using the version 2.1E and the results are shown in Table 3.5 in terms of energy cost savings and consumption savings. The measures resulting in the largest cost savings are ECM IV among the groups of measures and ECM 6 from the individual measures. Similar to the calculations performed previously, the payback period and benefit-cost ratio are calculated for the measures requiring an initial investment and having a positive cost savings. The results (Table 3.6) show that ECM IV is still the best choice, with the lowest payback period and highest benefit-cost ratio.

Table 3.5 The predicted annual cost and consumption savings for each ECM using MICRO-DOE2.1E

Measure	Cost savings		Reduction in energy consumption	
	$	%	kWh	%
ECM 1	-287.00	-0.19	-4 707	-0.21
ECM 2	-109.00	-0.07	-1 879	-0.08
ECM 3	-6 153.00	-4.05	73 276	3.26
ECM 4	4 178.00	2.75	55 818	2.48
ECM 5	2 442.00	1.61	37 545	1.67
ECM 6	5 524.00	3.64	79 383	3.53
ECM 7	256.00	0.17	7 177	0.32
ECM 8	3 164.00	2.08	110 311	4.90
ECM 9	1 406.00	0.93	45 384	2.02
ECM I	6 649.00	4.38	88 929	3.95
ECM II	689.00	0.45	241 310	10.72
ECM III	5 847.00	3.85	303 973	13.51
ECM IV	10 359.00	6.82	209 792	9.32

Table 3.6 The payback period and benefit-cost ratio for some selected energy conservation measures simulated using DOE-2.1E

Measure	Payback period (years)	Benefit-cost ratio
ECM 8	1.7	1.41
ECM 9	3.9	0.60
ECM II	15.6	0.15
ECM III	1.8	1.27
ECM IV	1.0	2.25

3.3 Inter-model comparison of BESA-Design, MICRO-DOE 2.1D and MICRO-DOE 2.1E

One of the validation techniques often used, in addition to the empirical validation, is the inter-model comparison. This type of comparison allows the user to detect any anomalies or large discrepancies between the results of various programs. However, due to differences in mathematical methods and program limitations, differences between program results are expected, and hence, this renders it difficult to diagnose the nature of the discrepancies and impossible to prove the accuracy of any one program. For this reason, this technique must be complemented by other validation techniques.

3.3.1 Comparison of DOE-2.1D and DOE-2.1E

In order to determine the effect of the modifications made to the new version of the MICRO-DOE program, the results from version E are compared to the results from version D and the discrepancies are recorded. These discrepancies are related to: the peak electric demand; the space, system and plant cooling demand; the space, system and plant heating energy consumption; and the distribution of annual energy consumption among its end-uses.

The peak electric demand in summer increases from version D to version E by approximately 55 kW (8.9%) in June. This increase is caused by several factors, such as an increase in fan consumption and demand for SYS-1 in summer only; an increase in condenser demand for the hour of the monthly peak electric demand; and an increase in chiller demand by 35.8 kW (14.9%) for the hour of peak demand in June, although, overall, the monthly peak demand for the chiller increases by only 8.8%. Consequently, the significant increase in peak demand cannot be attributed to one specific phenomenon and it must be assumed that it is the result of some modifications in the program code.

It is expected that the space cooling load predicted by the version E be 10-20% higher due to some modifications in the LOADS part of the program [50]. This can be interpreted as an increase in cooling load calculated for the space or the peak load on the cooling system. In either case, no consistent trend is found to support this estimate. The differences in the space cooling load predicted by versions D and E, show that the cooling load calculated for the space on a yearly basis decreases by 4.1% instead of the expected increase of 10-20%. On a monthly basis, the space cooling load decreases by 2.0 to 5.2% for each month. However, the peak cooling demand for the space, that is the highest cooling load calculated for the space at a given hour, increases slightly, less than 2.0%, for the months of November through March as well as June as seen in Figure 3.14.

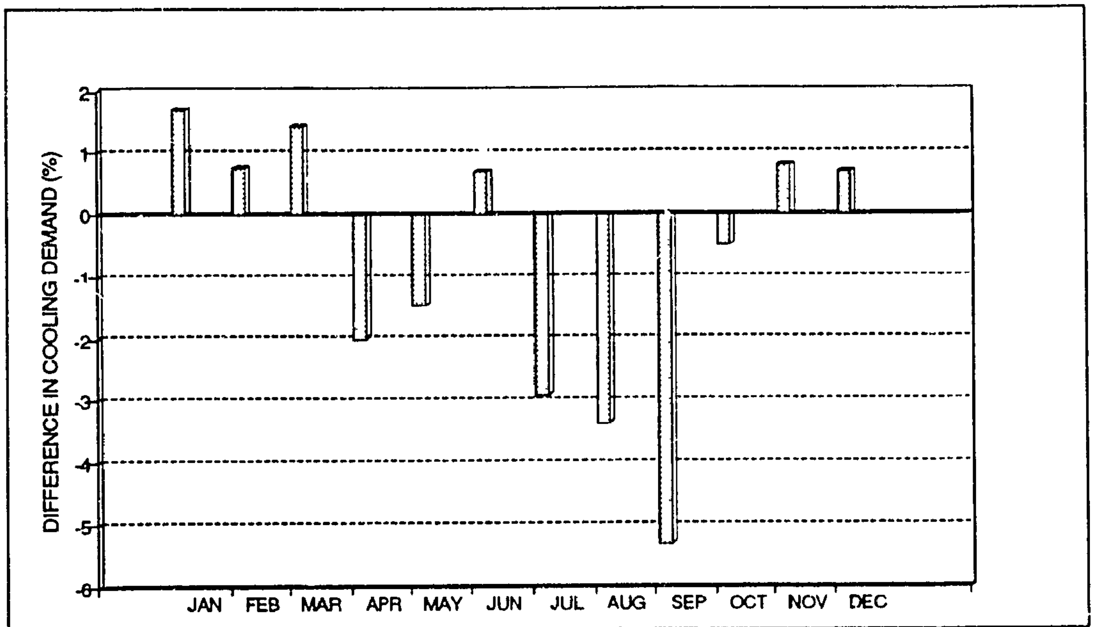

Figure 3.14 Difference in the prediction of the peak cooling demand for space as calculated by MICRO-DOE2.1 versions D and E

The focus now moves to the other interpretation of the expected increase in cooling load, namely an increase in the peak cooling load on the plant equipment. The results show that from version D to version E, the total annual cooling load on the plant decreases by 6.1%. Although there is a general decrease in cooling energy requirements for both the system and the plant, the peak cooling demand of the system and plant show an increase in almost every area for June, July and August as shown in Figures 3.15 and 3.16. For both the system and plant, the FD-SYS coil shows the largest increase in demand. However, overall, the predicted increase in cooling load [50] is not clearly evident.

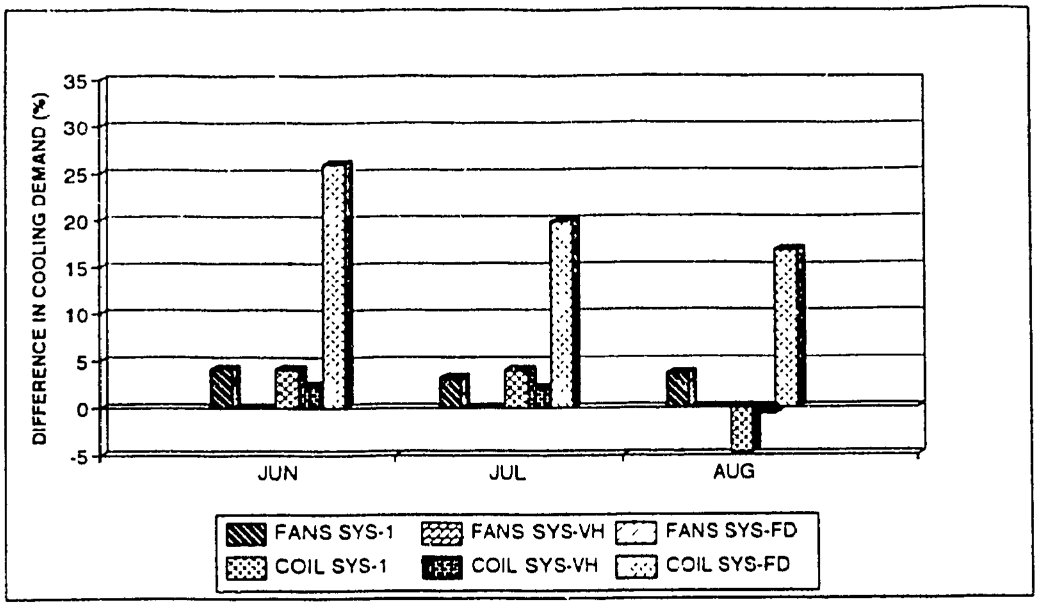

Figure 3.15 Difference in the prediction of the system peak cooling demand components, as calculated by MICRO-DOE2.1 versions D and E

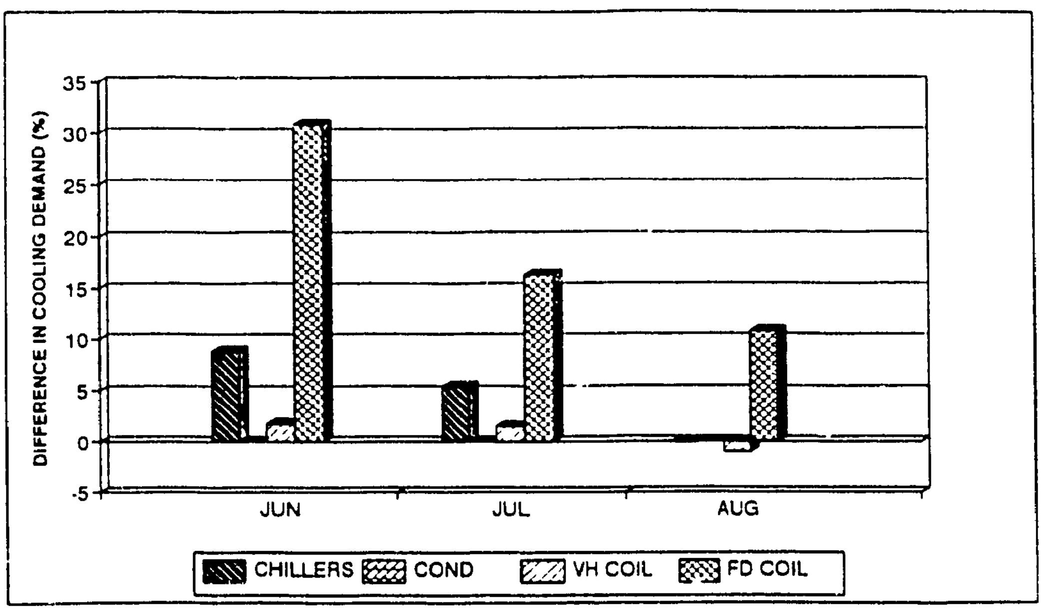

Figure 3.16 Difference in the prediction of the central plant peak cooling demand components, as calculated by MICRO-DOE2.1 versions D and E

Annual heating consumption for space, system and plant all show a decrease of 22-27% from version D to version E. The space heating load decreases 21.7% as compared to the expected 10-20% [50]. Monthly heating consumption and demand show a decrease year-round for space, system and plant which correspond to the predictions (Figures 3.17 and 3.18).

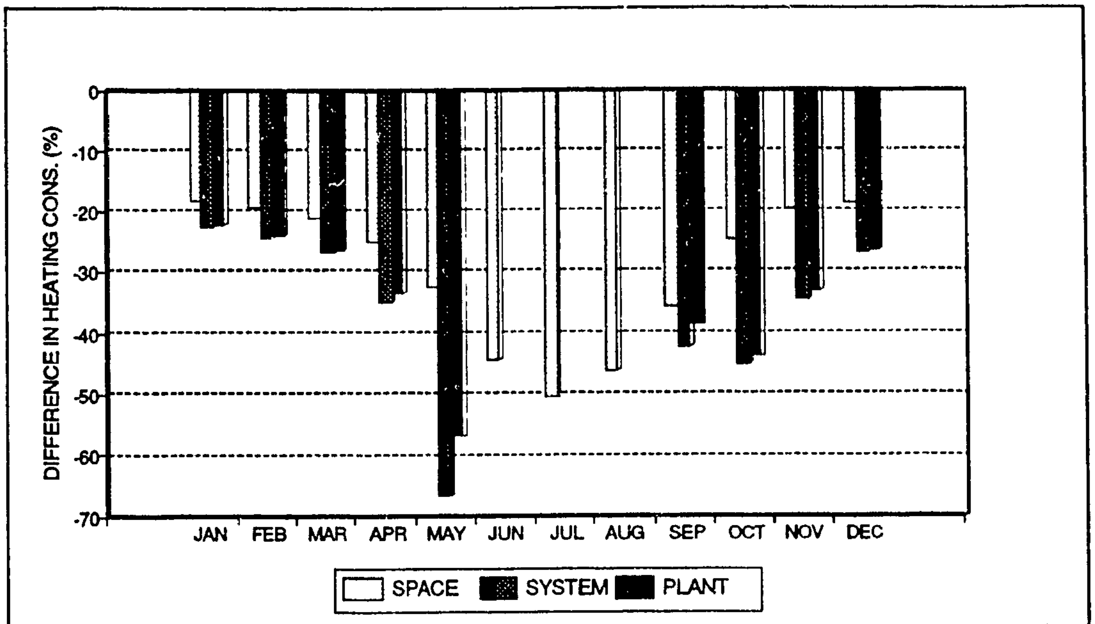

Figure 3.17 Difference in monthly heating consumption as simulated by MICRO-DOE2.1 versions D and E

The breakdown of the annual energy consumption, presented in Table 3.7, shows a decrease in consumption for lighting by 25.6% and an increase in equipment consumption by 89.4%. However, the sum of these categories remains constant. Further investigation shows that in version D, the electrical consumption from the miscellaneous equipment in BUILDING-RESOURCES is lumped in the lighting category, while the consumption for the elevators from BUILDING-RESOURCES is added to the equipment category. In version E, the lighting category only includes energy consumption for lights, while the consumption for office equipment and miscellaneous equipment (including elevators) is included in the equipment category.

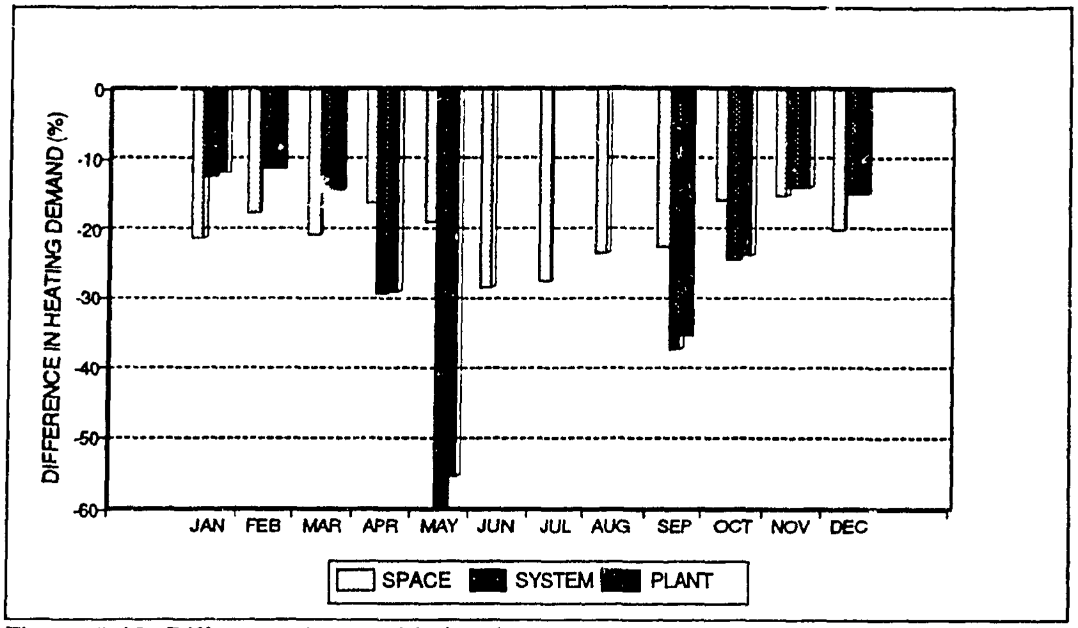

Figure 3.18 Difference in monthly heating demand as simulated by MICRO-DOE2.1 versions D and E

Table 3.7 The breakdown of annual energy consumption as reported in DOE 2.1 versions D and E

	DOE 2.1D (kWh)	DOE 2.1E (kWh)	% Diff.
SPACE HEAT	471.0	344.4	-26.9
SPACE COOL	171.9	148.8	-13.4
HVAC AUX.	325.1	324.0	-0.3
LIGHTS	994.8	740.4	-25.6
EQUIP.	284.9	539.6	89.4
DOM. HOT WATER	132.1	153.9	16.5
TOTAL	2379.8	2251.1	-5.4

The domestic hot water is defined differently in version E, and although the characteristics of the system defined in the two versions remain constant, the consumption increases by 16.5%.

Some discrepancies are discovered in the space cooling defined in this output report (Table 3.8) in comparison to the values listed in the hourly output reports. In version D, energy consumption used by HVAC equipment is categorized into SPACE COOL and HVAC AUX in the output report. The SPACE COOL includes energy consumed by chillers as well as by the coils of the two unitary systems. Upon comparison of the consumptions for the chillers and coils reported in the hourly data with the values listed in the output report for version D, no discrepancies are found. In addition to this consumption, other energy consumers listed in the output report include the condensers and fans. In version D, the hourly data calculates the consumption for condensers and fans as 346.3 kWh while the report indicates 325.1 kWh, a difference of 21.2 kWh.

In version E, the consumption for HVAC listed in the output report is divided into more categories: SPACE COOL, HEAT REJECT, PUMPS & MISC, VENT FANS. The consumption defined in the category VENT FANS corresponds to the consumption listed in the hourly results for the central fans plus the two unitary system fans, but excluding the garage fans. The category HEAT REJECT in the output report corresponds to the energy consumption for the condensers as calculated from the hourly reports. The category PUMPS & MISC, shows an energy consumption of 0.5 kWh which is unaccounted for in the hourly data. The category SPACE COOL of the output report should include the energy consumption for the chillers and the unitary system coils; however, the consumption reported is 148.8 kWh instead of the 169.5 kWh calculated from the hourly reports, a difference of 20.7 kWh.

Aside from this discrepancy, the annual energy consumption for space cooling defined in the hourly report shows a 13% decrease from version D to version E, while the energy consumption for the HVAC auxiliary equipment remains almost constant.

Table 3.8 Comparison of output report results for HVAC equipment consumption with hourly values for versions D and E of the MICRO-DOE2.1 program

Version D		Version E	
Section of the output report	Comparison with hourly data	Section of the output report	Comparison with hourly data
SPACE COOL: chillers and coils of unitary systems	hourly data same as report	SPACE COOL: chillers and coils of unitary systems	hourly = 169.5 kWh report = 148.8 kWh (20.7 kWh missing)
HVAC AUX: condensers and fans	hourly data = 346.3 kWh report = 325.1 kWh (21.2 kWh missing)	HEAT REJECT: condensers	hourly data same as report
--	--	PUMPS & MISC	report includes 0.5 kWh unaccounted for
--	--	VENT FANS: all fans	report does not include garage fans

3.3.2 Comparison of the BESA, MICRO-DOE-2.1D and MICRO-DOE-2.1E programs

The results from the three programs are compared in terms of monthly energy consumption and peak electric demand, as well as annual energy consumption, peak demand, and cost predictions. The comparison of the simulations of energy conservation measures in terms of cost savings is also presented. In the case of the BESA-Design program, the results from the hourly simulation of the final calibrated model are used.

Table 3.9 presents the annual energy consumption, peak electric demand, and cost as predicted by the three programs and compared to the data from the utility bills. Of the three programs, the BESA program predictions are in closest agreement with the measured data, the differences being less than 8%.

Table 3.9. Annual consumption, peak demand, and cost estimated by the BESA-Design, MICRO-DOE 2.1D and 2.1E programs and compared to the data from the utility bills.

	Normalized value	BESA-Design		MICRO-DOE 2.1D		MICRO-DOE 2.1E	
		Result	Diff. (%)	Result	Diff. (%)	Result	Diff. (%)
Consumption (kWh/m²/yr)	245.9	234.7	-4.5	228.5	-7.1	216.2	-12.1
Peak Demand (kW)	645	692	7.3	749	16.1	669	3.7
Cost ($/m²/yr)	15.23	15.62	2.6	15.16	-0.5	14.58	-4.3

Figure 3.19 presents the monthly variation of energy consumption simulated by the three programs as compared to the measured energy consumption. The consumption is underestimated from June through November by each program. In addition, all three programs show a large underestimate in February (13.69% to 21.89%) as well as overestimates in April (7.45% to 12.24%). However, the general shapes of the curves follow that of the utility bills relatively well.

The monthly variation of peak demand predicted by the three programs is compared to the utility data, and the shape of the curves is similar to the curve from the utility data (Figure 3.20). On average, the peak demand is overestimated by the programs; however, there is not much consistency between results, as is seen in the monthly consumption variation (Figure 3.19). For instance, the peak demand in March shows differences of +1.96%, -5.72% and -16.67% for BESA, DOE-2.1D, and DOE-2.1E, respectively. In December, the errors in estimating the peak demand are +25.50%, +11.24% and -1.61% for BESA, DOE-2.1D and DOE-2.1E. The only common trend in the simulation of the monthly peak demand by the three programs, is that none of the programs can predict the monthly peak demand within the acceptable range of 15% error for every month. This could be due to the method of normalization used to estimate the monthly peak electric demand from the recorded utility data (Chapter 2). However, in general, the peak demand is overestimated by the programs, which shows some deficiencies either in the input file or in the calculation procedures.

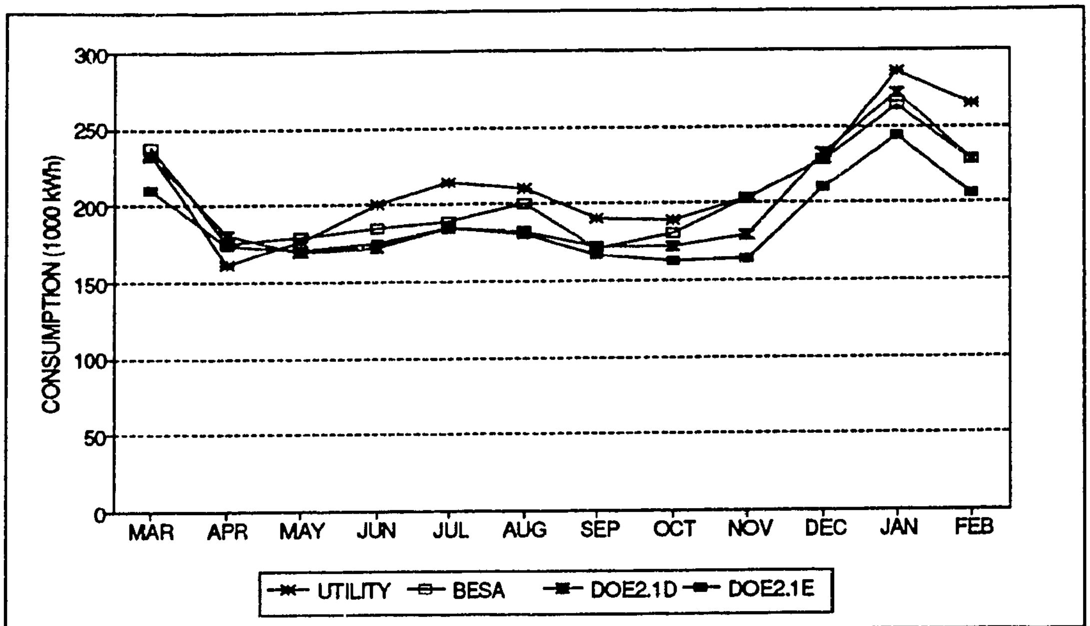

Figure 3.19 Monthly variation of energy consumption as simulated by the three programs and compared to the utility bills

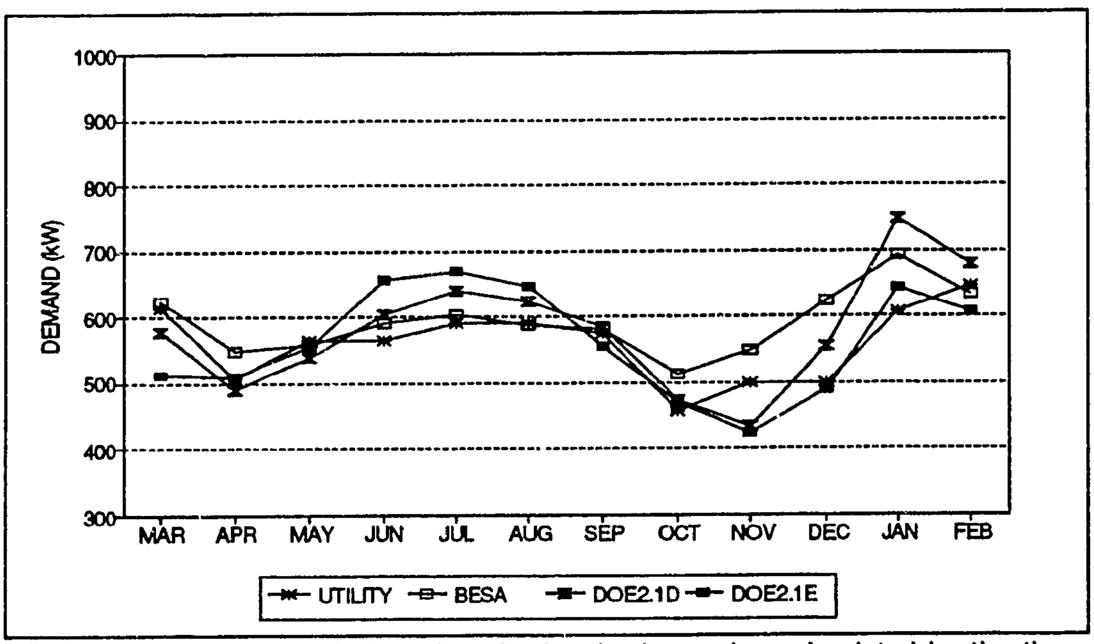

Figure 3.20 Monthly variation of peak electric demand as simulated by the three programs and compared to the utility bills

Figure 3.21 shows the percent cost savings as predicted for each energy conservation measure by the three programs. The agreement between programs is relatively good in most cases, and they all estimate ECM IV as resulting in the highest cost savings. However, for ECM 1, 2, and II, the savings are estimated as positive hy one program and negative by another. This type of discrepancy could be very important in the decision of recommending an energy conservation measure, and emphasizes the significance of the inaccuracies which exist in the programs or input files.

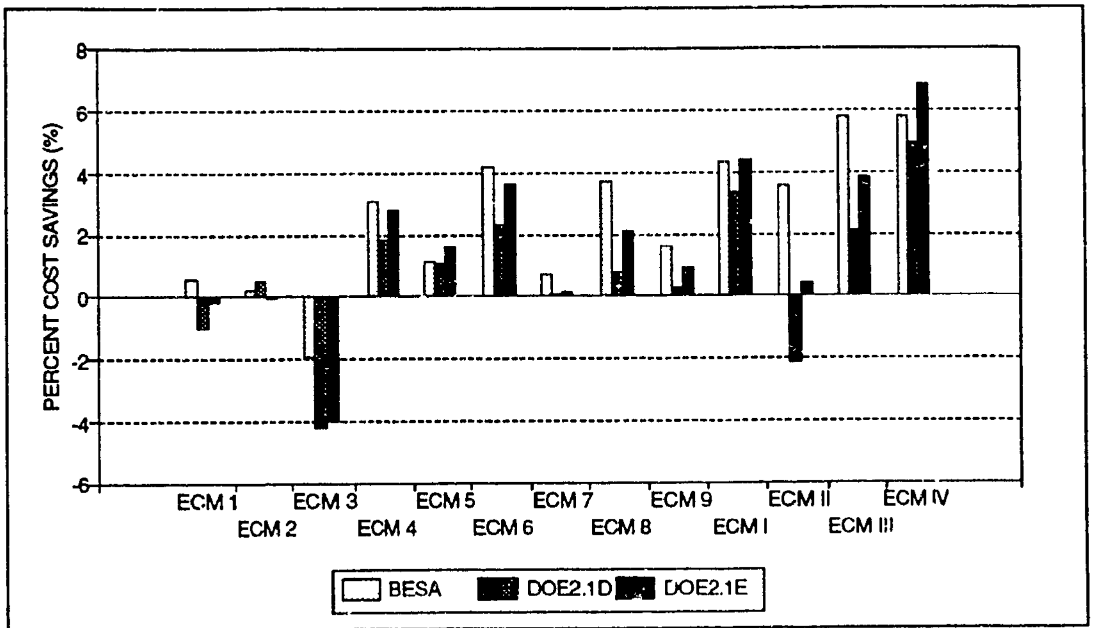

Figure 3.21 The energy cost savings predicted by the three programs for each of the energy conservation measures

In a comparison of the BESA-Design, MICRO-DOE2.1D and PC-BLAST simulation programs, the same energy conservation measures presented previously were simulated by three users [51]. User A simulated the measures using all three programs, user B (the author) used BESA-Design and DOE 2.1D, and user C performed simulations using BLAST. The results for various simulations, presented in Table 3.10, show large discrepancies between the programs, with closer agreement between BLAST and DOE2.1D then between BLAST and BESA, in most cases. However, ECM 8 resulted in significant cost increases (between $793 and $1840) as simulated by BLAST while showing cost savings for the two other programs (between $5213 and $6104 for BESA and between $1280 and $3592 for the DOE program). Discrepancies such as these can have serious repercussions if recommendations are made which lead to significant increases in energy cost. Furthermore, these types of anomalies lead to the lack of confidence which many consultants display for energy simulation software.

Table 3.10 Comparison of annual cost savings ($) estimated by three users with BESA-Design, MICRO-DOE 2.1D and PC-BLAST

Measure	USER	BESA-Design	MICRO-DOE 2.1D	PC-BLAST
ECM 1	A B/C	964 1 025	-283 to 319 -1 668	20 -16 to 0
ECM 2	A B/C	704 363	848 to 912 807	101 to 142 475
ECM 3	A B/C	-10 838 -3 171	3 090 to 4 353 -6 866	10 391 to 10 411 3 170 to 3 803
ECM 4	A B/C	7 884 5 175	1 193 to 3 594 2 973	4 932 to 5 075 -317 to 3 486
ECM 5	A B/C	624 1 852	2 411 to 2 823 1 747	3 255 to 3 275 1 109 to 1 585
ECM 6	A B/C	5 611 6 898	5 127 to 5 689 3 688	6 894 to 6 914 4 120 to 5 705
ECM 7	A B/C	6 043 1 127	260 to 280 106	61 to 101 159 to 317
ECM 8	A B/C	5 213 6 104	2 745 to 3 592 1 280	-1 780 to -1 840 -1 110 to -793
ECM 9	A B/C	4 619 2 628	2 400 to 3 279 525	566 to 1011 -475 to 0
ECM I	A B/C	7 871 7 064	3 532 to 5 821 5 385	7 823 to 7 965 793 to 4 754
ECM II	A B/C	9 795 5 924	839 to 1 754 -3 504	18 640 to 19 550 5 547 to 7 448
ECM III	A B/C	16 135 9 450	4 345 to 6 273 3 421	21 268 to 26 161 5 071 to 10 143
ECM IV	A B/C	16 699 9 498	8 703 to 11 062 8 030	9 400 to 9 725 -

3.4 Conclusions

The empirical and inter-model validation techniques were presented for the MICRO-DOE energy simulation software as the first part of a global validation procedure. It was found that, although these techniques have several advantages, they are not sufficient to detect or diagnose errors in the programs.

The empirical validation of the MICRO-DOE program tested the program's ability to simulate the energy consumption of an existing commercial building. The program limitations made it difficult to simulate certain aspects of the building, such as the carbon dioxide sensors for the control of outdoor air brought into the system and the carbon monoxide sensors for the control of the garage exhaust fans. However, acceptable calibration with the measured utility data was established for version D of the program after several modifications to the input file. The same input file was used for version E with the necessary modifications required for the new version, such as more detailed data for the domestic hot water system and modifications in the definition of the energy costs. The qualitative evaluations showed reasonable results for both versions of the program, in terms of heating and cooling energy consumption and peak demand. The breakdown of the annual energy consumption into its end-uses, as predicted by both versions, also presented reasonable results; however, some discrepancies were observed between the hourly data calculated by the programs and the programs' output reports.

During the inter-model comparison of the BESA, MICRO-DOE 2.1D and 2.1E programs, some discrepancies were detected, particularly in the evaluation of the energy conservation measures; however, the source of the error could not be identified. In order to accurately identify the source of the discrepancies in program results, a systematic approach is required for the analysis and evaluation of the results. The importance of accurate simulation results was established particularly during the comparison of the energy conservation measures simulations when one program showed a positive cost savings while the other predicted a negative savings. This type of discrepancy can result in the recommendation of a particular measure which after implementation, may not show any cost savings.

The second part of the procedure consists of various validation techniques, which are described in the following chapter. The techniques are used to complement the results obtained with the empirical validation and inter-model comparison and ensure that the results are carefully analyzed and that program errors are clearly identified. Once the errors, or lack thereof, have been detected and the limits of the program have been identified, the software can be used with confidence and in a knowledgeable manner.

CHAPTER 4
VALIDATION OF THE MICRO-DOE 2.1E PROGRAM. PART 2 - OTHER VALIDATION TECHNIQUES

In the empirical validation and inter-model comparison techniques a large emphasis was placed on the simulated annual and monthly consumption as well as peak demand. However, the accuracy of the program must be tested in various sections of the software to ensure that the complete model is well simulated, even though the consumption and peak demand results might be within acceptable limits.

The discrepancies discovered during the empirical validation and inter-model comparison described in the previous chapter, as well as the problems encountered during their implementation, have demonstrated that these techniques are not sufficient to determine the accuracy of an energy simulation program. Although many researchers have attempted to develop a validation procedure for building energy simulation software, most validation studies have been performed on test rooms and residential buildings which do not have the complexity of large commercial buildings. Furthermore, the validation techniques have been developed by researchers for researchers, without consideration to the limited facilities available to the consultants themselves, such as time, money, measurement devices and testing facilities.

Consultants faced with the great advantages of using energy simulation software to perform detailed energy analyses of buildings, are hesitant due to their lack of confidence in the simulation results. There is a need for a validation procedure which can be easily used by consultants to increase their understanding of the limitations of the program as well as determine possible program errors.

As a second part of the validation procedure, several techniques have been developed and applied to further verify the simulation results of the MICRO-DOE2.1E program. The proposed techniques are: (1) response of the model to a given perturbation in the outdoor environment, (2) comparison with another modelling tool, (3) sensitivity analysis, and (4) simulations using simple models. These four techniques and their application to the simulations performed using the MICRO-DOE2.1E program are described in the following sections.

4.1 Response to a given perturbation in the outdoor environment

To test the mathematical models used by the DOE-2.1E program to estimate the indoor air temperature and the heating or cooling energy consumption, a given perturbation in the outdoor temperature is generated. The results from the computer program are first evaluated in a qualitative way, and then they are compared with analytical solutions for simple configurations. In addition, the time constant of the building, that is the time for the indoor temperature to increase or decrease by approximately 63% of the change in outdoor temperature, is calculated using the results of the simulation, as well as using two mathematical techniques.

The weather file is modified to create a large instantaneous change in outdoor temperature (Appendix A), using the capabilities offered by the DOE-2.1E program. All solar radiation is omitted from the weather file in order to isolate the effect of outdoor temperature on the building. The various perturbations used in this verification technique are listed in Table 4.1. For example, a decrease in temperature is simulated with no solar radiation but including wind effects in order to observe the effect of infiltration (perturbation A). The outdoor dry-bulb temperature is maintained at 22.2°C for 36 hours and then suddenly decreased to -20.0°C and maintained at this value for the next 12.5 days, due to the limitation of the maximum number of hours the weather file can be altered (ie. 14 days).

Table 4.1 Perturbations in the outdoor weather conditions

Perturbation	Outdoor air temperature for first 1.5 days (°C)	Outdoor air temperature after sudden change (°C)	Diffuse and direct solar radiation	Wind effects
A	22.2	-20.0	no	yes
B	22.2	-20.0	no	no
C	22.2	48.9	no	no
D	-20.0	22.2	no	no

4.1.1 Response of indoor temperature to perturbation A

To evaluate the response of a sudden decrease in outdoor temperature, a base case is modelled starting with the existing building and assuming that there are no windows or doors, lighting or equipment, occupancy, infiltration, or HVAC system (model BASE). The actual wall construction is maintained; however, to avoid any heat losses through the garage, the ground floor is thoroughly insulated. In addition, five other models are simulated: (1) base case with lighting (model LIGHTING), (2) base case with infiltration (model INFILTRATION), (3) base case with windows (model WINDOWS), (4) base case with occupancy (model OCCUPANCY), and (5) base case with an increase of FLOOR-WEIGHT from 73.2 kg/m² to 146.5 kg/m² (model FLOOR-WEIGHT). The six models are subjected to perturbation A.

Figure 4.1 shows the predicted variation of the indoor air temperature over the 48 hours following the decrease in outdoor temperature. The response is shown as the change in indoor temperature from time t_0 to time t divided by the maximum change in indoor temperature from time t_0 to time t_∞ (DT_0). As shown in the figure, the response is very slow. In four of the six simulations, the reduction of indoor air temperature is less than 10% of the final value (ie. the air temperature at time t_∞) after 48 hours. Due to the low thermal resistance of the windows and the high window area, the simulation with the windows shows the fastest response, with a temperature decrease of approximately 50% after 48 hours. The simulations LIGHTING, FW, and OCCUP indicate a slower response than the base case, which is expected since the lighting and occupancy add to the internal heat gains, thereby increasing the room temperature; the increase in floor weight adds to the thermal storage effects which results in a longer reaction time.

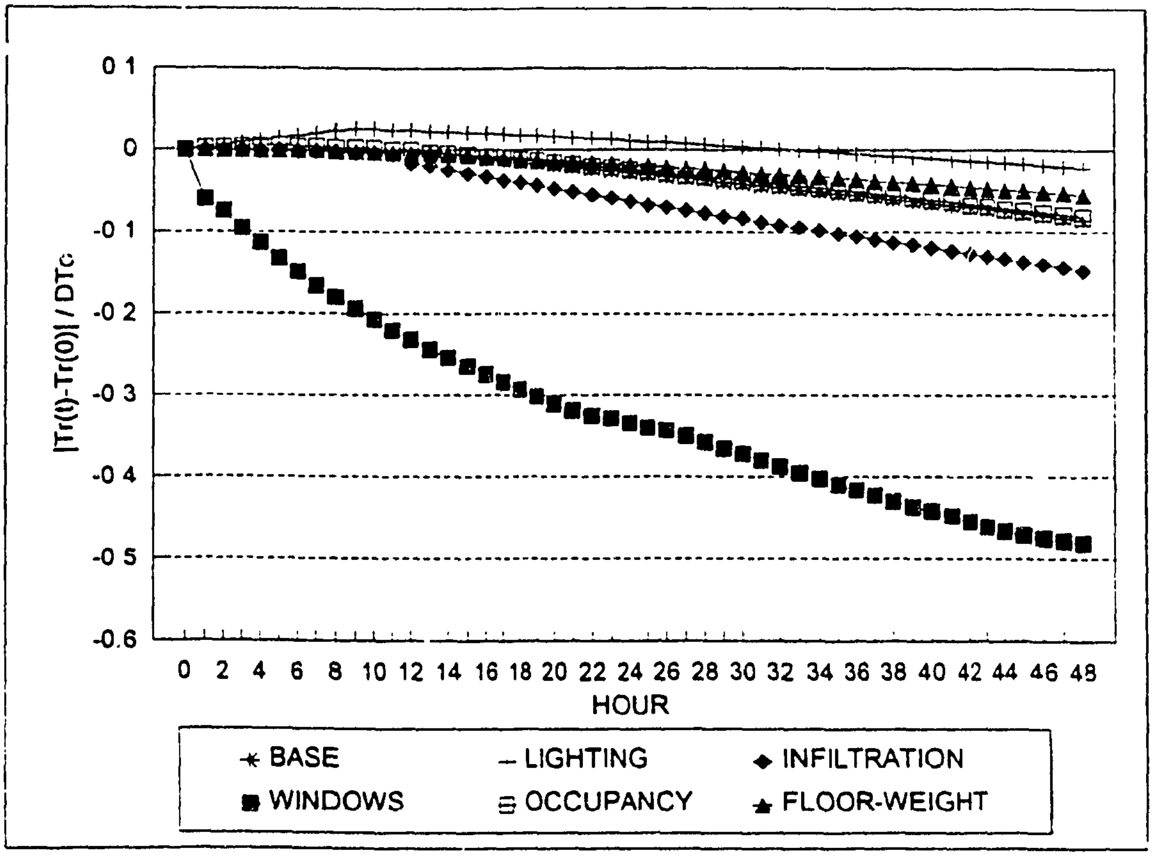

Figure 4.1 Room air temperature response to a sudden decrease in outdoor air temperature

In addition, the results for simulations LIGHTING and OCCUPANCY show a slight increase in room temperature just after the change in outdoor temperature. Since there is no HVAC system available during this simulation, the indoor air temperature is not constant before the sudden decrease in outdoor air temperature, but rather, it rises continuously due to the internal gains. Therefore, even after the decrease in temperature, the internal gains are sufficient to maintain a slight increase in indoor temperature for a few hours.

4.1.2 Comparison of the response of indoor temperature to perturbations B and C

The same base model is simulated for both a decrease in outdoor temperature from 22.2°C to -20.0°C (perturbation B) and an increase in outdoor temperature from 22.2°C to 48.9°C (perturbation C) with no solar or wind effects. Figure 4.2 presents the results of these two simulations for the first 48 hours after the sudden change in outdoor temperature as the ratio of the change in room temperature from time t_0 to time t and the maximum change in room temperature. Regardless that after 48 hours, the change in indoor air temperature is less than 10% of its final value, the responses (in absolute value) of the two simulations are almost identical, with differences within 0.002% of the final value. Since the solar radiation is eliminated, this result is expected. In other words, the model responds in the same manner whether the outdoor temperature is increased or decreased.

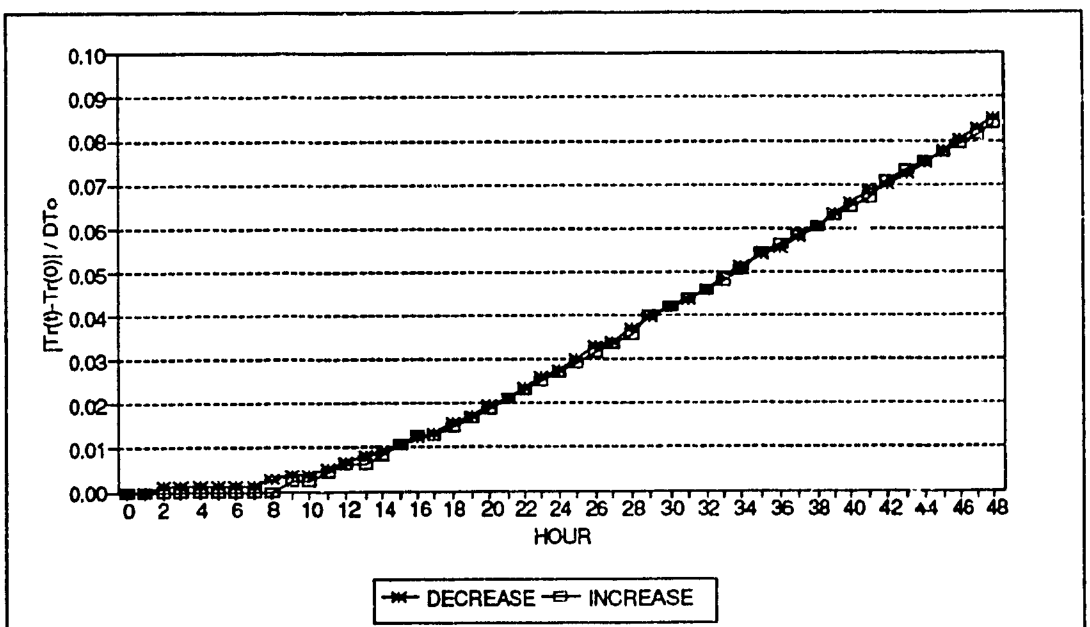

Figure 4.2 Room air temperature response to a sudden increase or decrease in outdoor air temperature

4.1.3 Effect of a change in outdoor temperature on the required heating demand

The variation of the energy consumption for heating is evaluated for two perturbations: (1) a decrease in outdoor temperature from 22.2°C to -20.0°C (perturbation B), and (2) an increase in outdoor temperature from -20.0°C to 22.2°C (perturbation D). For these simulations, the base model is modified so that the room temperature is maintained at 22.2°C ± 0.003°C, and the HVAC system and baseboard heaters are activated. This throttling range was not required in the previous sections since the HVAC system was not used to maintain a constant space air temperature. All other characteristics of the model remain unchanged.

The baseboard peak electric demand estimated by the program, after an increase or a decrease in outdoor temperature is presented in Figure 4.3 as a ratio of the change in demand at time t (DE_t) to the maximum change in demand (DE_{max}) from time t_0 to time t_∞. The figure shows a slower response during the first 11 hours when the outdoor temperature is decreased than when it is increased. It is assumed that the heat stored in the building mass is released to the space even though the outdoor temperature has fallen. In the case of the increase in temperature from -20.0°C to 22.2°C, there is no heat stored initially, and therefore there is a faster response of the heating system.

The heat loss through the exterior walls long after the sudden decrease in outdoor temperature is calculated and compared to the maximum required heating energy from the simulation results. The following equation is used assuming a steady-state condition [48]:

$$q = U * A * (T_i - T_o) \tag{4.1}$$

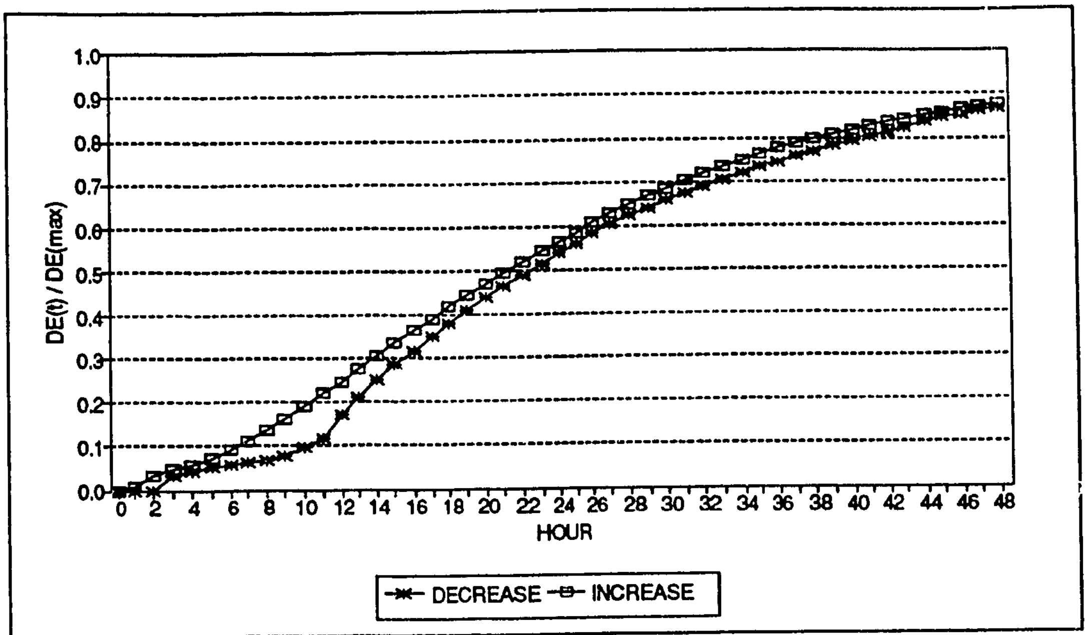

Figure 4.3 Response of the peak electric heating demand to an increase or a decrease in outdoor air temperature

where: q = heat loss due to conduction, W

U = overall U-value of the exterior wall, W/m²·°C

A = exterior wall area, m²

U * A = 1025.7 W/°C (from DOE program)

T_i = 22.2 °C

T_o = outdoor temperature after the sudden decrease, °C

T_o = -20.0°C

$$q = 1025.7\ (22.2 - (-20.0))$$
$$q = 43\ 283\ W = 43.28\ kW$$

The result from the equation shows a heat loss of 43.28 kW whereas the peak electrical demand for heating predicted by the model is 43.84 kW, a difference of +1.3% over the equation result.

4.1.4 Effect of an increase in outdoor temperature on the cooling demand

The outdoor temperature is increased suddenly from 22.2°C to 48.9°C (perturbation C) in order to evaluate the response of the cooling system. The previously described model is maintained with the same room temperature setpoint, 22.2°C ± 0.003. The system's response is evaluated in terms of the demand of the cooling coils, the chiller demand and the supply air flow rate. Figure 4.4 presents these values for the 48 hours following the increase in outdoor temperature as a ratio of the change in the corresponding value at time t (DE_t) to the maximum change in value (DE_{max}). The curves corresponding to the demand of the cooling coils and supply air flow rate are almost identical, whereas the curve for the chiller demand shows a faster response after approximately 12 hours.

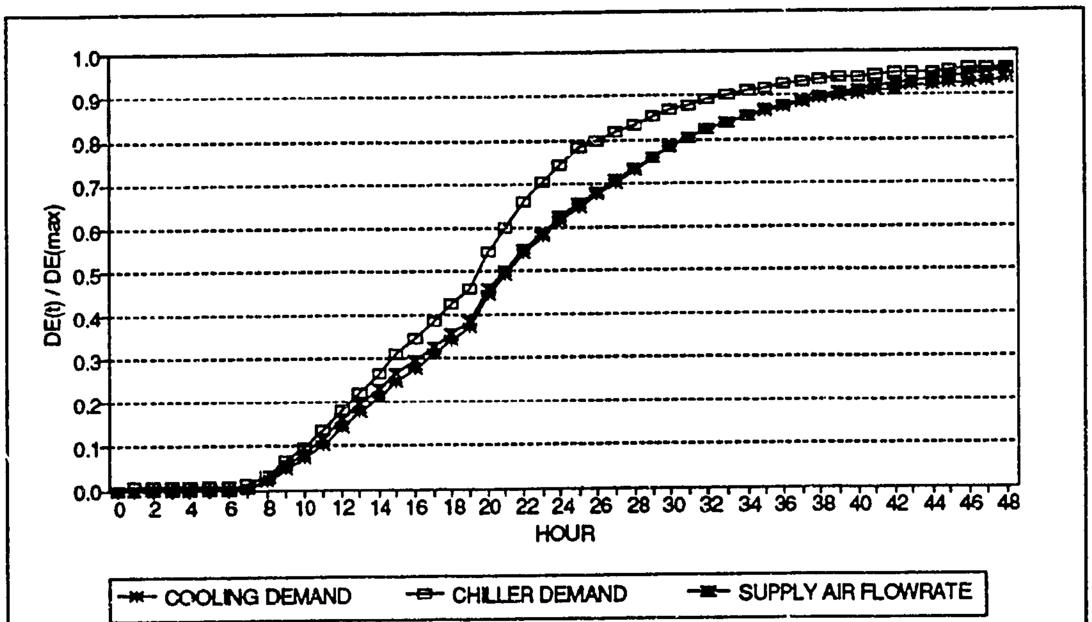

Figure 4.4 Response of the central cooling system to an increase in outdoor air temperature

In Figure 4.5, the response of the heating system to a decrease in outdoor temperature (perturbation B) is compared with the response of the chillers when the outdoor temperature is increased (perturbation C). For the first 20 hours after the sudden change, the response of the heating demand surpasses that of the cooling demand by approximately 12%. However, later the cooling demand response is faster: after 35 hours, the response of the cooling demand surpasses that of the heating demand by over 18%, and after 48 hours the cooling demand surpasses 93% of its maximum value while the heating demand reaches 87%. The heat stored in the thermal mass before the sudden decrease in temperature tends to slow the response time of the heating demand while increasing the response of the cooling demand.

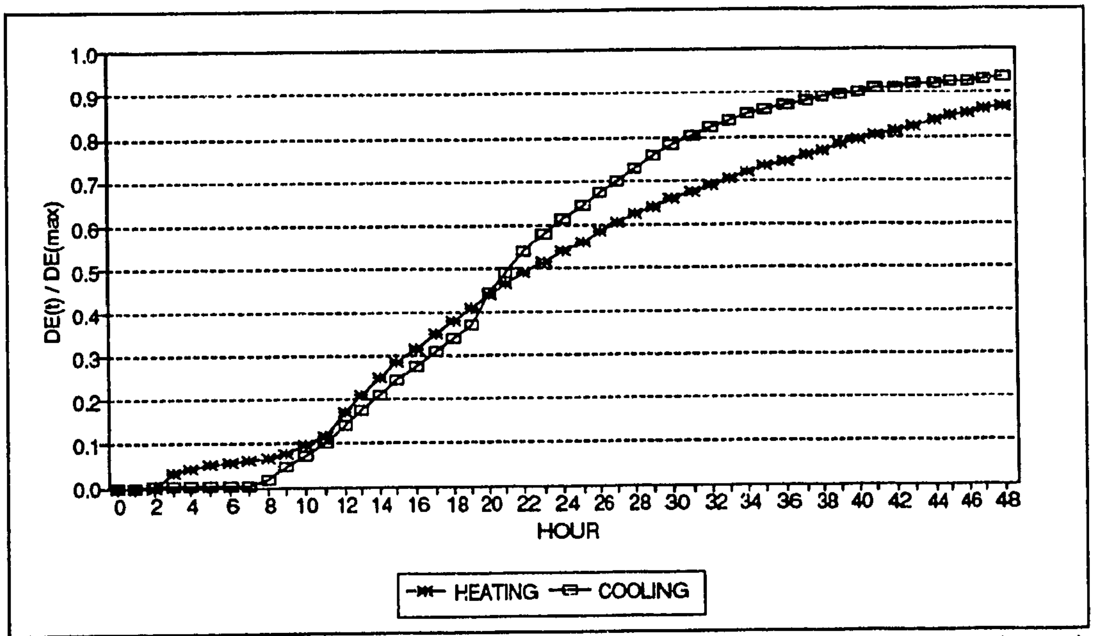

Figure 4.5 Response of the heating and cooling demand to a change in outdoor air temperature

The cooling demand is also calculated using equation 4.1 and the result shows a demand of 27.1 kW compared to 27.3 kW from the simulation results, a difference of +0.7%:

$$q = U * A * (T_i - T_o)$$
$$q = 1025.7\ (48.6 - 22.2)$$
$$q = 27\ 078\ W = 27.1\ kW$$

The load on the cooling coil is calculated for the supply air conditions on January 15 at 1:00 am, using fundamental equations [36]:

$$_1q_2 = \dot{m}_a[(h_1 - h_2) - (W_1 - W_2) * h_{w2}] \qquad (4.2)$$

where: $_1q_2$ = heat loss from initial state 1 to final state 2, kW

m_a = mass air flow rate, kg/s

h_1, h_2 = enthalpy of the air at state 1 and state 2, kJ/kg, and calculated using the following equation:

$$h = 1.006T + W(2501 + 1.805T) \qquad (4.3)$$

W_1, W_2 = humidity ratio of the air at state 1 and state 2, kg water/kg dry air

h_{w2} = enthalpy of water vapour, kJ/kg

T = dry-bulb temperature, °C

Calculations are performed using the corresponding values, calculated by the DOE 2.1E program, for January 15, at 1:00 am:

T_1 = 22.67°C

T_2 = 20.11°C

W_1 = 0.0149 kg/kg

W_2 = 0.0149 kg/kg

h_{w2} = 84.46 kJ/kg [36]

m_v (volumetric flow rate) = 9.067 m^3/s

v (specific volume) = 0.8378 m^3/kg (from psychrometric chart)

$$h_1 = 1.006T_1 + W_1(2501 + 1.805T_1) = 60.68\ kJ/kg$$

$$h_2 = 1.006T_2 + W_2(2501 + 1.805T_2) = 58.04\ kJ/kg$$

$$\dot{m}_a = \frac{\dot{m}_v}{v} = \frac{9.067}{0.8378} = 10.823\ kg/s$$

$${}_1q_2 = 10.823\ [(60.68-58.04) - (0.0149 - 0.0149)\ 84.46]$$

$${}_1q_2 = 28.57\ kW$$

The calculation results in a cooling coil load of 28.57 kW whereas the load calculated by the DOE simulation is 27.49 kW; hence, there is good agreement between the program results and the calculation, with the program predictions being 3.8% lower than the calculated value.

4.1.5 Comparison of simulated indoor temperature variation with estimates using a mathematical model

The predictions of the DOE program are compared with results from mathematical models of transient heat transfer problems. A mathematical model developed by Pratt [52] is used to calculate the response of indoor air temperature to a sudden decrease in outdoor temperature from 22.2°C to -20.0°C (perturbation B). Several assumptions are made in the mathematical model: (1) the exterior wall consists of a homogeneous material, (2) the outdoor and indoor air temperatures are assumed to be uniform over the respective surfaces, (3) the thermal capacity of the indoor air is assumed to be negligible, (4) the temperature of the internal mass is uniform throughout and is initially equal to the temperature of the indoor air, and (5) heat conduction through the exterior wall is one-dimensional. The variation of indoor temperature from time t_0 to time t with respect to the variation of outdoor temperature $[(T(0) - T(t)) / DT_0]$, is given by [52]:

$$\frac{TR(0) - TR(t)}{DT_o} = 1 - \frac{(B_s - C\alpha_1^2)\alpha_2^2}{B_s(1 + VA)(\alpha_2^2 - \alpha_1^2)}$$

$$x\left(1 + \frac{VB_i(B_s - C\alpha_1^2)(\cos\alpha_1 + (B_o/\alpha_1)\sin\alpha_1)}{CB_o(B_i + B_s + V)(\beta - \alpha_1^2)}\right) x \exp(-\alpha_1^2\tau)$$

$$+ \frac{(B_s - C\alpha_2^2)\alpha_1^2}{B_s(1 + VA)(\alpha_2^2 - \alpha_1^2)}$$

$$x\left(1 + \frac{VB_i(B_s - C\alpha_2^2)(\cos\alpha_2 + (B_o/\alpha_2)\sin\alpha_2)}{CB_o(B_i + B_s + V)(\beta - \alpha_2^2)}\right)$$

$$x \exp(-\alpha_2^2\tau) - \frac{VB_s^2}{C\beta(B_i + B_s + V)^2}$$

$$x\left(1 + \frac{B_i(B_s - C\beta)^2(B_i + B_s + V)[\cos\sqrt{\beta} + (B_o/\sqrt{\beta})\sin\sqrt{\beta}]}{B_oB_s^3(1 + VA)(1 - \beta/\alpha_1^2)(1 - \beta/\alpha_2^2)}\right)$$

$$x \exp(-\beta\tau) \qquad (4.4)$$

where α_n^2 are the positive roots of:

$$\alpha\tan\alpha = \frac{C\alpha^4[(V + B_s)(B_i + B_o) + B_iB_o] - B_s\alpha^2[V(B_i + B_o) + B_iB_o]}{C\alpha^4(B_i + B_s + V) - \alpha^2[CB_iB_o(V + B_s) + B_s(V + B_i)] + VB_iB_oB_s}$$

where:

$$B_i = \frac{h_i l}{k} \qquad B_o = \frac{h_o l}{k} \qquad B_s = \frac{h_s l}{k} \qquad C = \frac{cK}{lk} \qquad V = \frac{vl}{k}$$

$$A = 1 + 1/B_i + 1/B_o \qquad \beta = \frac{B_s(B_i + V)}{C(B_i + B_s + V)} \qquad \tau = \frac{Kt}{l^2}$$

and:

c = thermal capacity of internal mass, J/m²·°C

h_i = heat transfer coefficient on interior surfaces, W/m²·°C

h_o = heat transfer coefficient on exterior surfaces, W/m²·°C

h_s = heat transfer coefficient at surface of internal mass, W/m²·°C

K = thermal diffusivity, m²/s

k = thermal conductivity, W/m·°C

l = thickness of solid wall, m

DT_o = temperature drop of outdoor air, °C; DT_o = 22.2 - (-20) = 42.2°C

TR = room air temperature, °C

t = time, hrs

v = ventilation heat loss rate, W/m²·°C

The initial base model from the DOE program is simplified, to be compatible with the simple mathematical model: (1) the wall consists of only one layer of concrete, 0.3048m thick, with no windows or doors; (2) the building does not contain internal heat sources (lighting, equipment, people); (3) there is no HVAC system. The comparison is performed for a building with and without air infiltration, for one perimeter zone as well as for an entire floor.

The input variables for equation 4.4 used in the four cases for one zone, one floor, with and without infiltration are as follows:

h_i = 8.347 W/m²·°C (from DOE manual p. III.38)

h_s = 7.422 W/m²·°C (from DOE manual p. III.38)

h_o = 6.252 W/m²·°C (from DOE output report)

$k = 0.0091$ W/m·°C (from DOE materials library)

$l = 0.3048$ m

$\rho = 2242.5$ kg/m^3

$c_p = 0.8374$ kJ/kg·°C

$K = (k/\rho c_p) = 1.745 * 10^{-5}$ m^2/hr

m_1 = internal mass for one zone = 38 482.6 kg

A_1 = external wall area for one zone = 127.03 m^2

$c_1 = m_1 * c_p / A_1 = 253.68$ kJ/m^2·°C

m_2 = internal mass of entire floor = 409 020.2 kg

A_2 = external wall area for entire floor = 467.64 m^2

$c_2 = m_2 * c_p / A_2 = 730.07$ kJ/m^2·°C

When the infiltration rate is eliminated, the value of the heat loss rate due to ventilation, v, is set equal to 0 W/m^2·°C. In another simulation, the infiltration rate is set equal to one air change per hour, and the heat loss rate is calculated using the following equation:

$$v = \frac{(\dot{V} * \rho * c_p)}{A} \qquad (4.5)$$

where V = volume flow rate of the air, m^3/s, which is equal to the number of air changes per hour multiplied by the volume of the space and divided by 3600 seconds per hour

ρ = density of the air, kg/m^3

c_p = specific heat of the air, kJ/kg·°C

A = area of the external envelope, m^2

For one zone:

$v_1 = (1 * 411.84 * 1.2014 * 1\,005) / (127.03 * 3600)$

$v_1 = 1.087$ W/m^2·°C

For an entire floor:

$v_2 = (1 * 3647.80 * 1.2014 * 1\,005) / (467.64 * 3600)$

$v_2 = 2.616$ W/m^2·°C

The program code, written in FORTRAN, for the calculation of the variation of indoor air temperature based on equation 4.4 is presented in Appendix B. Figure 4.6 presents results over the first 48 hours from the simulation and the mathematical model for one perimeter zone with no air infiltration, while Figure 4.7 presents the results over an extended period of 150 hours. The results show very good agreement, with the largest differences of almost 6% occurring within the first few hours. The curve from the DOE simulation shows an initial slower response which could be attributed to thermal storage effects; however, this phenomenon is not reproduced by the mathematical model. The two curves intersect after 29 hours, and then the simulated response exceeds that of the mathematical model by less than 5%.

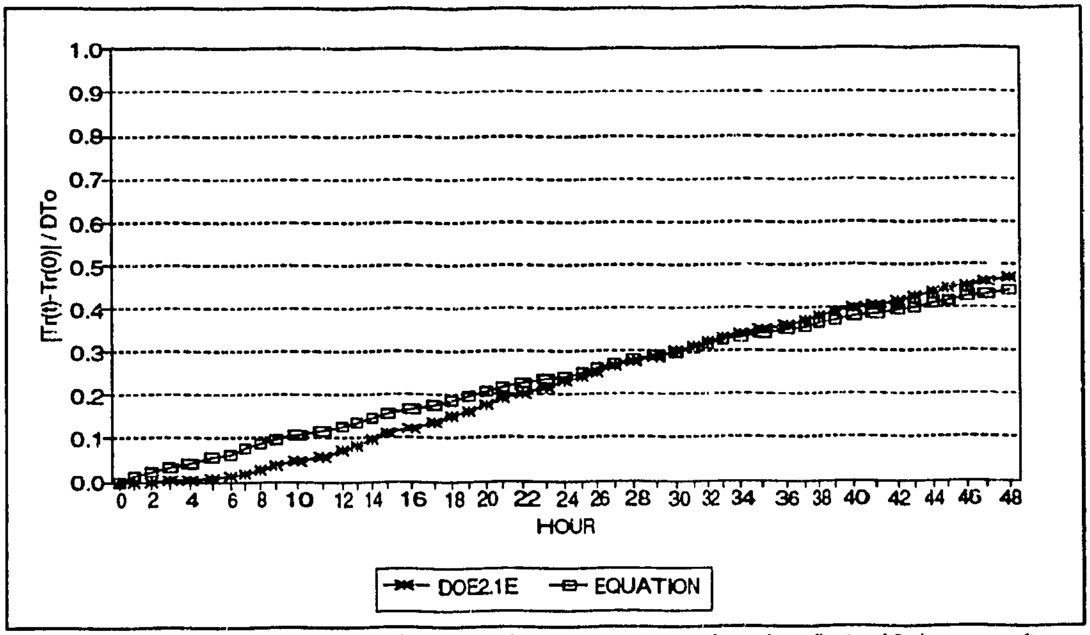

Figure 4.6 Response of the indoor air temperature for the first 48 hours after a sudden change in outdoor air temperature, as predicted by DOE2.1E and a mathematical model. Only one zone is considered, without infiltration effects.

Figure 4.8 compares the results from the mathematical model and the computer simulation for the following configurations:

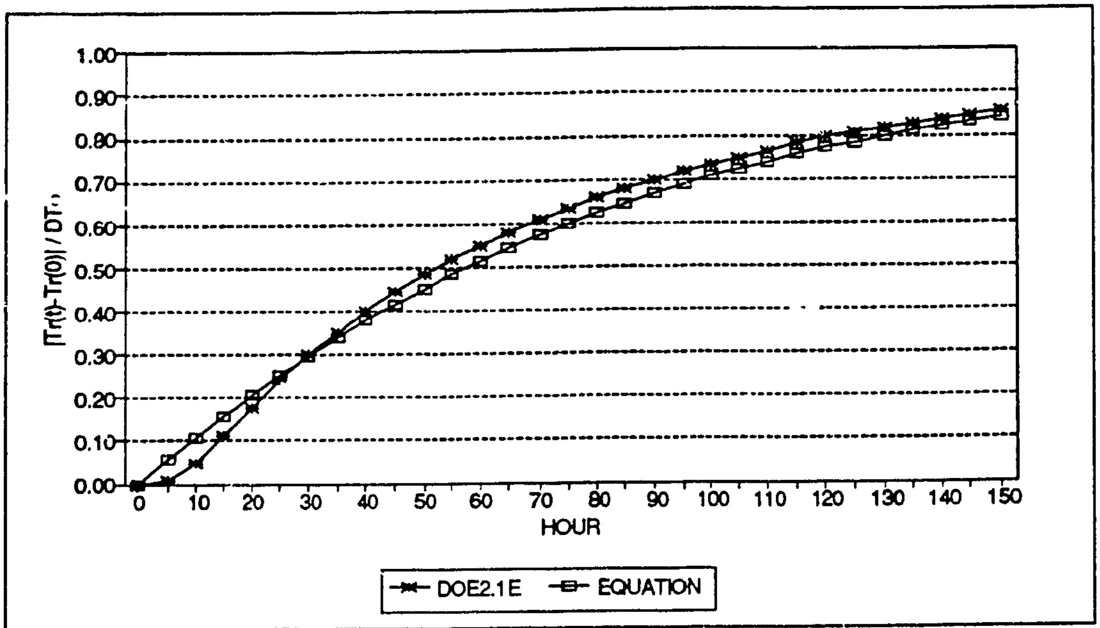

Figure 4.7 Response of the indoor air temperature for the first 150 hours after a sudden decrease in outdoor air temperature, as predicted by DOE2.1E and a mathematical model. Only one zone is considered, without infiltration effects.

1. Case A, where the mathematical model considers the surface area of one floor.

2. Case B, where the simulation results of only a perimeter zone are considered (same as the simulation results presented in Figures 4.6 and 4.7 which was compared to the mathematical model results for the surface area of a perimeter zone).

3. Case C, where the simulation results of only one interior zone are considered.

4. Case D, where the simulation results are weighted by the floor area of internal and perimeter zones.

In all cases, the air infiltration is neglected. For the first 18-20 hours, the three computer simulations show a slower response of indoor air temperature than the mathematical model. The interior zone shows the slowest response, as expected, since it does not have exterior surfaces to facilitate the heat loss.

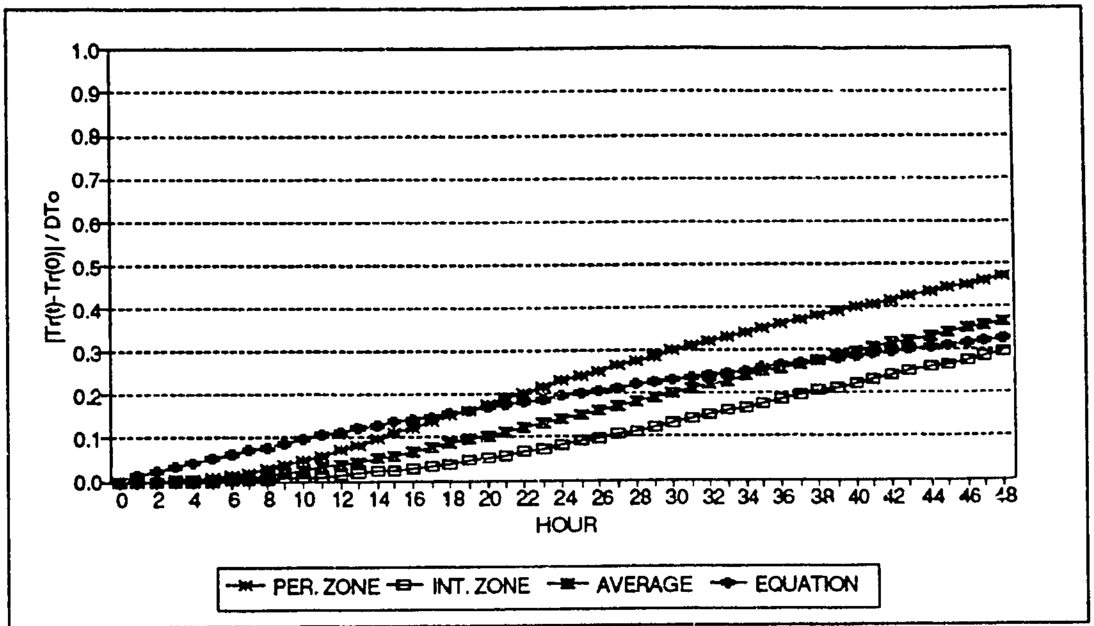

Figure 4.8 Response of the indoor air temperature predicted by the DOE2.1E program and the mathematical model to a sudden change in outdoor air temperature. The entire floor is considered and infiltration effects are neglected.

The mathematical model response is slower in Figure 4.8, where the entire floor area is considered, as compared to Figure 4.6, where only the perimeter zone area is used. Furthermore, a slightly larger difference, as high as 7.6%, is found between the simulation results weighted by the floor areas (case D) and the mathematical model (case A) than is seen in Figure 4.6 between the simulation results of the perimeter zone and the mathematical model results which considers only the perimeter zone surface area.

When the air infiltration is included in both the simulation and mathematical models, a larger difference is found, as shown in Figure 4.9 for one perimeter zone (maximum difference of 11.2%), and Figure 4.10 for the entire floor (maximum difference of 25.0%). The mathematical model predicts a faster reduction in indoor air temperature during the first hour than the DOE program. However, for the following 28-30 hours, the rate of variation predicted by the DOE program is higher than that of the mathematical model.

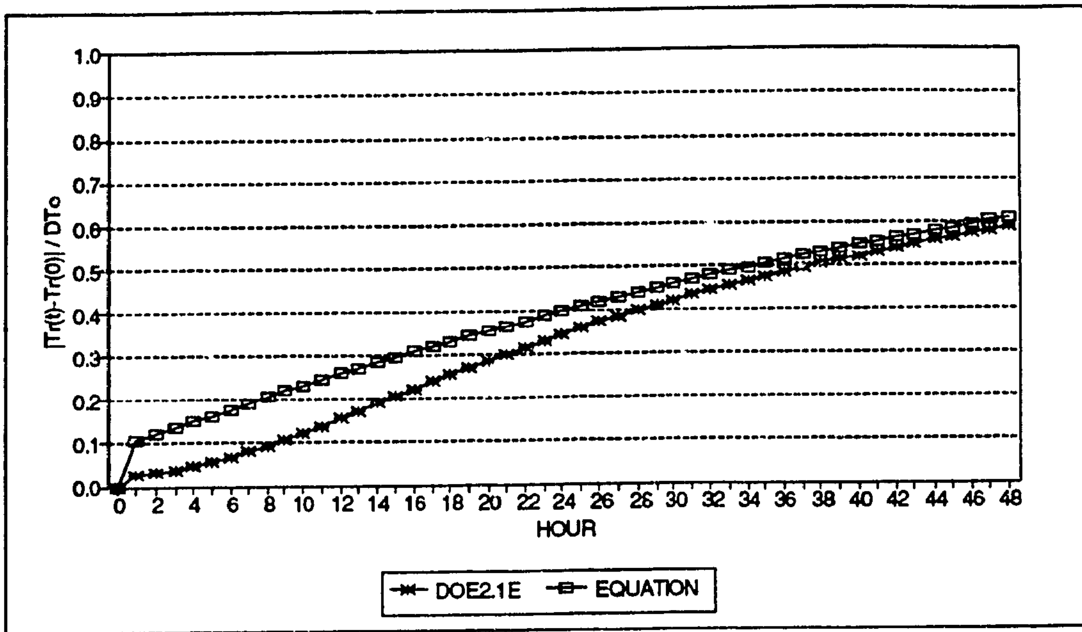

Figure 4.9 Response of the indoor air temperature to a sudden change in outdoor air temperature as predicted by the DOE2.1E program and the mathematical model. One perimeter zone is considered and the infiltration effects are included.

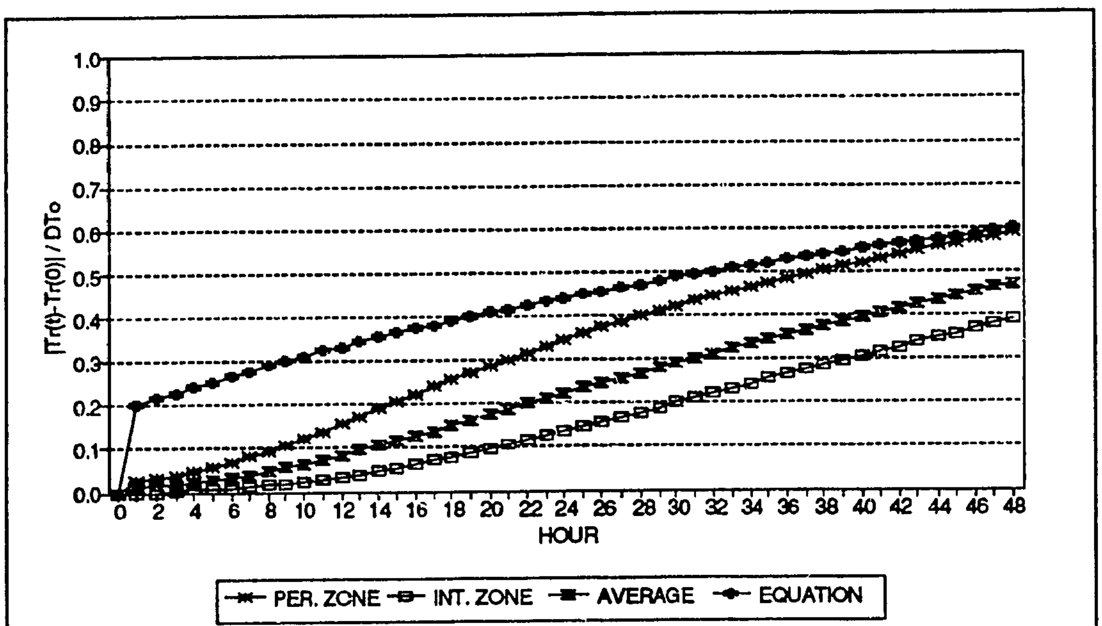

Figure 4.10 Response of the indoor air temperature to a sudden change in outdoor air temperature as predicted by the DOE2.1E program and the mathematical model. The entire floor is considered and infiltration effects are included.

The results of the mathematical model are also compared to the simulated response of the indoor air temperature to an increase in outdoor temperature from 22.2°C to 48.9°C (perturbation B) for one perimeter zone only. Figure 4.11 compares the results of the mathematical model, as well as the simulation results with an increase and decrease in outdoor air temperature and without air infiltration. Once again, slight differences are observed which may be due to the effect of thermal storage in the building mass, as previously described. Both curves from the DOE predictions intersect the curve from the mathematical model, indicating a faster rate of response after the first few hours, although they follow a very similar pattern. When the air infiltration is considered in each model, larger differences are observed (Figure 4.12).

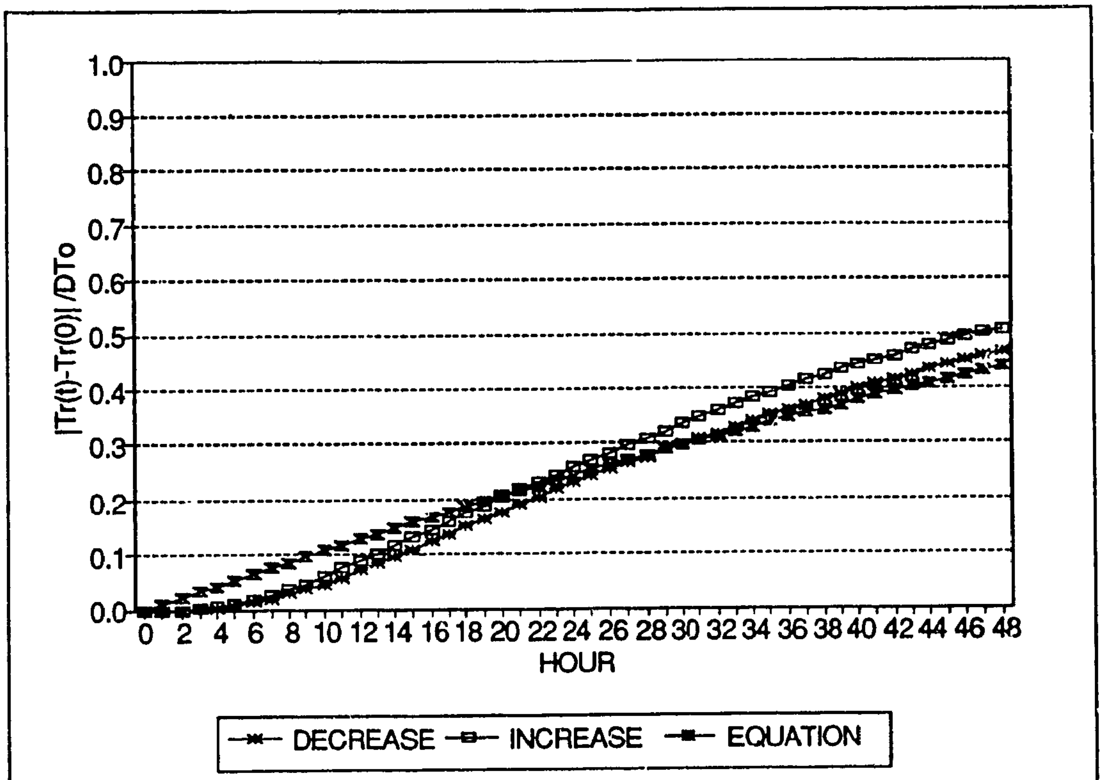

Figure 4.11 DOE2.1E program predictions of the indoor air temperature response to both an increase and a decrease of outdoor air temperature compared to the mathematical model. Infiltration is neglected.

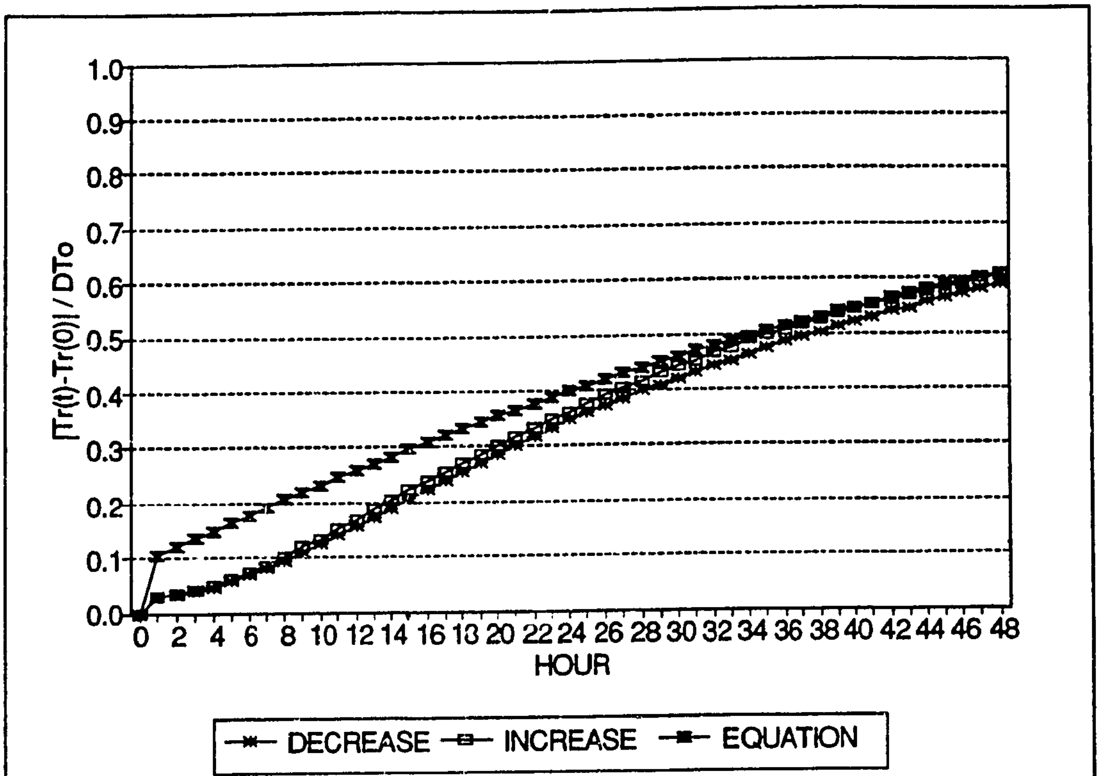

Figure 4.12 DOE2.1E program predictions of the indoor air temperature response to both an increase and a decrease of outdoor air temperature compared to the mathematical model. Infiltration is included.

4.1.6 Time constant of the base model building estimated by the computer program and two mathematical models

The thermal time constant τ is defined as the time it takes for the indoor temperature to change by approximately 63% of the step change in outdoor air temperature, assuming all other factors remain constant, and is equal to [52]:

$$TR_i(0) - TR_i(t) = DT_o * (1 - e^{-1})$$
$$TR_i(t) = TR_i(0) - (0.632 * DT_o) \quad (4.6)$$

where: $TR_i(0)$ = initial indoor temperature at time 0, °C

$TR_i(t)$ = indoor temperature at time t, °C

DT_o = change in outdoor temperature, °C, which is equal to 42.2°C for perturbation B

The time constant is determined for the base building model, described in the previous section. based on the simulation results as well as on the results of this mathematical model, called MAT-1.

In addition, the lumped-capacity method is also used to calculate the time constant [53], assuming the indoor air temperature and the temperature of the interior mass and exterior walls are uniform and the building mass is homogeneous. Since the lumped-capacity method assumes a homogeneous material, a weighted average is calculated for each of the required material properties. The effect of the air is assumed negligible compared to the other materials. This method is named MAT-2:

$$\frac{T - T_\infty}{T_0 - T_\infty} = e^{-\left(\frac{\bar{h} A_s}{c_p \rho V}\right) t} \tag{4.7}$$

where h = average heat transfer coefficient, W/m²·°C

A_s = exterior surface area of the building, m²

c_p = specific heat of the building mass, kJ/kg·°C

ρ = density of the building mass, kg/m³

V = volume of the building mass, m³

from where:

$$\tau = \frac{c_p \cdot \rho \cdot V}{\bar{h} \cdot A} \tag{4.8}$$

The time constants calculated with the various methods, namely the computer simulations, MAT-I and MAT-2, are presented in Table 4.2, as well as in Figures 4.13 and 4.14. The results from the simulations, which show a time constant of 73 hours (without infiltration) and 55 hours (with infiltration), are similar to those from the mathematical model MAT-1, when only one zone is modelled, with a time constant of 83 hours (without infiltration) and 52 hours (with infiltration). For these cases, the simulation shows a difference of -12.0% when the infiltration is not considered, and a difference of +5.8% when it is considered. The time constant calculated by the lumped-capacity method, however, is greatly underestimated, with a difference of -55.4% over the mathematical model and -49.3% over the simulation result. This large discrepancy is expected, due to the assumptions of the lumped-capacity method which do not reflect the actual situation; the zone is an enclosed space rather than a solid mass.

Table 4.2 Time constant of the base model building evaluated using the computer program and two mathematical models

Calculation method	Configuration	Time constant without infiltration (hours)	Time constant with infiltration (hours)
Mathematical (MAT-1)	surface area of one zone	83	52
Mathematical (MAT-1)	surface area of one floor	141	56
Simulation	perimeter zone	73	55
Simulation	interior zone	97	81
Simulation	average for one floor	89	71
Lumped-capacity method (MAT-2)		37	--

The time constant calculated with the mathematical model MAT-1 shows a larger difference compared with the results of the simulation when the entire floor is considered (141 hours for the mathematical model and 89 hours for the simulation, or -36.9%) compared to when only one zone is considered (83 hours for the mathematical model and 73 for the program, -12.0%). When the infiltration is considered, the simulation result for the entire floor, 71 hours, exceeds the mathematical predicted value of 56 hours by 26.8%.

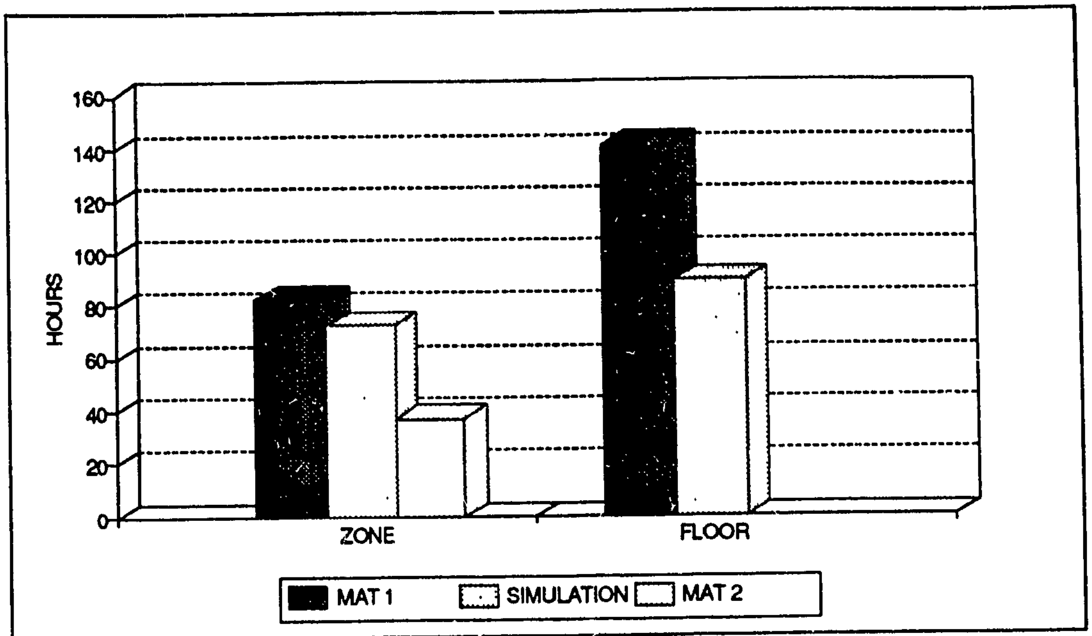

Figure 4.13 Time constant calculated by the various models, when the infiltration effects are neglected

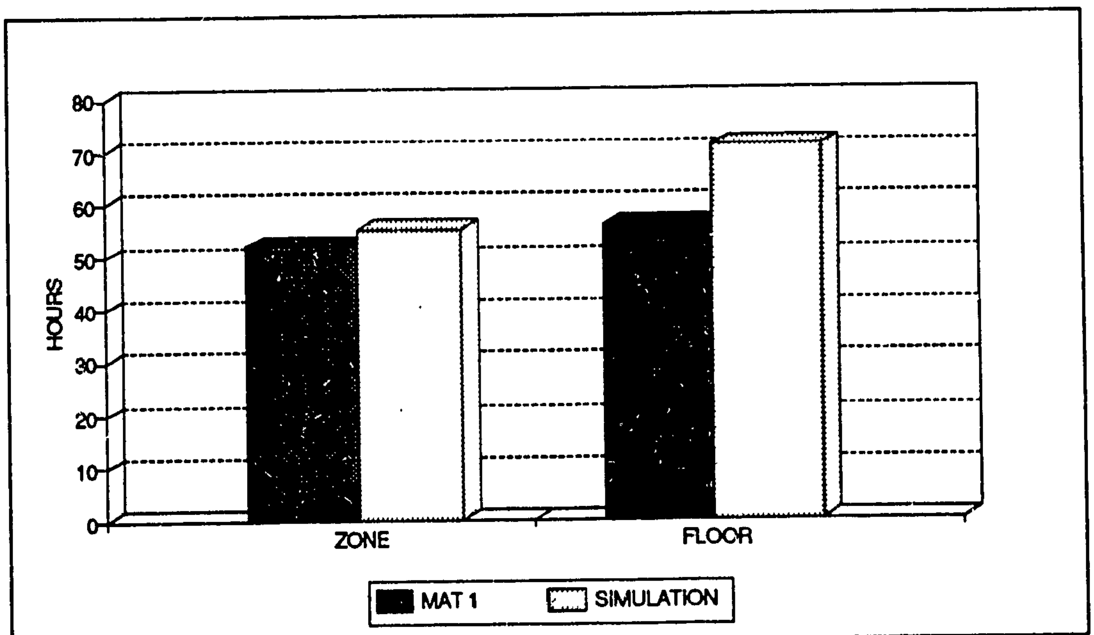

Figure 4.14 Time constant estimated by DOE2.1E and the mathematical model, MAT-1, when the infiltration effects are included

In the DOE simulations, the infiltration has a much less significant effect on the time constant of the building than is seen in the mathematical model. In the computer simulations, the time constant decreases by 24.7% for one zone and by 20.2% for the floor average when the infiltration is considered. However, in the mathematical model, the time constant decreases by 37.3% for one zone due to the infiltration effect, and by 60.3% for the model of the entire floor.

The qualitative analysis of the system's response to a perturbation in outdoor air temperature as a function of the indoor air temperature, cooling demand and heating demand revealed no significant discrepancies in the simulation model. The comparison of the simulation results with the mathematical model showed some discrepancies, particularly in the first 10 to 15 hours, where the simulated indoor air temperature response was significantly slower than the mathematical model. However, it was clear from the beginning that the complexity of the heat transfer processes within a building or between the building and the outdoor environment, will prevent us from obtaining an excellent agreement between the computer program, which uses some specific algorithms, and the simple mathematical models. A comparison between their results can indicate, in a relative rather than absolute manner, if errors are propagated within the computer program.

4.2 Comparison of specific program algorithms with the HVAC toolkit

In order to verify the accuracy of particular algorithms in the MICRO-DOE2.1E simulation program, related to the air handling systems, a simple modelling tool is used as a basis of comparison. The HVAC2-TOOLKIT [54] was developed by ASHRAE as a set of simple subroutines, each one focusing on a particular HVAC calculation, such as cooling or heating coil loads. The toolkit also calculates the psychrometric properties of air when two properties are known, such as dry-bulb temperature and humidity ratio. The source code, written in FORTRAN, is detailed in the user manual for each algorithm. Furthermore, the mathematical models and assumptions used for the calculations are also described. The toolkit is accessed by a driver program, through which the user can select the subroutine to be called. The program then prompts the user to enter the values for the required input variables.

In this study, the toolkit is used to simulate (1) the dry-bulb temperature economizer, (2) the enthalpy economizer and (3) the cooling coil load. The values obtained from the DOE2.1E program simulation reports are used as input values for the toolkit subroutines, to ensure compatibility between the two models.

4.2.1 Definition of design-day weather data

To ensure that the conditions are representative of typical ranges of temperatures and humidities, three design-day periods were defined in the DOE program:

1. Day 1, corresponding to winter conditions; outdoor dry-bulb temperature varies from 10°C to -6.7°C, and the humidity ratio remains constant with the dewpoint temperature at -6.1°C.

2. Day 2, corresponding to fall or spring conditions; outdoor dry-bulb temperature varies from 21.1°C to 10°C, the dewpoint temperature varies from 18.3°C to 6.1°C, and the relative humidity is almost constant at approximately 90%;

3. Day 3, corresponding to summer conditions with high humidity; outdoor dry-bulb temperature varies from 30.5°C to 18.9°C, and the dewpoint temperature is constant over the day and equal to 18.3°C.

The minimum dry-bulb and dewpoint temperatures are assumed to occur at 2:00 am and the maximum values at 2:00 pm. The other weather data (wind speed and direction, cloud amount, clearness, ground temperature and cloud type) are listed in Table 4.3.

Table 4.3 Design-day data used in comparison between DOE2.1E and HVAC2-TOOLKIT

Parameter	Day 1	Day 2	Day 3
maximum dry-bulb temperature	10°C	21.1°C	30.5°C
minimum dry-bulb temperature	-6.7°C	10.0°C	18.9°C
time of maximum dry-bulb temp.	2:00 pm	2:00 pm	2:00 pm
time of minimum dry-bulb temp.	2:00 am	2:00 am	2:00 am
maximum dewpoint temperature	-6.1°C	18.3°C	18.3°C
minimum dewpoint temperature	-6.1°C	6.1°C	18.3°C
time of maximum dewpoint temp.	2:00 pm	2:00 pm	2:00 pm
time of minimum dewpoint temp.	2:00 am	2:00 am	2:00 am
wind speed	0.51 m/s	0.51 m/s	0.51 m/s
wind direction	14 (North-West)	14 (North-West)	14 (North-West)
amount of cloud cover	5 (partly cloudy)	5 (partly cloudy)	5 (partly cloudy)
clearness index	1.03*	1.03	1.03
ground temperature	7.2°C	7.2°C	12.8°C
type of cloud cover	1**	1	0

* This value is estimated and accounts for the clearness factor due to city pollution

** This value is given in the DOE user manual and accounts for the predominant cloud type during the winter or summer months

4.2.2 Dry-bulb temperature economizer

The DOE2.1E program is used to predict the operation of a dry-bulb temperature economizer control for the three design-day periods. The switchover temperature used in the DOE program is equal to 22.8°C, which indicates the following:

1. When the outside air temperature exceeds 22.8°C, the inlet air dampers are set to the position which reduces to the minimum the amount of outdoor air brought into the HVAC system;

2. When the outdoor temperature is less than 22.8°C but greater than the supply air temperature (which varies between 13.0°C and 16.0°C due to the reset control), the dampers are completely open to let 100% of outdoor air in the system;

3. When the outdoor temperature is less than the supply air temperature, the dampers are automatically adjusted between the minimum and maximum positions to create a mixing temperature closest to the setpoint for the supply air temperature.

The values of some important parameters affecting the operation of dry-bulb economizer systems, as used or predicted by the DOE program or calculated using the results of this program, are used as input data for HVAC2-TOOLKIT: dry bulb temperature of return air, humidity ratio of return air, dry bulb temperature of outdoor air, humidity ratio of outdoor air, mass flow rate of mixed air, minimum mass flow rate of outdoor air, setpoint for mixed air temperature, switchover temperature, and the control variable (the outdoor dry bulb temperature in this case).

The results of the toolkit subroutine ECON, in terms of fraction of outdoor air flow rate to the total supply air flow rate, mixed air temperature, and mixed air humidity ratio, are compared to the hourly results of the DOE simulation. As seen in Figures 4.15 to 4.17, the values from the two programs are almost identical.

Figure 4.15 presents the fraction of outdoor air flow rate to the total supply air flow rate in relation to the outdoor air temperature. At low outdoor air temperatures, the dampers are modulated, and therefore, the amount of outdoor air varies in terms of outdoor air temperature in order to attain the required mixed air temperature. At higher outdoor air temperatures, the dampers are open at the maximum position to allow for free cooling, until the switchover temperature (22.8°C) is reached; then the dampers are closed to their minimum position. Figure 4.16 presents the variation of the mixed air temperature as a function of the outdoor air temperature, while Figure 4.17 shows the humidity ratio of mixed air as a function of outdoor air temperature. In Figure 4.17, the humidity ratio of the mixed air decreases significantly once the outdoor air temperature exceeds the switchover temperature and the dampers are set to their minimum position. This is due to the high humidity level of the outdoor air which was defined in Day 3 (ranging from 18.9°C to 30.5°C).

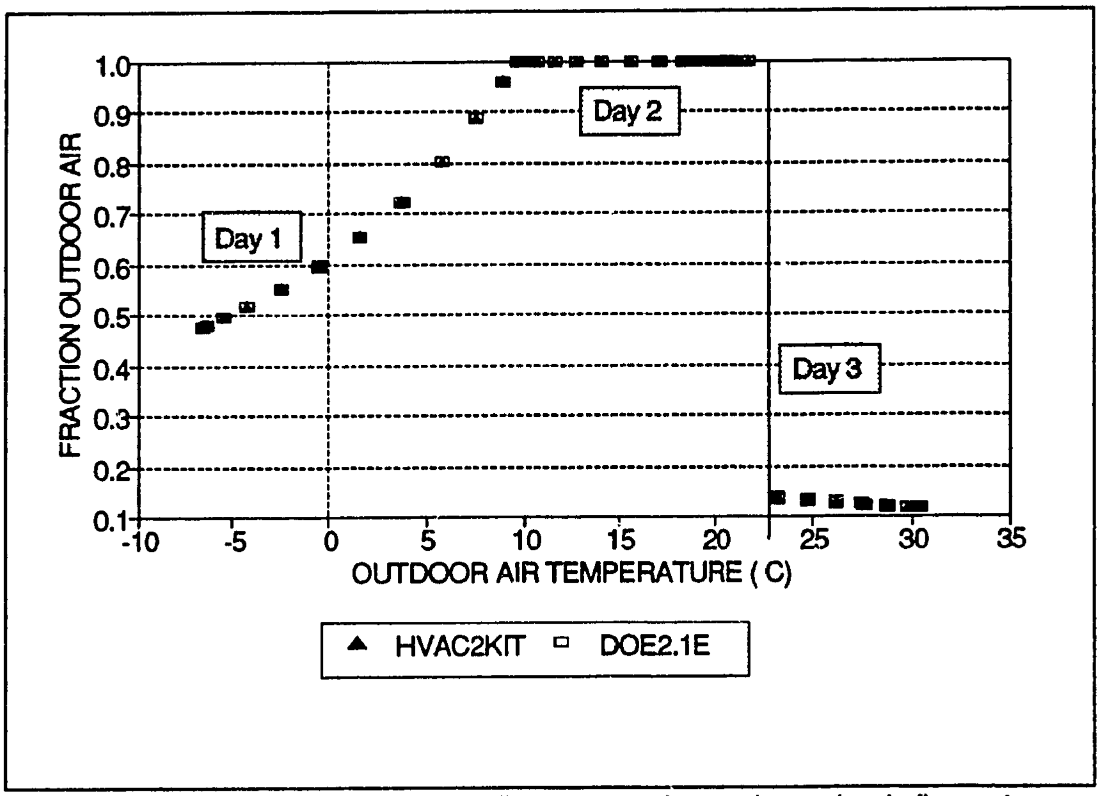

Figure 4.15 Ratio of the outdoor air flow rate to the total supply air flow rate as a function of the outdoor air dry bulb temperature when a dry-bulb temperature economizer is modelled

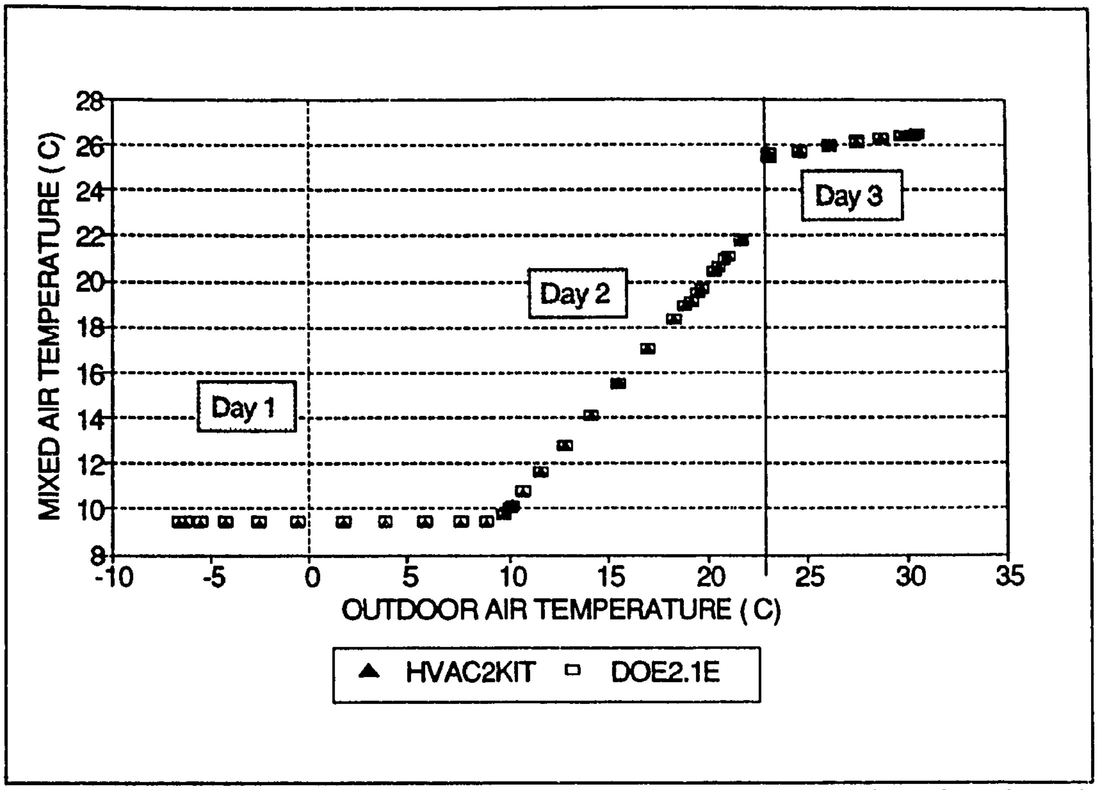

Figure 4.16 Mixed air temperature of the central system as a function of outdoor air dry-bulb temperature when a dry-bulb temperature economizer is modelled

4.2.3 Enthalpy economizer

The operation of the enthalpy economizer is similar to that of the dry-bulb temperature economizer, except the dampers are set to their minimum position when the enthalpy of the outdoor air is greater than the enthalpy of the return air. This results in lower cooling energy consumption on hot and humid days, while taking advantage of free cooling when available.

The same subroutine from the HVAC2-TOOLKIT (ECON) is used for the enthalpy economizer as for the dry bulb temperature economizer. However, for the enthalpy economizer, the ambient air control variable is set to the outdoor air enthalpy instead of outdoor air dry-bulb temperature, and the ambient air design parameter for minimum

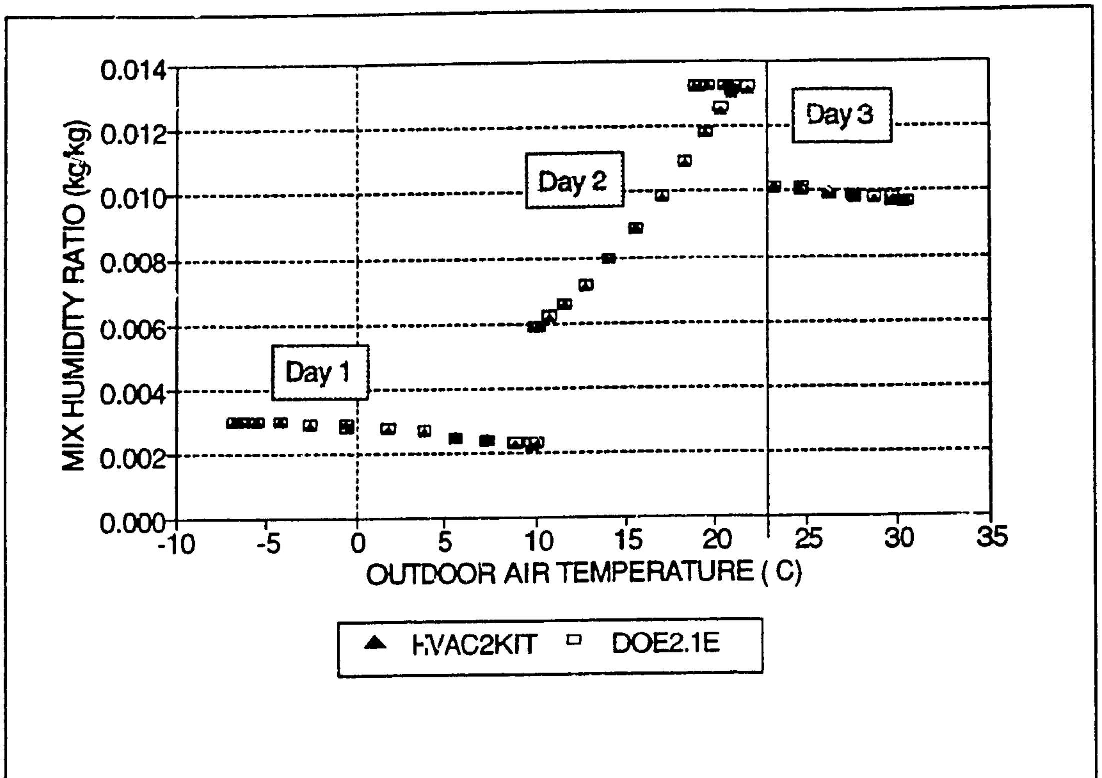

Figure 4.17 Mixed air humidity ratio of the central system as a function of outdoor air dry-bulb temperature when a dry-bulb temperature economizer is modelled

damper position is set to the return air enthalpy rather than the switchover temperature. In order to determine the enthalpy of the outdoor air for each hour, another subroutine from the toolkit is used (TDB_W) which calculates several psychrometric properties given the dry-bulb temperature and the humidity ratio of the air.

Figure 4.18 presents the fraction of outdoor air as a function of the outdoor air temperature, as predicted by the two programs for the enthalpy economizer control. It is clear that in the last design-day, Day 3, representing summer conditions with high humidity, the dampers are set to their minimum position due to the high enthalpy of the outdoor air. When the dry-bulb temperature economizer is used, the dampers are closed only when the outdoor air temperature is less than the switchover temperature (Figure 4.15) even though on humid days, this may result in an increased cooling load.

The operation of the enthalpy economizer is better presented as a function of the outdoor

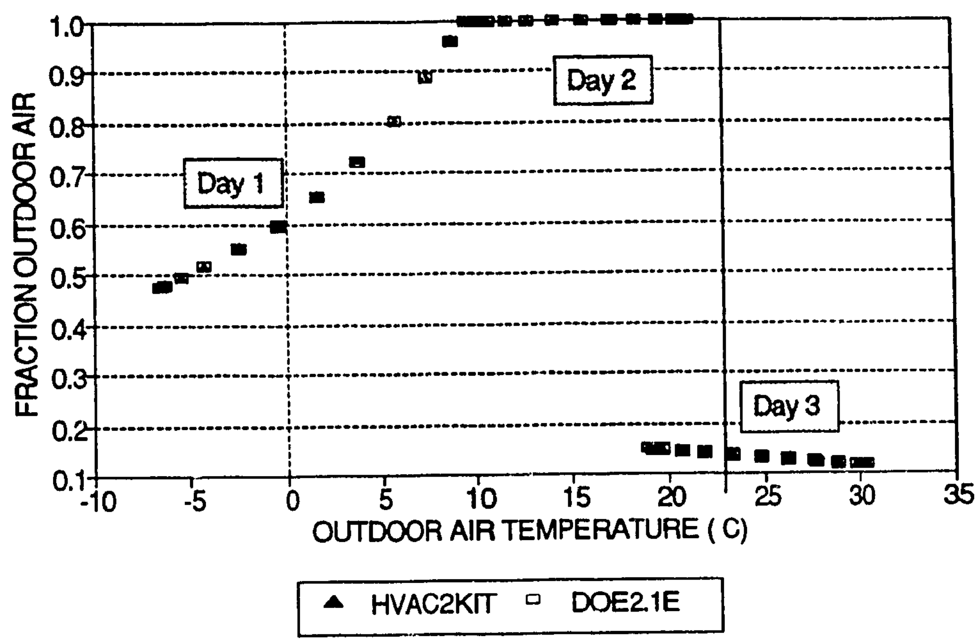

Figure 4.18 Ratio of the outdoor air flow rate to the total supply air flow rate as a function of the outdoor air dry-bulb temperature, when an enthalpy economizer is modelled

air enthalpy (Figure 4.19). The limit at which the outdoor air dampers are set to the minimum position (ie. when the fraction of outdoor air brought into the system is at a minimum), is not as apparent as in the case of the temperature economizer, since the outdoor air enthalpy is compared with the return air enthalpy, which varies during the day, instead of a fixed value, such as the switchover temperature. Therefore, there is an overlap when, for the same outdoor enthalpy, the dampers are at one time fully open, while at another time, are set to their minimum position.

4.2.4 Cooling coil load

A subroutine from the HVAC2-TOOLKIT is also used to estimate the load on the cooling coil (CCCOIL). Since the subroutine calls for several input parameters for rating conditions, some assumptions and estimates are required:

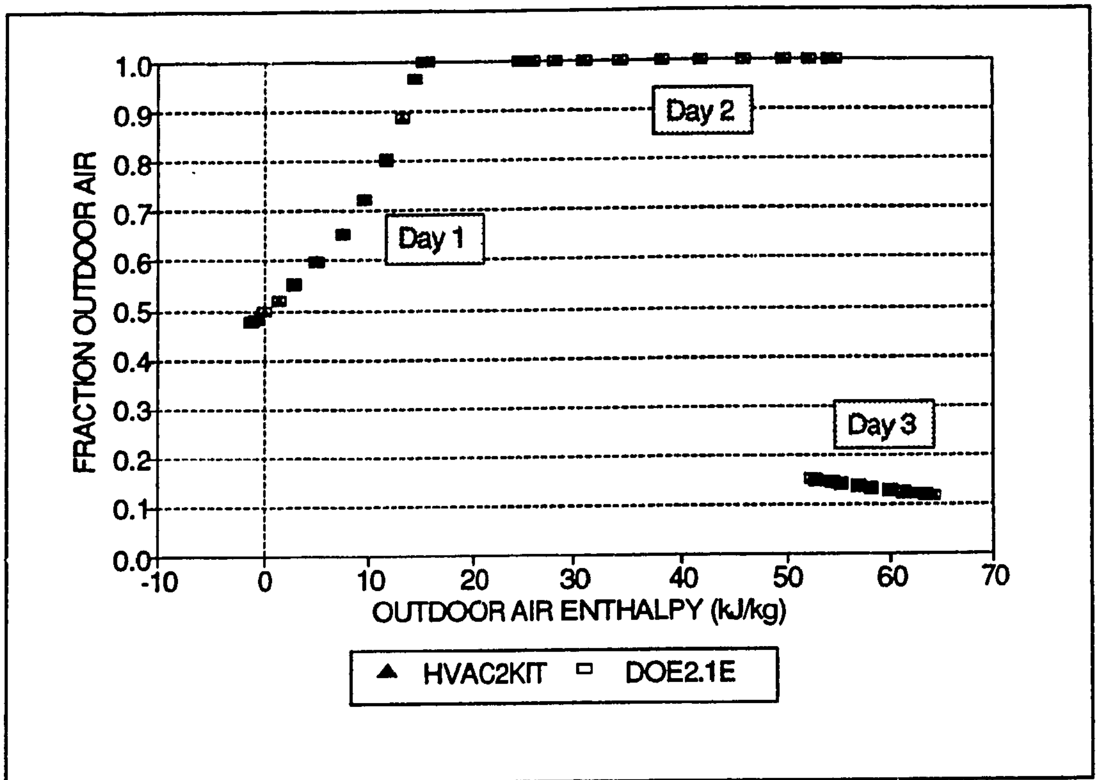

Figure 4.19 Ratio of the outdoor air flow rate to the total supply air flow rate as a function of the outdoor air enthalpy, when an enthalpy economizer is modelled

1. Inlet air at rating conditions is at 26.7°C dry bulb and 19.4°C wet bulb (as specified in the DOE manual p. IV.40).

2. Supply air at rating conditions is at 10°C and 90% relative humidity and a flow rate of 38.23 m^3/s.

3. The total heat transfer rate at rating conditions is calculated using equation 4.2 and the previous assumptions to determine h_1, h_2, W_1, W_2, m_v, v, and h_{w2}:

$$q_T = \dot{m}_a[(h_1 - h_2) - (W_1 - W_2) * h_{w2}]$$

$$q_T = \frac{38.23}{0.865}((73.5 - 45.1) - (0.0112 - 0.0069)*223.3)$$

$$q_T = 1\ 212.2\ kW$$

4. The sensible heat transfer rate at rating conditions is calculated using the following equation [55]:

$$q_s = \frac{\dot{Q}}{v_o} * c_p * (T_i - T_o) \qquad (4.9)$$

where q_s = sensible heat flow, W

Q = the volumetric flow rate of the air through the coil at rating conditions, m^3/s

v_o = specific volume of the air through the coil, m^3/kg

c_p = specific heat capacity of moist air, J/kg·°C

T_i = the inlet air temperature at rating conditions, °C

T_o = the outlet air temperature at rating conditions, °C

5. The volume flow rate at rating conditions used in the previous calculation (equation 4.9) is assumed to be equal to the maximum flow rate capacity of the simulated system.

6. The required value for the dry air mass flow rate at rating conditions is based on the volume flow rate capacity specified in the simulated system and the specific volume of the air at rating entering conditions.

7. The entering liquid temperature at rating conditions, is defined from the values specified in the DOE manual.

8. The liquid mass flow rate in the cooling coil at rating conditions is estimated using the following equation [55]:

$$\dot{Q} = \frac{q * \rho}{c_p * (T_i - T_o)} \qquad (4.10)$$

where
Q = volumetric flow rate of water, L/s
q = heat conveyed by water, W; assumed to be equal to the total cooling coil capacity calculated previously
ρ = density of water, L/kg
c_p = specific heat of water, J/kg·°C
T_i = water inlet temperature, °C
T_o = water outlet temperature, °C

The temperature difference (T_i - T_o) is assumed to be 5.6°C as used in common practice [56]. Once the flow rate is obtained in L/s, a chart is consulted [56] and, with an estimated friction loss of 226 Pa/m, the fluid velocity is estimated at 2.4 m/s with a pipe diameter of 0.15 m. Consequently, the liquid mass flow rate is calculated.

Other input variables are required by the subroutine for the specific hour considered. These are derived directly from the DOE simulation hourly reports: (1) entering liquid temperature, (2) dry air mass flow rate, (3) entering air dry bulb temperature, (4) entering air humidity ratio, and (5) leaving air dry bulb temperature.

The CCCOIL subroutine output consists of: (1) liquid mass flow rate, (2) leaving liquid temperature, (3) leaving air humidity ratio, (4) total heat transfer rate, (5) sensible heat transfer rate, and (6) the fraction of surface area wet.

The comparison in Figure 4.20 reveals an error in the calculation of the humidity ratio of the leaving air in the DOE program, since the humidity ratio surpasses the saturation point (approximately 0.0077 kg/kg) for a number of cases during Day 2 and Day 3. The humidity ratio given by the DOE program reaches as high as 0.0117 kg/kg for an outdoor air temperature of 18.9°C. This error in calculating the humidity ratio is expected to affect the prediction of the latent cooling load.

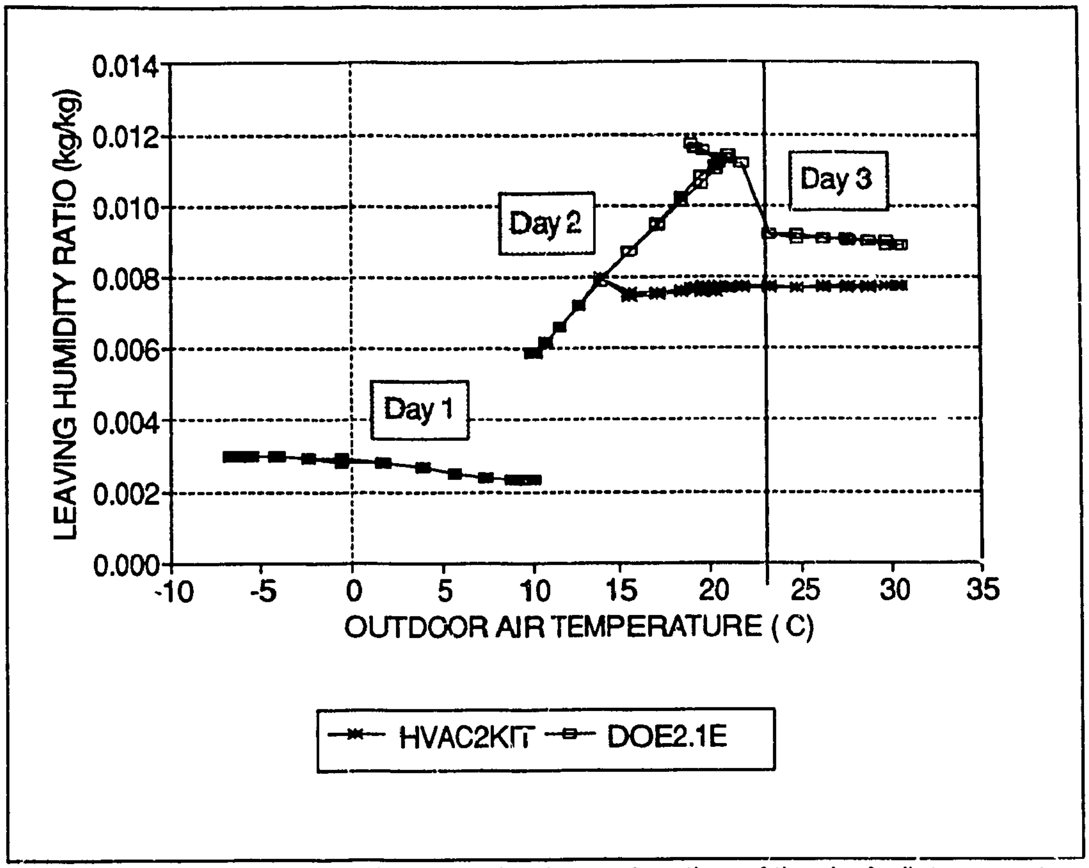

Figure 4.20 Humidity ratio of the supply air as a function of the dry bulb temperature of the outdoor air when a dry-bulb temperature economizer is modelled

Figures 4.21 and 4.22 present the sensible cooling loads for the temperature and enthalpy economizers, respectively, simulated by the DOE program and calculated by the TOOLKIT program. The values for the sensible cooling loads are in good agreement, with differences under 4%. An increase in sensible cooling load is observed for the enthalpy economizer as compared to the temperature economizer for the last design day when the outdoor temperature is less than the switchover temperature. This increase in sensible cooling load for the enthalpy economizer simulation is expected since the dampers are closed due to the high enthalpy of the outdoor air, even though the outdoor air dry-bulb temperature is less than the return air temperature. However, the total cooling load is expected to decrease on hot and humid days when the enthalpy economizer is used.

Figure 4.23 presents the total cooling load for a system with a dry bulb temperature economizer as a function of the outdoor temperature. A gradual increase is observed in

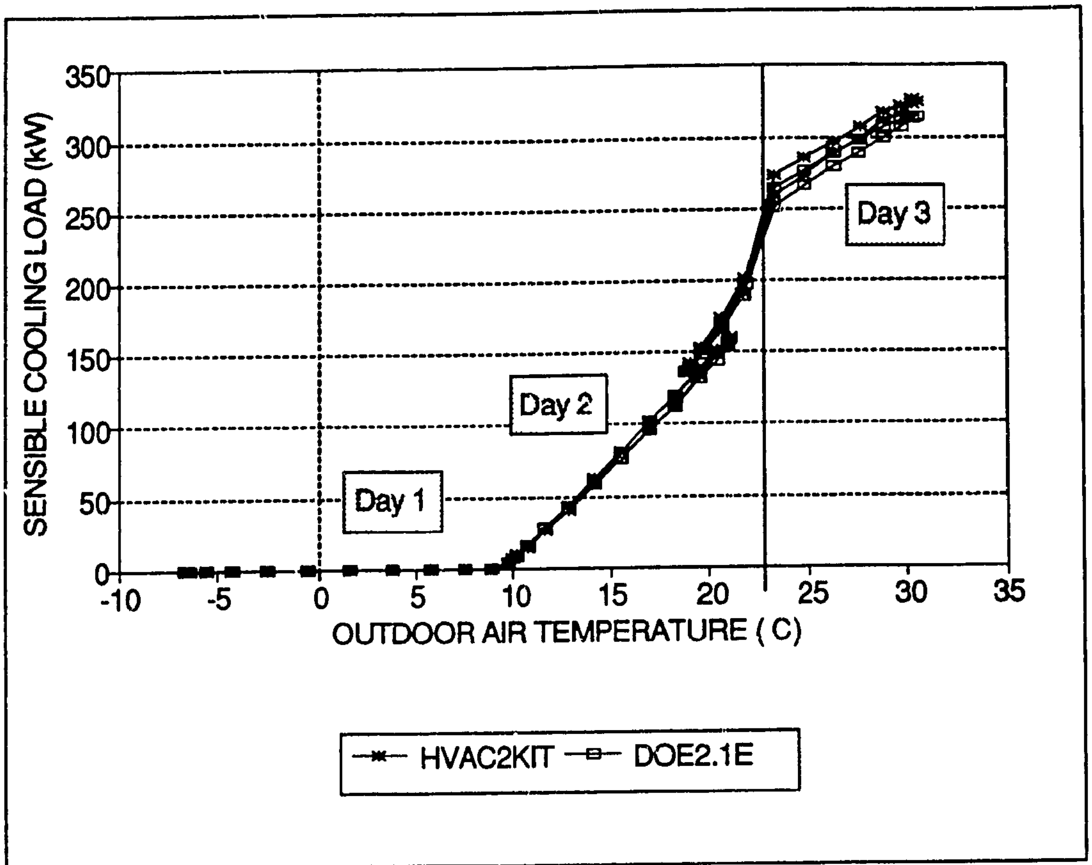

Figure 4.21 Sensible cooling load as a function of the outdoor air dry bulb temperature when a dry-bulb temperature economizer is modelled

the cooling load for an increase in outdoor temperature during Day 2, whereas the last period with high temperatures and humidity ratios (Day 3), shows an even larger cooling load. The DOE simulation results clearly show an underestimation of the cooling load as high as 36% due to the humidity ratio calculation error. Since the sensible cooling loads show good agreement (Figure 4.21), this underestimation is attributed to the latent cooling load alone. Furthermore, the economizer is not well simulated, showing an increase in cooling load after the switchover temperature instead of the decrease as in the TOOLKIT results, which accurately predict the decrease of the latent cooling load after the dampers are closed.

The variation of specific cooling load (cooling load divided by the mass flow rate of the air moving through the system at that particular hour) in Figure 4.24 exhibits the same trend apparent in Figure 4.23, except after the switchover temperature, the cooling load per unit

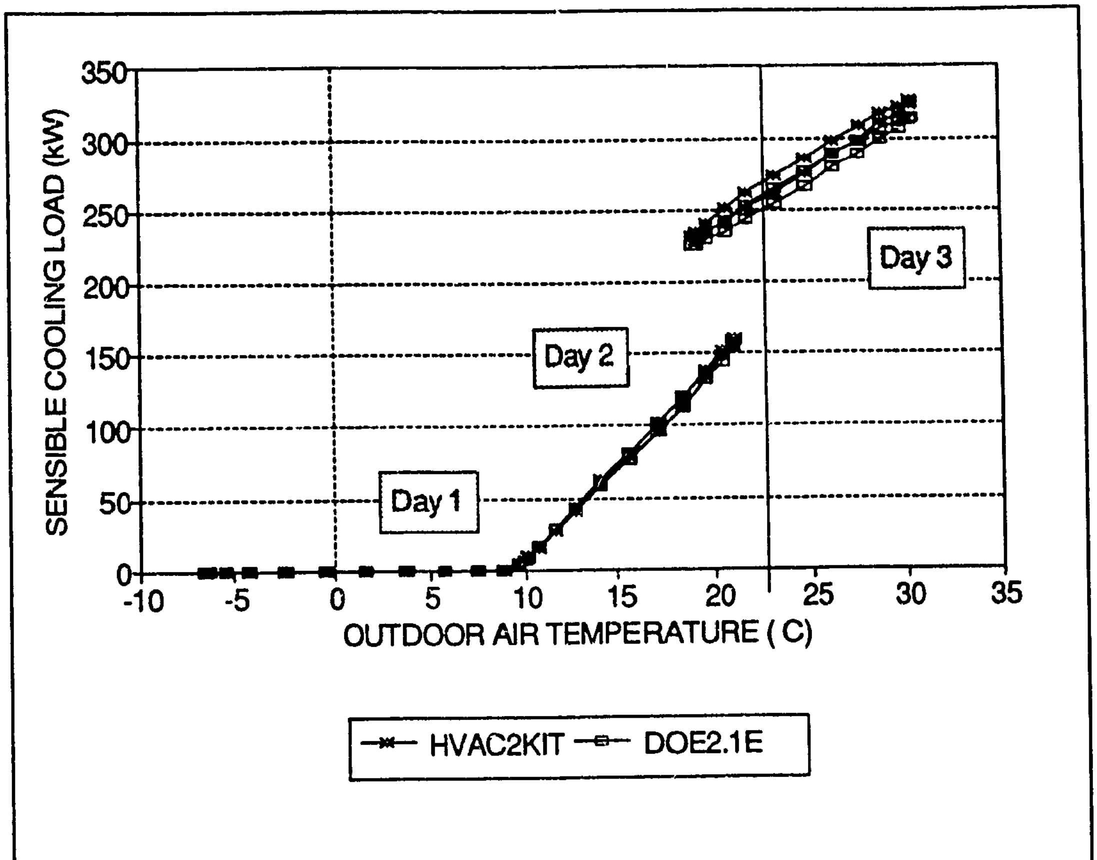

Figure 4.22 Sensible cooling load as a function of the outdoor air dry-bulb temperature when an enthalpy economizer is modelled

mass flow rate remains almost constant for both models, even though the cooling load increases. This would indicate that the air flow rate in the system increases proportionally to the increase in cooling load in order to accommodate the additional cooling requirements. The DOE program underestimates the specific cooling load by as much as 35% before the switchover temperature and 17% after.

The cooling load resulting from the simulation of the enthalpy economizer is presented in Figure 4.25 as a function of outdoor temperature. In comparison to Figure 4.23, Figure 4.25 shows a decrease in cooling load simulated by the toolkit of approximately 15% for the last design day, just prior to the switchover temperature. This is anticipated since the advantage of the enthalpy economizer is to reduce the cooling loads on hot and humid days. The DOE simulation, however, shows an increase in cooling load of approximately 25% during this same period, which can be attributed to the error related to the calculation

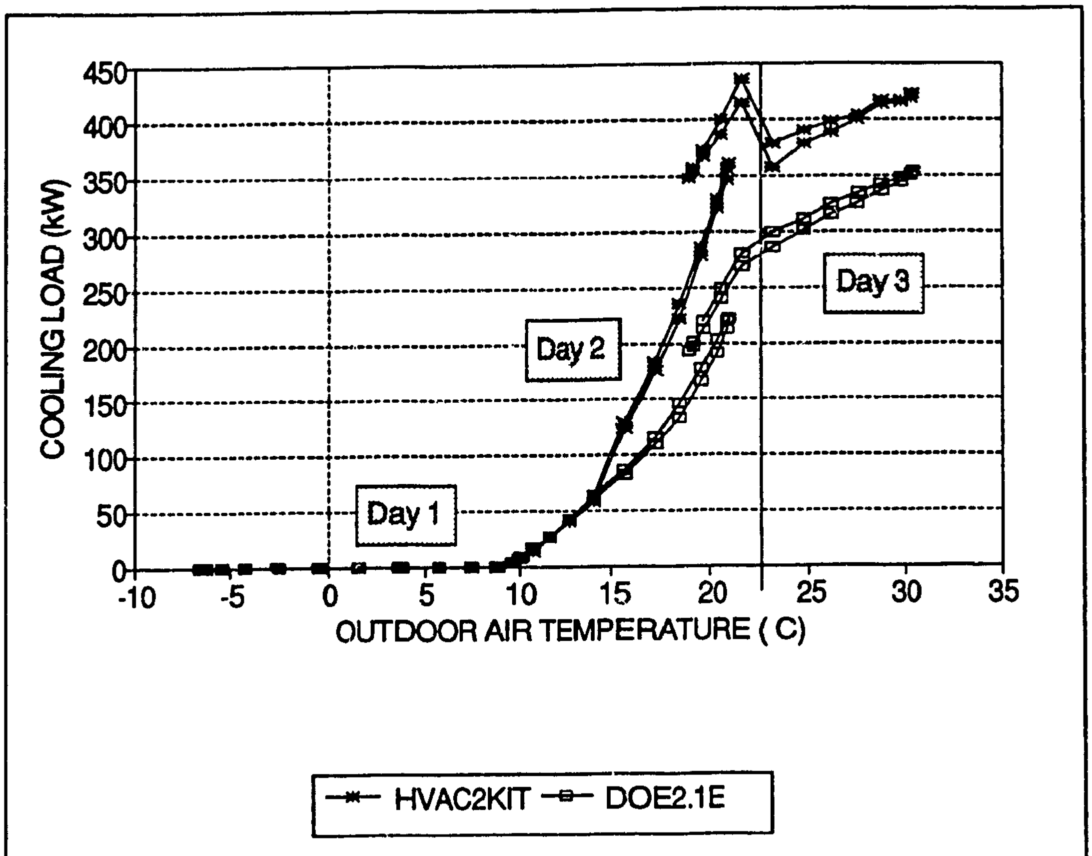

Figure 4.23 Total cooling coil load as a function of outdoor air dry bulb temperature when a dry-bulb temperature economizer is modelled

of the supply air humidity ratio.

The errors discovered in the calculation of the latent cooling in the MICRO-DOE2.1E program could be responsible for the discrepancies found between the simulated monthly consumption and peak demand and the data from the utility bills in the summer months (Figures 3.10 and 3.11). It is clear that the impact this error has on the results depends greatly on the temperature and humidity ratio of the outdoor air.

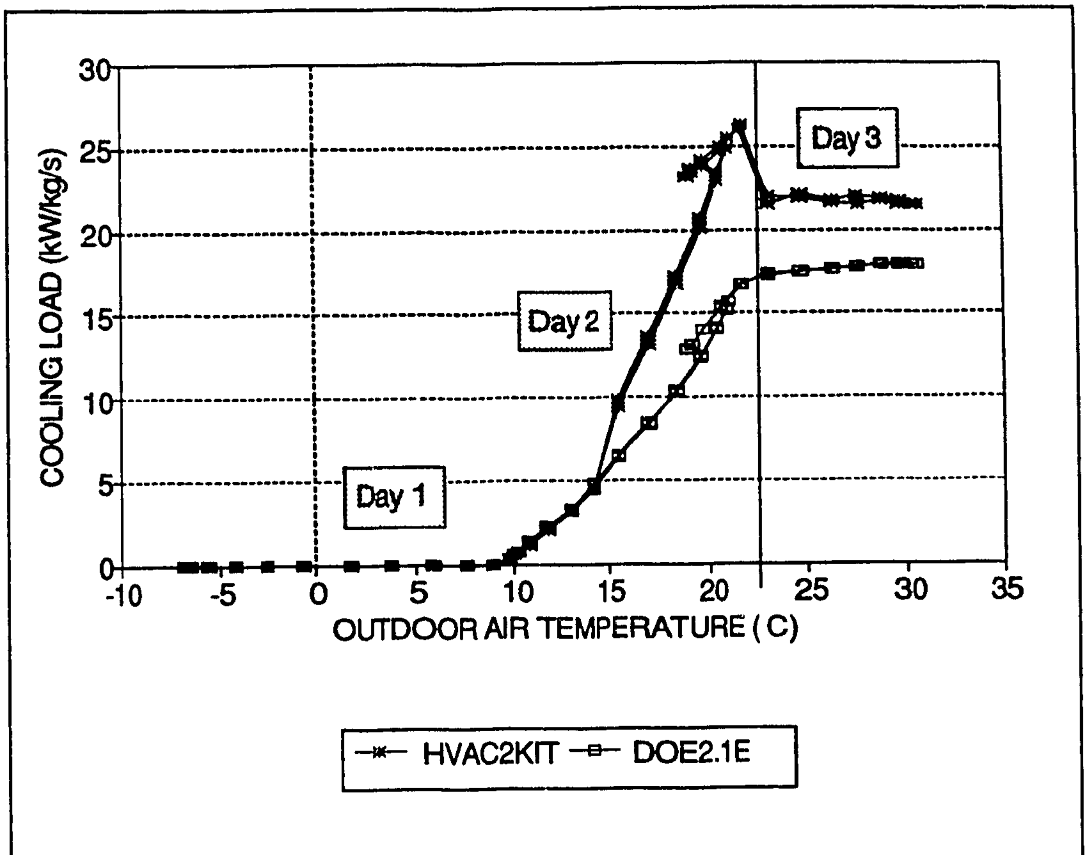

Figure 4.24 Variation of the specific cooling load as a function of the dry bulb temperature of outdoor air when a dry-bulb temperature economizer is modelled

4.3 Sensitivity analysis

Several studies have identified sensitivity analysis as an important part of any validation procedure [1, 5, 7, 11, 19, 25, 29]. However, the acceptable range of results or the types of parameters which should be analyzed have not been defined. In addition, the interpretation of the results of the sensitivity analyses has been left to the discretion of the user. In this study, several parameters are tested in two ways: (1) by using elimination parametrics, where the influence of each selected parameter is recorded for a minimum and a maximum value; and (2) by calculating the coefficient of influence for each parameter. The results indicate the parameters which are expected to have a large

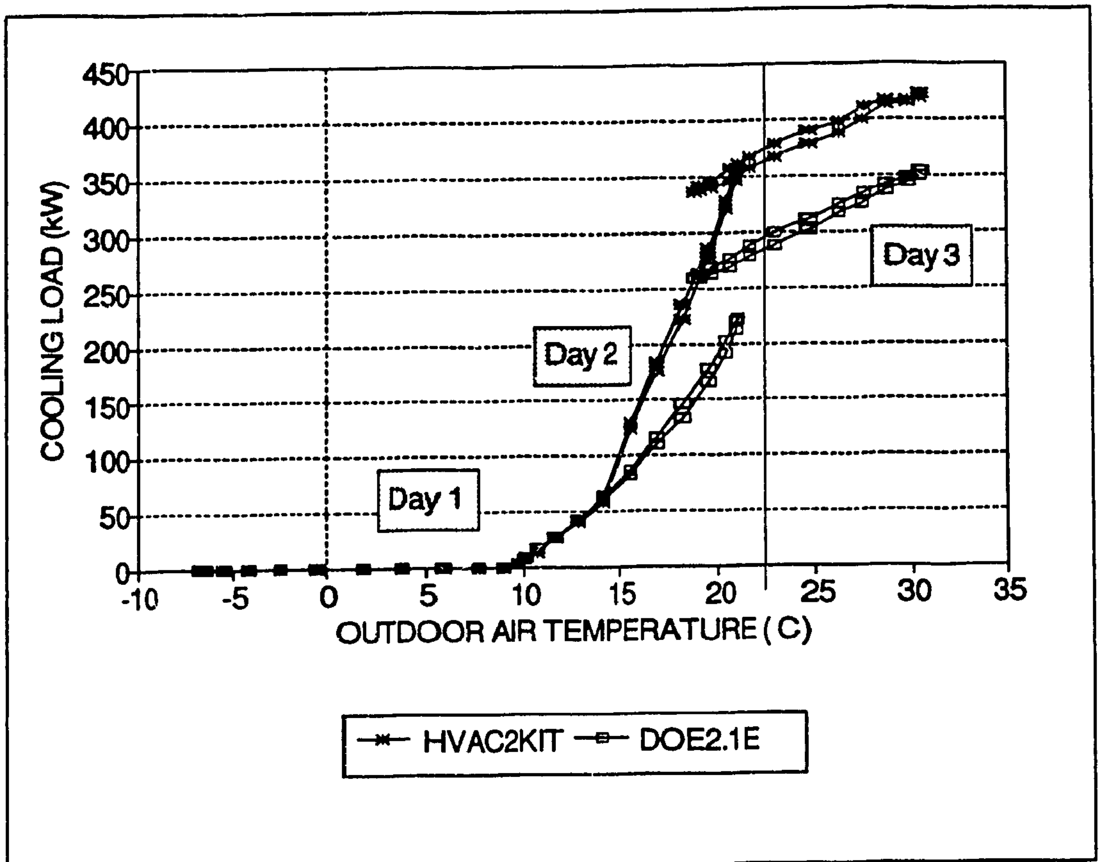

Figure 4.25 The total cooling coil load as a function of the dry-bulb temperature of outdoor air when an enthalpy economizer is modelled

influence on the simulation output, as well as the sensitivity which could be expected for certain parameters. Once these sensitivities are known, the parameters which are most sensitive can be determined and more effort can be placed on ensuring the accuracy of these input values. Also, these sensitive parameters can be modified during calibration of a model in order to achieve the target energy performance. Furthermore, the sensitivities of the input parameters can be used to determine anomalies in the program results, and in this capacity, this technique is included as part of the validation methodology.

4.3 1 Elimination parametrics

In the elimination parametric study, 29 parameters related to different areas of the building model are studied (Table 4.4). The effect of these parameters is then completely removed from the simulation, or in some cases, fully introduced in the model. The parameters are divided into five specific sections: envelope, internal gains, indoor environmental conditions, secondary systems, and central plant. This diversity is adopted in order to ensure a sampling of parameters used in several algorithms in the simulation software.

Table 4.4 lists the results of simulations in terms of percent difference in energy cost and consumption compared to the base case. Some parameters, such as the relative humidity which is defined by the values for the maximum and minimum relative humidity, and also the setpoint temperatures, which are defined by the cooling and heating setpoint temperatures, are assigned simultaneously high and low values for the maximum and minimum variables, respectively, in order to simulate the absence of a control mechanism. Other parameters, such as the percentage of heat generated by the lighting fixture which is related to the space, or the percent of outdoor air in the total air supply, are simulated first with a 0.0% value and then with a 100.0% value, in order to define the extremes of the parameter sensitivity.

Figures 4.26 and 4.27 display the percent difference in annual energy consumption and cost resulting from the elimination of some parameters related to the external building envelope. In the DOE program, when only the U-value of the walls is defined, the program does not consider the thermal storage effects related to the wall construction. These effects are only considered when the user defines the complete wall construction. Consequently, when the U-value of the wall is set to zero (U-WALL), the annual energy consumption and cost increase due to the absence of the thermal storage effects. However, when the resistance of the wall is increased by using several layers of insulation (R-WALL), the program accounts for the thermal storage of the structure, and the consumption and cost both decrease by 2.4 and 1.5%, respectively.

Table 4.4 Parameters used in elimination parametric study

Parameter	Description	Baseline value	Value	Cons. (%)	Cost (%)
ENVELOPE					
U-WIN	U-value of windows	3.63 $W/m^2 \cdot °C$	0.0006 $W/m^2 \cdot °C$	-8.6	-2.45
U-WALL	U-value of walls (no thermal storage)	--	0.0 $W/m^2 \cdot °C$	10.07	2.70
R-WALL	R-value of walls (with thermal storage)	0.3 $m^2 \cdot °C/W$	22.9 $m^2 \cdot °C/W$	-2.44	-1.50
WIN-AR	Window area	1603.3 m^2	0 m^2	-13.23	-10.57
SC-0	Shading coefficient	0.38	0	2.48	-1.95
SC-1	Shading coefficient	0.38	1	0.86	3.18
INF	Infiltration	0.3 ach (offices), 0.25 ach (ground floor)	0 ach	-2.51	-1.22
INTERNAL GAINS					
LIT	Lighting power density	14.0 W/m^2	0 W/m^2	-2.07	-13.11
EQU	Equipment power density	7.0 W/m^2	0 W/m^2	-8.80	-8.75
FW-0	Floor weight	73.2 kg/m^2	0 kg/m^2	-2.19	-3.41
FW-MAX	Floor weight	73.2 kg/m^2	976.5 kg/m^2	-1.73	-3.06
HW-LOSS	Service hot water system heat loss	10%	0%	-1.02	-0.54
LT-SP-0	Percent lighting load to the space	47%	0%	-0.06	-0.20
LT-SP-1	Percent lighting load to the space	47%	100%	0.23	0.10
HW-SIZE	Size of service hot water system	0.193 L/s	0 L/s	-6.83	-5.74
INDOOR ENVIRONMENTAL CONDITIONS					
RH	Relative humidity	minRH=20, maxRH=60	minRH=0, maxRH=80	-1.55	-1.59
OA-MIN	Minimum outdoor air ratio	5%	0%	-1.51	-2.01
OA-MAX	Minimum outdoor air ratio	5%	100%	31.65	28.14
TC-TH	Heating and cooling setpoints	Tc=22.8°C, Th=20.0°C	Tc=37.8°C, Th=-17.8°C	-14.74	-14.67

SECONDARY SYSTEMS					
ECON	Economizer control	temperature economizer	none, with fixed outdoor air of 5%	0.97	1.70
DELTA-T	Temperature increase in ventilation ducts	SUPPLY-DELTA-T=4, RETURN-DELTA-T=4	SUPPLY-DELTA-T=0, RETURN-DELTA-T=0	-0.65	-2.20
FANS	Size of supply, return and exhaust fans	1.96 W/L/s	0 W/L/s	4.78	4.89
CFM-0	Minimum air flow rate to zone	0.2	0.0	-0.51	0.83
CFM-1	Minimum air flow rate to zone	0.2	1.0	90.52	48.05
SUP-T	Control of supply air temperature	outdoor air reset	no reset schedule	1.09	0.46
FAN-PERF	Fan performance curve	default curve	consumption is 0 for a flow rate of 0	-5.96	-4.73
CENTRAL PLANT					
CH-PLR	Chiller part-load ratio curve	default curve	consumption is not a function oı part-load ratio	0.96	1.17
CH-EIR	Chiller electric-input-ratio	0.366	0.0	-5.95	-11.19
COND-PWR	Condenser power ratio	0.0438	0.0	-0.90	-1.67

The figures also show that by removing the windows and doors as in NO-WIN, the largest decrease in cost and consumption is obtained for the envelope parameters. The consumption increases when the shading coefficient is both 0 and 1, as simulated in SC-0 and SC-1. The simulation INF where the infiltration is eliminated, shows a decrease in consumption and cost of only 2.5 and 1.2%, respectively. This low sensitivity is due to the low infiltration rate in the base case as well as the absence of infiltration when the system was on.

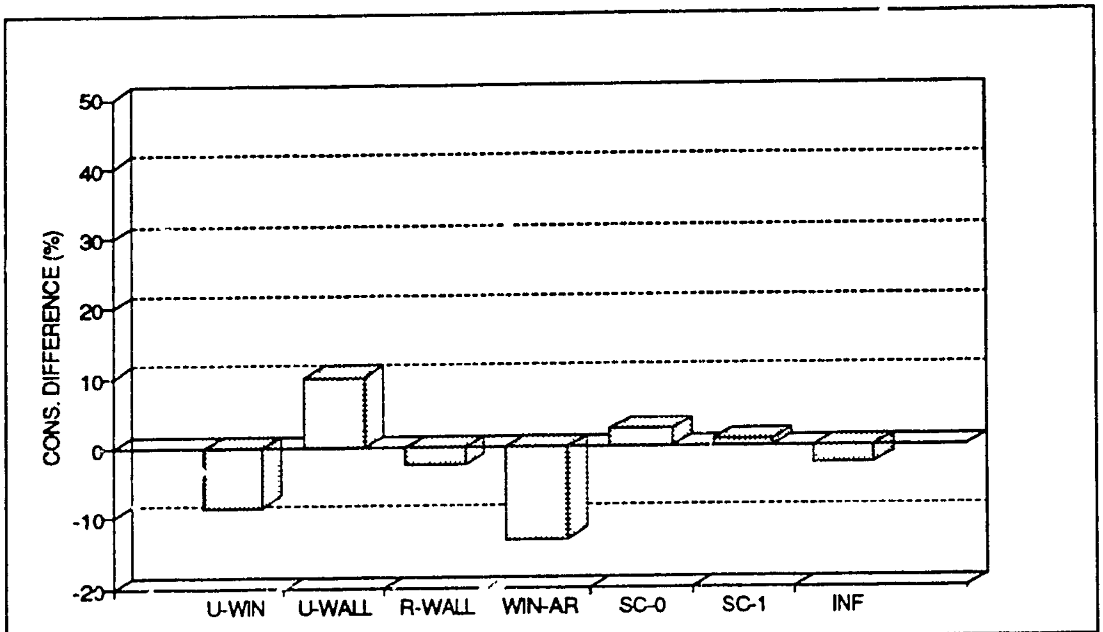

Figure 4.26 Effect of elimination of some parameters related to the exterior building envelope on the annual energy consumption

Figures 4.28 and 4.29 represent the percent increase or decrease in annual energy consumption and cost, respectively, for the elimination of some parameters related to internal gains. As shown, the elimination of lights and equipment, LIT and EQU, both result in a significant decrease in cost and consumption. There is almost no difference in results when the floor-weight is set to 0 and 976.5 kg/m², FW-0 and FW-MAX. However, the results of the simulation with FLOOR-WEIGHT=0 are questionable, since this parameter is related to the weighting factor calculations in the program. By eliminating the floor-weight, the program cannot accurately estimate the weighting factors.

The amount of heat from the lights released into the space has almost no effect on cost

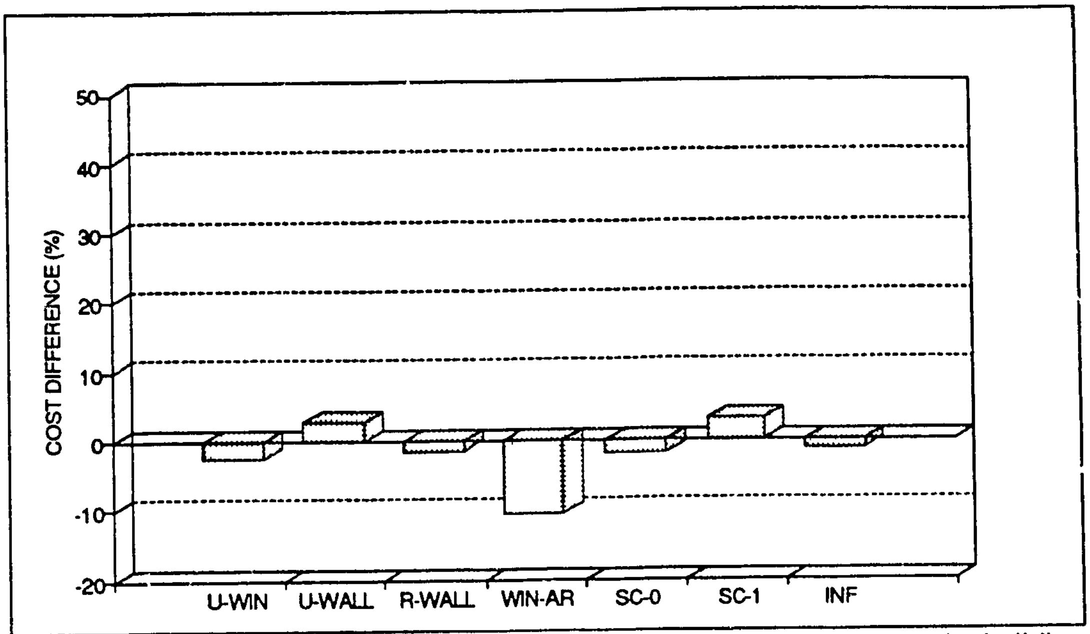

Figure 4.27 Effect of elimination of some parameters related to the exterior building envelope on the annual energy cost

or consumption as seen in the results for LT-SP-0 and LT-SP-1. The extreme cases tested show that regardless of the value assigned, the cost and consumption would vary by less than 1%. The elimination of hot water use, simulated in HW-SIZE, results in a 6.8% decrease in consumption and 5.7% decrease in cost. This is consistent with the energy distribution previously reported for the base case which showed that the hot water made up 6.8% of the annual energy consumption.

The consumption and cost variations resulting from the simulations of the parameters associated with indoor environmental conditions are represented in Figures 4.30 and 4.31. As expected, the most severe difference in consumption and cost is realized in OA-MAX, where the minimum percent outdoor air is set to 100%, with increases of 31.7% in consumption and 28.1% in cost. The TC-TH simulation presents the absence of cooling and heating controls by setting the cooling setpoint to 37.8°C and the heating setpoint to -17.8°C. This case results in a 14.7% decrease in both consumption and cost. This value seems low, considering that the heating and cooling systems account for 24.5% of the annual energy, excluding the energy used for ventilation fans (Figure 3.13)

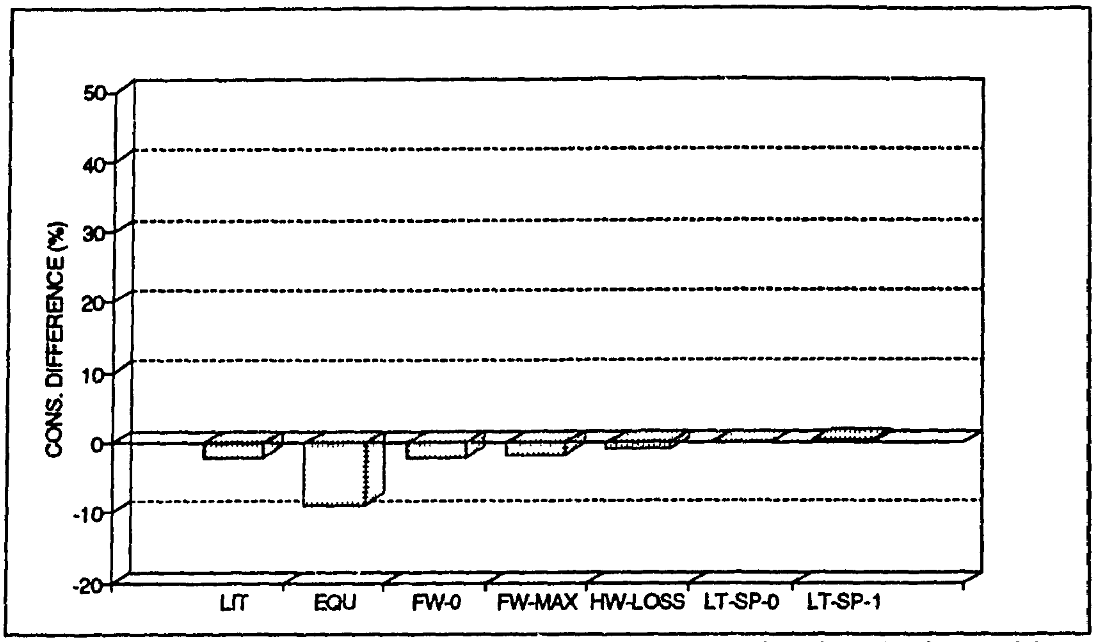

Figure 4.28 Effect of elimination of some parameters related to the internal heat gains on the annual energy consumption

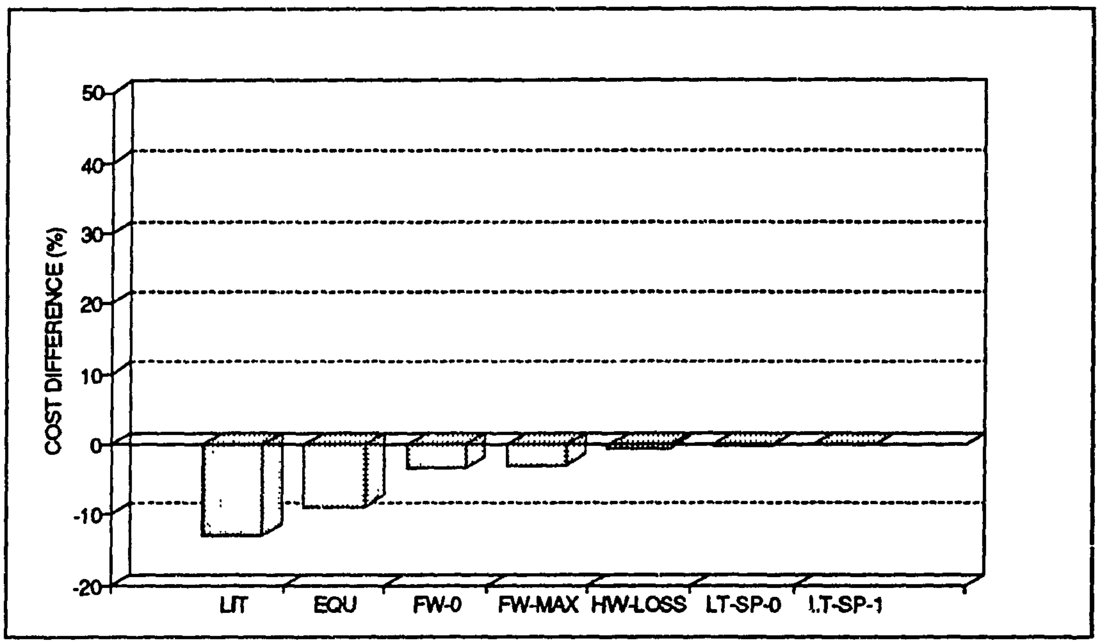

Figure 4.29 Effect of elimination of some parameters related to the internal heat gains on the annual energy cost

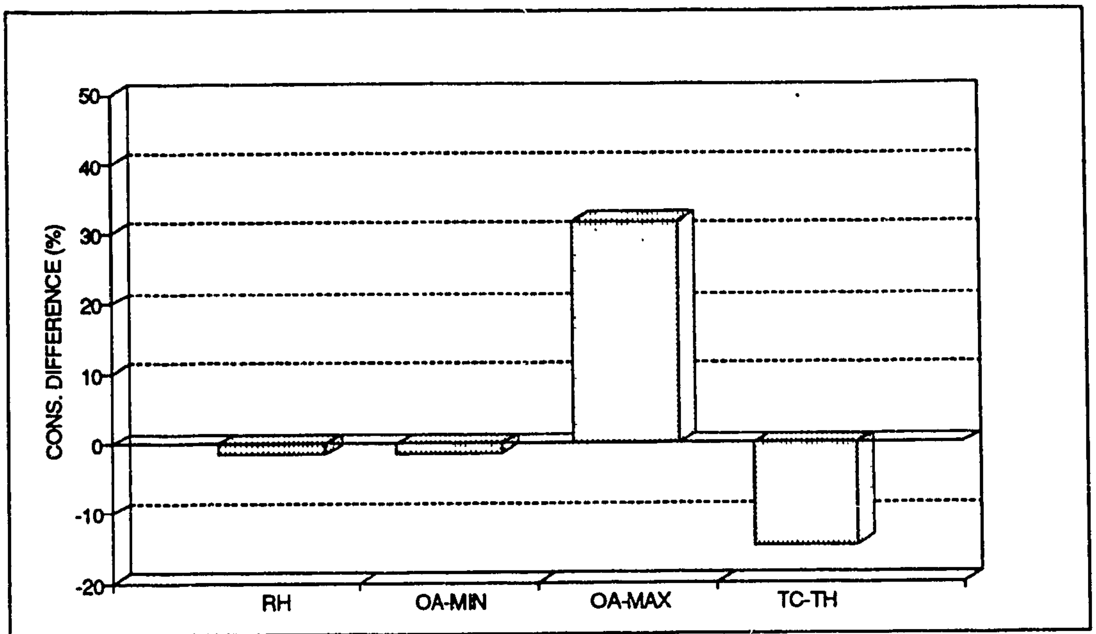

Figure 4.30 Effect of elimination of some parameters associated with indoor environmental conditions on the annual energy consumption

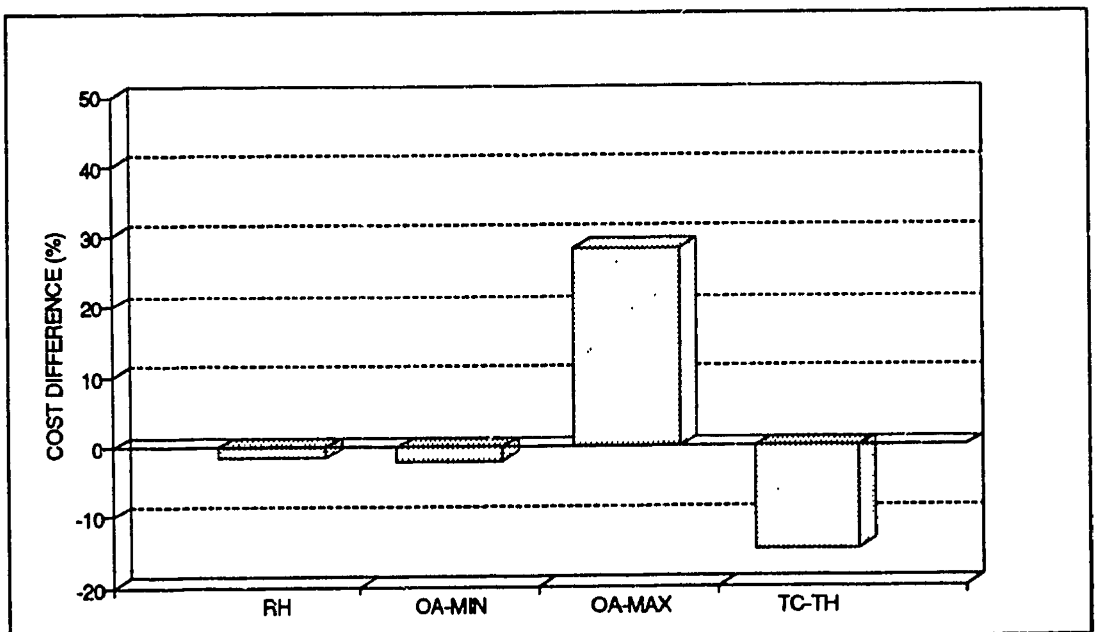

Figure 4.31 Effect of elimination of some parameters associated with indoor environmental conditions on the annual energy cost

Figures 4.32 and 4.33 show the percent change in consumption and cost, respectively, which results from the simulation of the elimination parametric study related to the secondary systems. Surprisingly, the elimination of the fans (FANS) causes an increase in consumption and cost of almost 5%. Although this could indicate an error in the program, the increase in consumption is probably attributed to the way the central plant handles the cooling load in the absence of ventilation fans. The analysis of the coefficients of influence, presented in the following section, will give a better indication if an error is present. When the minimum air flow rate to the zones is set to 1.0 in CFM-1, the consumption and cost increase drastically (90%, 48%), as expected. When the fan curve is modified so that the power input is 0 W at a supply air flow rate of 0 L/s, the consumption decreases by 6% and cost by almost 5%. Since the fan performance curves are usually unavailable for the actual equipment, the default curves are often specified for the simulations. This sensitivity reveals the importance of ensuring the accuracy of these default curves.

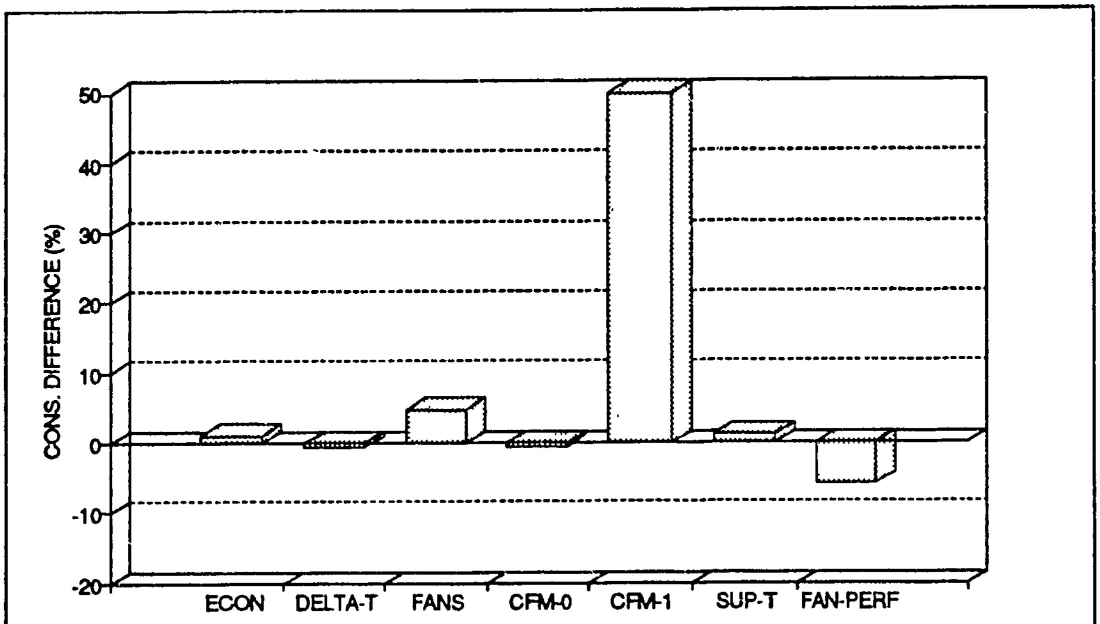

Figure 4.32 Effect of elimination of some parameters associated with the secondary systems on the annual energy consumption

The effect of eliminating certain parameters related to the central plant are represented in Figures 4.34 and 4.35. In CH-PLR, the part-load ratio performance curve for the chiller is modified so that the chillers run at the same efficiency, regardless of the part-load ratio.

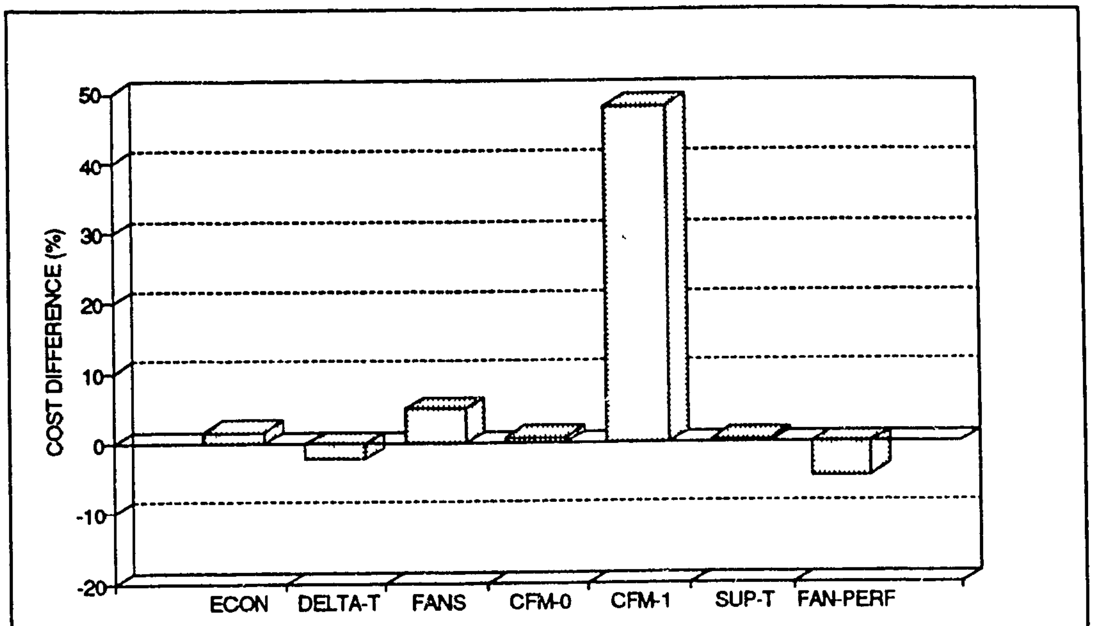

Figure 4.33 Effect of elimination of some parameters associated with the secondary systems on the annual energy cost

However, the part-load ratio of the chiller is not considered, therefore, each of the eight chillers run at full capacity when they are turned on. This results in a small increase in consumption and cost of approximately 1.0%. CH-EIR simulates a chiller with an electric input ratio of 0. In essence, this chiller would need no energy input in order to meet the required refrigeration effect. This results in a consumption decrease of 6.0% and a cost decrease of 11.2%. Although Figure 3.13 shows 7.1% of annual energy is used for space cooling, this value includes the two unitary systems. Therefore, the 6.0% decrease in consumption is reasonable.

The largest effects on the consumption and cost occur when the minimum flow rate to the space is set to 100% and when the minimum outdoor air is set to 100%. Aside from these extreme cases, the results showed significant changes in consumption and cost for several simulations. The simulations which provide a percent difference in consumption larger than 5.0% are, in decreasing order: TC-TH, NO-WIN, U-WALL, EQU, U-WIN, HW-SIZE, FAN-PERF, and CH-EIR. The simulations which provide a 5% or greater difference in cost are, in decreasing order: TC-TH, LIT, CH-EIR, NO-WIN, EQU, and HW-SIZE. However, no specific trend can be seen as to which category is most sensitive.

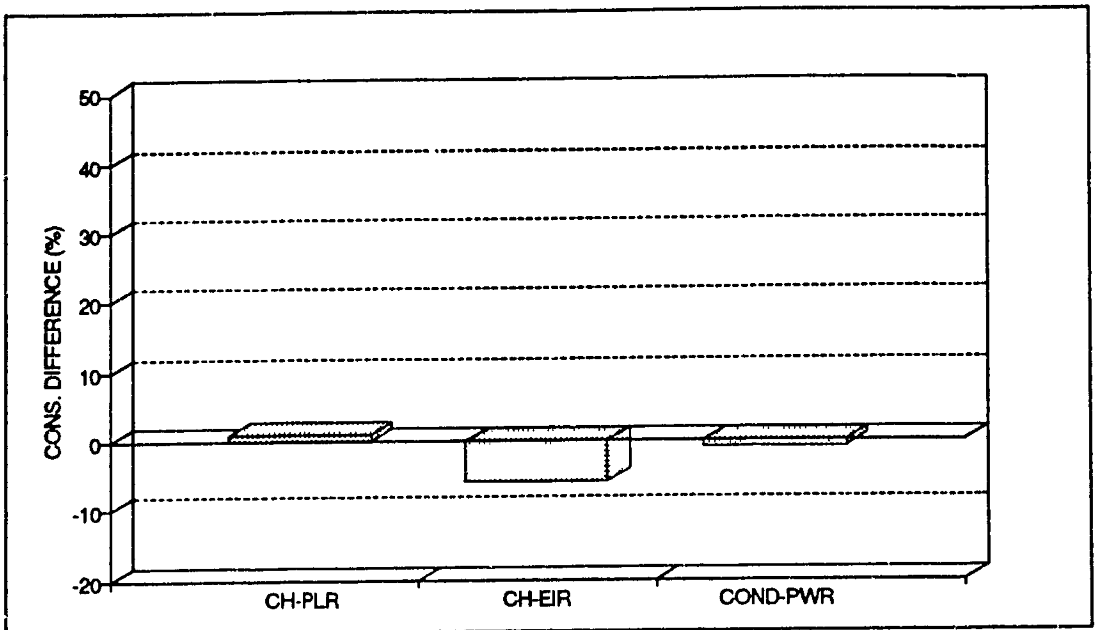

Figure 4.34 Effect of elimination of some parameters associated with the central plant on the annual energy consumption

The increase in cost and consumption when the ventilation fans are removed and when the chiller part-load ratio performance curve is modified is surprising at first glance. In addition, the decrease in cost and consumption is lower than expected when the temperature controls are set to the minimum for heating and the maximum for cooling. These discrepancies are all associated to the HVAC system and controls, which enforces the premise that this area of the simulation software might require further validation.

4.3.2 Coefficients of influence

In this approach, the values of the input variables from the list previously described are modified with positive and negative increments. The increments are chosen arbitrarily as a percentage of the original value. An attempt is made to maintain consistency by using 30% for most parameters; however, when the value of the parameter is small, a 50% increment is used. For the parameters related to temperatures, an increment of ± 1.1°C is used. The values of the input parameters are increased, such as U-WIN+, or decreased, such as U-WIN-. The simulation names are similar to those in Table 4.4

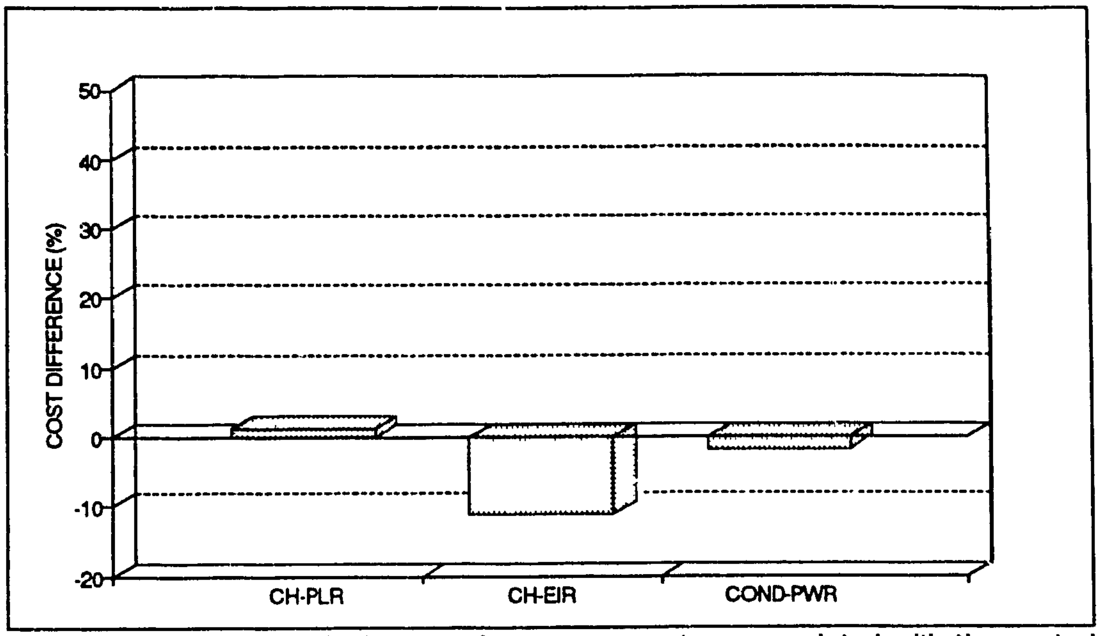

Figure 4.35 Effect of elimination of some parameters associated with the central plant on the annual energy cost

where each modified parameter is described. The results of these simulations are tabulated in terms of: (1) difference in energy consumption or cost per unit change of a parameter (coefficient COEFF-1); (2) percent change in consumption or cost per unit change of a parameter (COEFF-2); and, (3) percent change in consumption or cost per percent change in parameter value, multiplied by 100 (COEFF-3). These results show the sensitivity of each parameter in response to an incremental change in input value (Tables 4.5 and 4.6).

Table 4.5 Coefficients of influence of the energy consumption

Parameter	Cons. difference (kWh) [1]	Cons. difference (%)	Parameter increase/ decrease	Parameter unit	Parameter difference (%) [2]	Coeff 1 kWh / unit	Coeff 2 % / unit	Coeff 3 % / %
ENVELOPE								
U-WIN+	95 073	4.22	1.09	W/m²·°C	30.0	87 222.9	3.87	14.08
U-WIN-	-105 917	-4.71	-1.09		-30.0	97 171.6	4.32	15.69
U-WALL+	-18 441	-0.82	-1.00	W/m²·°C	30.0	18 441.0	0.82	-2.73
U-WALL-	32 867	1.46	1.00		-30.0	32 867.0	1.46	-4.87
WIN-AR+	115 544	5.13	4.81	100 m² window area	30.0	24 021.6	1.07	17.11
WIN-AR-	-116 679	-5.18	-4.81		-30.0	24 257.6	1.08	17.28
SC+	-3 808	-0.17	1.14	0.1 change in shading coefficient	30.0	-3 340.4	-0.15	-0.56
SC-	7 276	0.32	-1.14		-30.0	-6 382.5	-0.26	-1.08
INF+	26 130	1.16	1.41	0.1 change in air changes per hour	30.0	18 584.6	0.83	3.87
INF-	-26 759	-1.19	-1.41		-30.0	19 032.0	0.85	3.96
INTERNAL GAINS								
LIT+	189 796	8.43	4.20	W/m² lighting power density	30.0	45 189.5	2.01	28.11
LIT-	-159 004	-7.07	-4.20		-30.0	37 858.1	1.68	23.55
EQU+	67 176	2.98	2.10	W/m² equipment power density	30.0	31 988.6	1.42	9.95
EQU-	-63 616	-2.83	-2.10		-30.0	30 293.3	1.35	9.42
FW+	-10 925	-0.49	24.4	kg/m²	33.3	-447.7	-0.02	-1.47
FW-	7 615	0.34	-24.4		-33.3	-312.1	-0.01	-1.03
HW-LOSS+	6 206	0.28	3.0	change in % hot water heat loss	30.0	2 068.7	0.09	0.92
HW-LOSS-	-6 616	-0.29	-3.0		-30.0	2 205.3	0.10	0.98
LT-SP+	703	0.03	1.43	0.1 change in light-to-space ratio	30.0	491.6	0.02	0.101
LT-SP-	-275	-0.01	-1.43		-30.0	192.3	0.01	0.04

INDOOR ENVIRONMENTAL CONDITIONS								
RH-MAX+	-430	-0.02	10.0	change in % max. relative humidity	16.7	-43.0	-0.0	-0.11
RH-MAX-	2 613	0.12	-10.0		-16.7	-261.3	-0.01	-0.70
RH-MIN+	77 549	3.45	10.0	change in % min. relative humidity	50.0	7 754.9	0.34	6.89
RH-MIN-	-30 087	-1.34	-10.0		-50.0	3 008.7	0.13	2.67
OA-MIN+	10 678	0.47	1.7	change in % min. outdoor air	30.0	6 281.2	0.28	1.58
OA-MIN-	-9 271	-0.41	-1.7		-30.0	5 453.5	0.24	1.37
TC+	-31 904	-1.42	1.1	°C change in cooling setpoint	2.74	-29 003.6	-1.29	-51.74
TC-	42 310	1.88	-1.1		-2.74	-19 231.8	-1.71	-68.62
TH+	82 063	3.65	1.1	°C change in heating setpoint	2.94	74 602.7	3.32	124.03
TH-	-58 526	-2.60	-1.1		-2.94	53 205.5	2.36	88.46
SECONDARY SYSTEMS								
DELTA-T+	26 609	1.18	1.1	°C change supply, return delta-T	50.0	24 190.0	1.07	2.36
DELTA-T-	-13 830	-0.61	-1.1		-50.0	12 572.7	0.55	1.23
FANS+	90 945	4.04	5.87	0.1 W/L/s	30.0	15 493.2	0.69	13.47
FANS-	-90 946	-4.04	-5.87		-30.0	15 493.2	0.69	13.47
CFM+	33 046	1.47	10.0	% change in air flow rate to zone	50.0	3 304.6	0.15	2.94
CFM-	-12 251	-0.54	-10.0		-50.0	-1 225.1	-0.05	1.09
SUP-HI+	-8 468	-0.38	1.1	°C change in reset SUPPLY-HI	3.28	-7 698.2	-0.35	-11.47
SUP-HI-	8 409	0.37	-1.1		-3.28	-7 644.5	-0.34	-11.39
SUP-LO+	-9 575	-0.43	1.1	°C change in reset SUPPLY-LO	3.64	-8 704.5	-0.39	-11.69
SUP-LO-	9 700	0.43	-1.1		-3.64	-8 818.2	-0.39	-11.84
CENTRAL PLANT								
CH-EIR+	40 176	1.79	1.10	0.1 change in chiller EIR	30.0	36 590.2	1.63	5.95
CH-EIR-	-40 176	-1.79	-1.10		-30.0	36 590.2	1.63	5.95
COND-PWR+	6 075	0.27	1.31	0.01 change in cond. power ratio	30.0	4 623.3	0.21	0.90
COND-PWR-	-6 074	-0.27	-1.31		-30.0	4 622.5	0.21	0.90

[1] Consumption difference with respect to the base model

[2] Parameter increase/decrease divided by the initial value, expressed as a percent

Table 4.6 Coefficients of influence of the energy cost

Parameter	Cost difference (\$) [1]	Cost difference (%)	Parameter increase/ decrease	Parameter unit	Parameter difference (%) [2]	Coeff 1 \$/unit	Coeff 2 % / unit	Coeff 3 % / %
ENVELOPE								
U-WIN+	3 855	2.54	1.09	$W/m^2 \cdot {}^\circ C$	30.0	3 536.7	2.33	8.47
U-WIN-	-4 688	-3.09	-1.09		-30.0	4 300.9	2.83	10.29
U-WALL+	-799	-0.53	-1.00	$W/m^2 \cdot {}^\circ C$	30.0	799.0	0.53	-1.75
U-WALL-	1 691	1.11	1.00		-30.0	1 691.0	1.11	-3.71
WIN-AR+	6 071	4.00	4.81	100 m^2 window area	30.0	1 262.2	0.83	13.33
WIN-AR-	-6 177	-4.07	-4.81		-30.0	1 284.2	0.85	13.56
SC+	904	0.60	1.14	0.1 change in shading coeff.	30.0	793.0	0.52	1.99
SC-	-1 430	-0.94	-1.14		-30.0	1 254.4	0.83	3.14
INF+	869	0.57	1.41	0.1 change air changes/hour	30.0	618.1	0.41	1.91
INF-	-887	-0.58	-1.41		-30.0	630.9	0.42	1.95
INTERNAL GAINS								
LIT+	11 319	7.46	4.20	W/m^2 lighting power density	30.0	2 695.0	1.78	24.86
LIT-	-10 640	-7.01	-4.20		-30.0	2 533.3	1.67	23.37
EQU+	4 020	2.65	2.10	W/m^2 equip. power density	30.0	1 914.3	1.26	8.83
EQU-	-4 206	-2.77	-2.10		-30.0	2 002.9	1.32	9.24
FW+	-693	-0.46	24.4	kg/m^2	33.3	-28.4	-0.02	-1.38
FW-	391	0.26	-24.4		-33.3	-16.0	-0.01	-0.78
HW-LOSS+	237	0.16	3.0	change in hot water heat loss	30.0	79.0	0.05	0.52
HW-LOSS-	-258	-0.17	-3.0		-30.0	86.0	0.06	0.57
LT-SP+	18	0.01	1.43	0.1 in light-to-space ratio	30.0	12.6	0.01	0.04
LT-SP-	-130	-0.09	-1.43		-30.0	90.9	0.06	0.29

INDOOR ENVIRONMENTAL CONDITIONS								
RH-MAX+	21	0.01	10.0	change % max	16.7	2.1	0.00	0.08
RH-MAX-	307	0.20	-10.0	relative hum.	-16.7	-30.7	-0.02	-1.21
RH-MIN+	4 949	3.26	10.0	change % min	50.0	494.9	0.33	6.52
RH-MIN-	-1 961	-1.29	-10.0	relative hum.	-50.0	196.1	0.13	2.58
OA-MIN+	1 140	0.75	1.7	change in %	30.0	670.6	0.44	2.50
OA-MIN-	-986	-0.65	-1.7	min. out. air	-30.0	580.0	0.38	2.17
TC+	-1 677	-1.10	1.1	°C change in	2.74	-1 524.5	-1.00	-40.32
TC-	1 650	1.09	-1.1	cool. setpoint	-2.74	-1 500.0	-0.99	-39.67
TH+	2 738	1.80	1.1	°C change in	2.94	2 489.1	1.64	61.35
TH-	-1 115	-0.73	-1.1	heat. setpoint	-2.94	1 013.6	0.66	24.98
SECONDARY SYSTEMS								
DELTA-T+	1 973	1.30	1.1	°C change in supply and	50.0	1 793.6	1.18	2.60
DELTA-T-	-1 932	-1.27	-1.1	return delta-T	-50.0	1 756.4	1.15	2.55
FANS+	6 352	4.18	5.87	0.1 W/L/s	30.0	1 082.1	0.71	13.95
FANS-	-6 352	-4.18	-5.87		-30.0	1 082.1	0.71	13.95
CFM+	307	0.20	10.0	% in flow rate to	50.0	30.7	0.02	0.40
CFM-	1100	0.72	-10.0	zone	-50.0	-110.0	-0.07	-1.45
SUP-HI+	-118	-0.08	1.1	°C in reset	3.28	-107.3	-0.07	-2.37
SUP-HI-	99	0.07	-1.1	SUPPLY-HI	-3.28	-90.0	-0.06	-1.99
SUP-LO+	-1 401	-0.92	1.1	°C in reset	3.64	-1 273.6	-0.84	-25.36
SUP-LO-	666	0.44	-1.1	SUPPLY-LO	-3.64	-605.5	-0.40	-12.05
CENTRAL PLANT								
CH-EIR+	5 383	3.55	1.10	0.1 change in	30.0	4 902.6	3.23	11.82
CH-EIR-	-5 379	-3.54	-1.10	chiller EIR	-30.0	4 898.9	3.23	11.81
COND-PWR+	761	0.50	1.31	0.01 in cond.	30.0	579.1	0.38	1.67
COND-PWR-	-760	-0.50	-1.31	power ratio	-30.0	578.4	0.38	1.67

[1] Cost difference with respect to the base model

[2] Parameter increase/decrease divided by the initial value, expressed as a percent

The results are relatively consistent for the sensitivity of both energy consumption and cost. When the coefficient COEFF-3 is considered, a high sensitivity, that is, a coefficient greater than 10, is noticed in the following parameters: U-WIN (U-value of windows), WIN-AR (percent window area), LIT (lighting power density), TC-TH (heating and cooling setpoints), FANS (size of the supply, return and exhaust fans) and SUP-T (the supply air temperature). This indicates that for each 1% increase in parameter input value, there is, at minimum, a 0.1% increase in cost or consumption. Similar to the elimination parametric study, no trend is found as to which specific section is more sensitive, since the parameters displaying a high sensitivity are found in various categories: envelope, internal gains, indoor environmental conditions and secondary systems.

The most sensitive parameter is TC-TH, which relates to the heating and cooling setpoints of the HVAC system. This parameter has a COEFF-3 between -52 and 124 for consumption, and between -40 and 61 for cost. This indicates that a 1% increase in heating setpoint temperature would lead to a 1.2% increase in consumption and a 0.6% increase in cost. The evaluation of COEFF-2 shows that a 0.56°C increase in heating setpoint leads to a 3.3% increase in consumption and a 1.6% increase in cost. Since the heating setpoint temperature for the building modelled is controlled by individual thermostats. the actual value for this parameter is uncertain. In order to ensure the accuracy of the simulation results, a large emphasis must be placed on the estimation of this value.

The lighting power density also has a high coefficient of influence COEFF-3, approximately 24 to 28 for cost and consumption which indicates that a 1% increase/decrease in lighting power density leads to 0.24 - 0.28% increase/decrease in energy consumption and cost. The results in Tables 4.5 and 4.6 also indicate that for an increase of 4.2 W/m^2 (or 30%) of lighting power density, the consumption increases by 8.4% and the cost by 7.5%. Similar results are obtained for a decrease in lighting power density. These results would dictate that the accuracy of this input value is essential in obtaining a properly simulated model.

Two parameters, PAR-12 (service hot water system heat loss) and PAR-13 (percent lighting load to the space), show very little sensitivity, that is, the values for COEFF-3 are less than 1 for both an increase and decrease in parameter value.

In a similar sensitivity analysis of DOE-2.1D by Griffiths and Anderson for commercial buildings [57], the input variables which are found to be the most sensitive for an office building are, in descending order: minimum air flow to each zone, heating setpoint temperature, equipment capacity, operating hours per week, lighting capacity, lighting schedule, window U-value, glass shading coefficient and economizer control. Similarly, the heating setpoint temperature, the lighting capacity and the window U-value are also found in this analysis to be highly sensitive. The sensitivity of the equipment capacity is in the medium range but not as high as the lighting capacity. On the other hand, the glass shading coefficient and economizer control are relatively insensitive, in contradiction with the findings of Griffiths and Anderson. The window area is the only other parameter which is relatively sensitive in this analysis whereas the DOE-2.1D study rates it as relatively insensitive, probably due to the large glazing area of the building used in this study.

The results for the simulations where the fan power is modified (FANS+ and FANS-) show an equal increase and decrease in consumption and cost for a given increase and decrease in fan power. Furthermore, the coefficients calculated for these two simulations are within reasonable limits. This tends to suggest that the unexpected increase in consumption and cost resulting from the elimination of the fan power, as was presented in the previous section, is not due to an error in the program.

4.4 Simulations using simple models

In order to aid in identifying a programming or algorithm error, a simple building model is simulated, and then, parameter by parameter, the model's complexity is increased to finally arrive at the simulation of the actual building.

4.4.1 Model simulations

The simple model consists of a building without: (1) heat gains or losses through its exterior envelope (ie. a very high thermal resistance, no windows or doors, no infiltration), (2) internal heat gains (occupancy, lighting, equipment), (3) any air handling systems, or (4) domestic hot water system. Thermal storage effects are also neglected by specifying an overall U-value for the wall of 0 W/m²·°C without specifying the wall construction. When the HVAC system is introduced in the model, the simplest configuration includes: a cooling setpoint of 37.8°C; a heating setpoint of 10°C; and no reset of supply air temperature, economizer control, outdoor air or exhaust. It must be emphasized that each time a new variable is introduced in the model, the previous model is retained; in other words, the modifications to the model are incremental.

The simulations are grouped into three sections depending on the operation of the HVAC system:

1. The simple model is first simulated with the HVAC system on 24 hours/day, however, unrealistic air temperatures are obtained and, consequently, the systems are turned off for the next five runs. This first group of simulations concerns the modification of the building envelope.

2. In the following six simulations, the HVAC system is left on 24 hours/day with a heating setpoint of 10°C and a cooling setpoint of 37.8°C. These simulations concern the impact of internal heat gains and infiltration.

3. In the third group of simulations, beginning with T-SETPT, the actual setpoint temperatures for heating and cooling are introduced, and the impact of the modifications on the HVAC systems is evaluated.

4. The actual HVAC schedule is introduced in this group and the effect of the domestic hot water and the miscellaneous equipment defined in the PLANT-ASSIGNMENT section of the DOE-2.1E input file is evaluated.

These simulations are described as follows:

Group 1:

1. SIMPLE-ON: simple model as previously described, HVAC system on;
2. SIMPLE-OFF: simple model as previously described, HVAC system off;
3. WINDOW: with windows using a shading coefficient of zero to eliminate the solar heat gains through windows;
4. SHADING: using a shading coefficient of 0.38;
5. LAYERS: walls defined using a wall construction with a very high R-value, to take into consideration the thermal storage effect in the exterior envelope;
6. WALL: with the actual wall construction;

Group 2:

7. HVAC-24: HVAC system on 24hours/day;
8. OCC-100: 100% of the maximum occupancy is in the building 24hours/day;
9. LGT-100: 100% of the maximum lighting capacity operates 24hours/day;
10. EQ-100: 100% of the maximum equipment capacity operates 24hours/day;
11. OC-LT-EQ: actual schedules for occupancy, lighting, and equipment;
12. INFIL-1: infiltration rate one air change per hour 24hours/day;

Group 3:

13. T-SETPT: cooling and heating setpoints set to actual values;
14. INF-ACT: actual infiltration rates;
15. WARMEST: cooling supply air temperature is controlled by warmest zone;
16. RESET: cooling supply air temperature is set to the actual reset schedule in terms of outdoor temperature;
17. ECON-TEMP: dry-bulb temperature economizer used by all systems;
18. MIN-OA-ACT: actual values for minimum outdoor air percentage;
19. ECON-ENTH: enthalpy economizer used by all systems;
20. ECON-ACT: actual economizers in all systems (main system uses a temperature economizer, the restaurant unit uses an enthalpy economizer, the bank unit uses no economizer);

Group 4:

21. HVAC-ACT: actual HVAC schedule;
22. DHW-100: 100% of maximum domestic hot water load 24hours/day;
23. DHW-ACT: actual schedule of the domestic hot water usage;
24. MISC-100: 100% of maximum miscellaneous equipment capacity 24hours/day;
25. MISC-ACT: actual schedule of miscellaneous equipment usage.

4.4.2 Definition of design-day weather data

The simulations are performed using two user-defined design-day conditions to represent winter and summer conditions, rather than hourly weather files. To develop the hourly profile, the program requires the day's high and low dry-bulb temperatures and dewpoint temperatures as well as the time they occur. From this data, the hourly dry-bulb and wet-bulb temperatures are defined following a sine curve. The high and low temperatures are obtained from actual 1987 weather data for January and July. The summer dewpoint highs and lows are obtained from the psychrometric chart and their time of occurrence is defined using the actual weather file data. However, the winter dewpoints cannot be located on the psychrometric chart due to their low values; therefore, they are calculated using the following formula [36] :

$$T_d = 6.09 + 12.608\alpha + 0.4959\alpha^2 \quad (4.11)$$

where

$$\alpha = \ln(p_w) \quad (4.12)$$

where

$$p_w = \Phi * p_{ws} \quad (4.13)$$

and T_d = dewpoint temperature, °C

Φ = relative humidity, assumed to be 0.9

p_{ws} = saturation vapour pressure, kPa [36]

An example of this calculation is shown here for the outdoor temperature of -17.4°C and an assumed relative humidity of 90%:

p_{ws} = 0.132318 kPa (at T = -17.4°C)

$p_w = 0.9 * 0.132318 = 0.119086$ kPa

$\alpha = \ln (0.119086) = -2.1279$

$T_d = 6.09 + 12.608 * (-2.1279) + 0.4959 * (-2.1279)^2$

$T_d = -18.5°C$

The hour of the high and low dewpoint temperatures for the winter design-day are assumed to occur at the same time as the dry-bulb high and low temperatures. The design-day data used for the winter and summer days are presented in Table 4.7.

Table 4.7 Design-day data used in simple model simulations

Parameter	Winter design-day	Summer design-day
maximum dry-bulb temperature	-17.4°C	33.3°C
minimum dry-bulb temperature	-25.8°C	22.9°C
time of maximum temperature	5:00 pm	4:00 pm
time of minimum temperature	8:00 am	6:00 am
maximum dewpoint temperature	-18.5°C	23.5°C
minimum dewpoint temperature	-26.7°C	20.7°C
time of maximum dewpoint temp.	5:00 pm	3:00 pm
time of minimum dewpoint temp.	8:00 am	11:00 pm
wind speed	0.51 m/s	0.51 m/s
wind direction	14 (North-West)	14 (North-West)
amount of cloud cover	5 (partly cloudy)	5 (partly cloudy)
clearness index	1.03*	1.03
ground temperature	7.2°C	12.8°C
type of cloud cover	1**	0

* This value is estimated and accounts for the clearness factor due to city pollution

** This value is given in the DOE user manual and accounts for the predominant cloud type during the winter or summer months

4.4.3 Simulation results

The analysis of the results is performed in a qualitative manner, to notice any unreasonable values or pattern of variation for a particular parameter. Table 4.8 lists the results obtained from the simulations in terms of the average room air temperature, average electrical demand for baseboards and total baseboard energy for the winter design-day, average cooling load and total cooling load of the central plant for the summer design-day.

Table 4.8 Results from the simple model simulations

Simulation	Average room air temp. Jan 12 (°C)	Average room air temp. July 13 (°C)	Average basebd. demand Jan 12 (kW)	Average cooling demand July 13 (kW)	Total Basebd. energy Jan 12 (kWh)	Total cooling load July 13 (kWh)	Notes
SIMPLE-ON	386.0	-4 523.9	0.0	0.0	0.0	0.0	Note 1
SIMPLE-OFF	22.4	22.4	0.0	0.0	0.0	0.0	
WINDOW	10.1	27.1	136.0	0.0	3 265.1	0.0	
SHADING	10.1	27.1	136.0	0.0	3 265.1	0.0	
LAYERS	10.1	26.4	140.2	0.0	3 365.3	0.0	
WALL	9.8	26.2	161.7	0.0	3 880.8	0.0	
HVAC-24	12.6	19.0	120.6	84.2	2 894.4	2 019.8	Note 2
OCC-100	13.7	20.9	94.5	121.5	2 267.5	2 917.2	
LGT-100	27.2	30.7	0.0	205.7	0.0	4 936.2	
EQ-100	39.2	33.8	0.0	231.5	0.0	5 556.0	
OC-LT-EQ	17.3	25.4	23.1	147.1	555.1	3 531.2	
INFIL-1	12.7	26.6	118.9	193.1	2 852.7	4 634.3	
T-SETPT	20.4	25.1	223.6	277.5	5 365.8	6 660.6	Note 3
INF-ACTUAL	25.6	23.9	78.1	198.9	1 873.9	4 773.5	
WARMEST	25.6	25.1	78.1	218.4	1 873.9	5 241.6	
RESET	25.6	24.3	78.1	198.9	1 873.9	4 773.5	
ECON-TEMP	22.6	24.3	167.4	203.3	4 016.8	4 879.9	
MIN-OA	22.2	24.7	172.2	283.4	4 133.8	6 801.0	
ECON-ENTH	22.2	24.7	172.2	282.4	4 133.8	6 777.5	
ECON-ACT	22.2	24.7	172.2	283.4	4 133.8	6 801.0	

NOTES:

1. The program cannot simulate a building with a HVAC system but with thermal load. The results show unrealistic temperatures; therefore, the HVAC system is turned off for the first five simulations. The heating is available to keep the space air temperature at a minimum of 10°C.

2. The HVAC system is turned on at this point, operating 24 hours/day; the cooling setpoint is defined as 37.8°C to allow for a large air temperature swing.

3. The actual HVAC setpoint temperatures are introduced at this point which means the room air temperature in January should be kept between 19.4°C and 20.6°C, and in July between 22.2°C and 23.3°C.

Several observations can be made related to the first group of simulations:

1. The room air temperatures of 22.4°C, predicted by the simple model (SIMPLE-OFF), is reasonable since the model has no heat gains or losses. As expected, the heating energy and cooling loads are zero.

2. When windows with a shading coefficient equal to zero are introduced in the model, the room air temperatures fluctuates as expected, that is decreasing in the winter and increasing in the summer, due to the reduction of overall thermal resistance of the envelope. The peak electric demand required by the baseboards to maintain a minimum temperature of 10°C is 136 kW and the daily energy consumption is 3265 kWh.

3. When the shading coefficient is increased to 0.38, that is, allowing solar radiation to get through (simulation SHADING), there is no effect on the room temperatures or on the heating or cooling loads. Since this lack of sensitivity was not apparent when actual weather data was used, further investigation revealed that there was no direct or diffuse solar radiation recorded on the windows when the design-day was defined, even on a clear day.

4. In the LAYERS simulation, the summer room air temperature decreases slightly due to the thermal mass of the building. The heating energy increases slightly since the

walls are less insulated than in the previous simulation where the wall U-value is set to 0 W/m²·°C.

The results from the second group of simulations, also shown in Table 4.8, lead to the following observations:

1. Due to the operation of HVAC systems supplying air at 13.9°C, the space air temperature in the summer is significantly reduced, and it increases in the winter while the heating energy decreases. The increase in room air temperature in the winter is surprising since no heat gains are introduced in the model. Further investigation revealed that the program automatically sets the supply air temperature at the required minimum supply temperature, even if the return air temperature is below this value and the system has no heating capabilities.

2. The impact of increasing the internal heat gains over 24 hours is as expected (OCC-100, LGT-100, EQU-100): an increase in room temperature, an increase in cooling energy use and a decrease in heating energy use. In addition, the predicted peak demand for lights and equipment, 145.7 and 52.2 kW respectively, are verified with hand calculations as shown in Table 4.9.

Table 4.9 Calculation of lighting and equipment peak demand

Zone	Lights (W/m²)	Equip. (W/m²)	Area (m²)	Total Lights (kW)	Total Equip.(kW)
FL-1-INT	31.0	7.0	587.1	18.2	4.1
FL-1-PER	31.0	7.0	410.3	12.7	2.9
FL-2-INT	15.5	5.4	2935.3	45.5	15.9
FL-2-PER	12.4	5.4	2051.3	25.4	11.1
FL-7-INT	23.3	5.4	587.1	13.7	3.2
FL-7-PER	23.3	5.4	410.3	9.6	2.2
LB	4.7	--	1248.1	5.9	--
VH	26.4	43.8	164.3	4.3	7.2
FD	26.4	19.4	299.1	7.9	5.8
GAR	1.5	--	1711.6	2.6	--
TOTAL				**145.7**	**52.3**

3. Where the values for the three internal heat gains are defined as the actual values from the building (OC-LT-EQ), the indoor air temperature and the cooling energy use decrease, while the heating energy use increases.

4. When the air infiltration is considered (INFIL-1), a decrease in January temperature as well as an increase in July temperature are observed. Furthermore, the baseboard energy use and cooling energy use both increase, as expected.

In the third group of simulations, the following observations are made:

1. When the actual heating and cooling temperature setpoints are defined (T-SETPT), the HVAC system is able to increase the room air temperature in January and decrease it in July, as requested. In addition, the heating and cooling energy use also increase accordingly.

2. When the actual infiltration levels are defined (INF-ACTUAL), the heating and cooling energy decrease.

3. In WARMEST and RESET, different supply temperature control strategies are used. As expected, the reset control requires slightly less cooling energy.

4. The simulation ECON-TEMP introduces a dry-bulb temperature economizer in the system, and the results are, at first view, unexpected: an increase in heating energy and cooling energy (with respect to the results of the RESET simulation), as well as a decrease in room air temperature in January. Upon analysis, it was found that in the previous simulation, the supply air temperature in the winter is approximately 26.7°C due to the lack of outdoor air in the system and since the cooling system is not available. Therefore, when the economizer is introduced, the dampers are opened to allow for the specified supply temperature of 12.8°C, which results in lower room temperatures and higher heating loads. Although the simulation results show that the dampers are opened when the outdoor temperature is less than the specified switchover temperature, the cooling load increases nonetheless, due to the high

humidity defined in the design-day data, a situation which cannot be avoided by a dry-bulb temperature economizer.

5. The specification of the minimum outdoor air (MIN-OA) shows slight changes in room air temperatures, and an increase in both cooling load and baseboard energy. Since the outdoor temperature does not decrease significantly overnight, the outdoor air is not able to efficiently cool the building.

6. As anticipated, the use of the enthalpy economizer (ECON-ENTH) shows a reduction in cooling load as compared to the previous simulation (MIN-OA) which has a dry-bulb temperature economizer.

4.4.4 Limitations and detected problems

Due to the program limitations, one cannot run the PLANT block under design-day conditions; a weather file must be introduced. Since the domestic hot water and miscellaneous equipment are associated with the PLANT-ASSIGNMENT, these can only be calculated if the weather file is introduced. Therefore, for the last group of simulations, the actual weather file is used instead of the design-day data. The results of these simulations are identical in terms of temperature, heating load and cooling load. In other words, the domestic hot water and the miscellaneous equipment have no effect on these results.

The humidity ratios predicted for some of the simulations are greater than the corresponding value at saturation conditions. Table 4.10 presents the humidity ratio in the return air of the central system for the design days in January for those simulations where the HVAC system is turned on.

The load on the cooling coil is calculated using equations 4.2 and 4.3 and then compared to the predicted values from the ECON-TEMP and RESET simulations. The entering and leaving temperatures are taken directly from the results of the DOE program for the July design-day at 5:00 am. However, due to the problem previously described with the humidity ratios, the humidity ratios provided by DOE for the supply air conditions are out of range for these two simulations; therefore, the humidity ratio at saturation obtained from the psychrometric chart for the given supply air temperature is used.

Table 4.10 Humidity ratio for the return air of the central system

Simulation	Humidity ratio January 12	Humidity ratio at saturation
HVAC-24	0.0018	0.0091
OCC-100	0.1847*	0.0098
LGT-100	0.1933*	0.0229
EQ-100	0.2011	0.7570
OC-LT-EQ	0.0709*	0.0125
INFIL-1	0.0022	0.0092
T-SETPT	0.0030	0.0151
INF-ACTUAL	0.0736*	0.0209
WARMEST	0.0736*	0.0209
RESET	0.0736*	0.0209
ECON-TEMP	0.0036	0.0173
MIN-OA	0.0033	0.0170
ECON-ENTH	0.0033	0.0170
ECON-ACT	0.0033	0.0170

* Values out of range

The load on the cooling coil is calculated using equations 4.2 and 4.3, before and after the economizer control is introduced in the simple model:

RESET:

T_1 = 23.5°C (mixed air temperature at 5:00 am from DOE program)
T_2 = 9.8°C (supply air temperature at 5:00 am from DOE program)
W_1 = 0.0094 kg/kg (mixed air humidity ratio at 5:00 am from DOE program)
W_2 = 0.0076 kg/kg (from psychrometric chart at 9.8°C and assumed 100% R.H.)

h_{w2} = 41.27 kJ/kg [36]

$\dot{m}$ (flow rate) = 7.6456 m^3/s (supply air flow rate from DOE program)

v (specific volume) = 0.852 m^3/kg (from psychrometric chart for entering air conditions)

$$h_1 = 1.006T_1 + W_1(2501 + 1.805T_1) = 47.6\ kJ/kg$$
$$h_2 = 1.006T_2 + W_2(2501 + 1.805T_2) = 29.0\ kJ/kg$$

$$\dot{m}_a = \frac{7.6456}{0.852} = 8.974\ kg/s$$

$$_1q_2 = \dot{m}_a[(h_1 - h_2) - (W_1 - W_2) * h_{w2}]$$
$$_1q_2 = 8.974\ [(47.6-29.0) - (0.0094 - 0.0076) * 41.27]$$
$$_1q_2 = 165.8\ kW$$

ECON-TEMP:

T_1 = 23.0°C (mixed air temperature at 5:00 am from DOE program)

T_2 = 9.8°C (supply air temperature at 5:00 am from DOE program)

W_1 = 0.0163 kg/kg (mixed air humidity ratio at 5:00 am from DOE program)

W_2 = 0.0076 kg/kg (from psychrometric chart at 9.8°C and assumed 100% relative humidity)

h_{w2} = 41.27 kJ/kg [36]

$\dot{m}$ (flow rate) = 7.6456 m^3 (supply air flow rate from DOE program)

v (specific volume) = 0.862 m^3/kg (from psychrometric chart for entering air conditions)

$$h_1 = 1.006T_1 + W_1(2501 + 1.805T_1) = 64.6\ kJ/kg$$
$$h_2 = 1.006T_2 + W_2(2501 + 1.805T_2) = 29.0\ kJ/kg$$

$$\dot{m}_a = \frac{7.6456}{0.862} = 8.870\ kg/s$$

$$_1q_2 = \dot{m}_a\ [(h_1 - h_2) - (W_1 - W_2) * h_{w2}]$$
$$_1q_2 = 8.870\ [(64.6-29.0) - (0.0163 - 0.0076) * 41.27]$$
$$_1q_2 = 312.4\ kW$$

The load on the cooling coil predicted by the RESET simulation, is equal to 133.5 kW, compared to 165.8 kW from the calculations, an underestimation of 19.5%. The ECON-

TEMP simulation predicts a cooling coil load of 160.9 kW, as compared to the 312.4 kW from the calculations, an underestimation of 48.5%. These results indicate a possible error in the simulation of the cooling load.

The qualitative evaluation presented with this simple model technique was successful in detecting some anomalies in the DOE program as well as provide reasonable results in the majority of the simulations. The unexpected results led to the discovery of errors in the program, such as the program setting the minimum supply air temperature even when the return air temperature is below this value and the HVAC system has no heating capabilities. In addition, an error was detected in the calculation of the air humidity ratio, and consequently, an error may exist in the simulation of the cooling load.

4.5 Conclusions

The validation procedure developed consists of an empirical validation and inter-model comparison in addition to some simple but extensive tests which can be applied to any energy simulation software in order to determine the accuracy of the results. In addition, the techniques developed do not require any expensive monitoring of buildings or test cells, and can therefore, be applied by any end-user. In this study of the MICRO-DOE 2.1E software, various program errors were discovered as well as some limitations:

-- a problem was detected in calculating the humidity ratio in the air

-- the latent cooling load was underestimated on hot humid days due to the problems related to the humidity ratio calculations

-- the supply air temperature was found to be set to the setpoint temperature even when the return air temperature was lower than the supply setpoint temperature and no heating was available

-- the shading coefficient was found to have a low sensitivity

-- the program was unable to simulate an empty building with a HVAC system but with no heat gains or losses

The problem detected with the cooling load calculation could explain the underestimation of the energy consumption during the summer months as compared to the measured utility data that was observed in Chapter 3. This would have had a large effect when the latent cooling load was relatively high, as on hot humid days.

During the validation procedure, an emphasis was placed on the simulation of the heating, ventilating and air-conditioning equipment since the verification of envelope heat transfer is more straight-forward and has been the subject of several research studies. The following techniques were used as part of the validation procedure:

- -- empirical validation
- -- inter-model comparison
- -- model response to a change in outdoor weather in terms of indoor temperature, heating energy, and cooling energy
- -- comparison of indoor temperature response with a mathematical model
- -- comparison of the model's time constant using two mathematical models
- -- analysis of specific program algorithms, such as economizer controls and cooling load, by comparison with results from a simple modelling tool
- -- elimination parametrics
- -- coefficients of influence
- -- modifications from a simple to a complex model

Together, these techniques provide a complete analysis of the simulation results and interpret their significance in modelling this particular building. It must be emphasized that not all HVAC systems were tested; therefore, it is possible that more errors are present in this program.

CHAPTER 5

DECISION MODELS UNDER UNCERTAINTY FOR THE EVALUATION OF ENERGY CONSERVATION MEASURES

The most practical aspect of energy simulation software is the ability to predict the savings resulting from the implementation of an energy conservation measure. Several measures have been simulated in order to select which are the most profitable. However, due to the large uncertainties involved in developing the input file of the base model (which must be representative of the existing building), the predicted savings may differ significantly from the actual savings realised after implementation. The theory of decision models under uncertainty is applied to this situation in order to determine the most profitable energy conservation measure, given possible errors in the estimated input variables.

5.1 Definition of the payoff matrix

A payoff matrix is developed using several design alternatives, the possible states of nature and the resulting outcomes, and shows the interaction between the various alternatives and possible future events [58]. The design alternatives are the various choices from which a decision is ultimately taken. The design alternatives are represented by the energy conservation measures under consideration, which were previously listed in Chapter 2. These alternatives include the nine individual ECMs, the four groups of ECMs, as well as the alternative of not implementing a measure.

By definition, the states of nature must be mutually exclusive, must cover all possible future events and cannot be controlled by the decision maker. The states of nature are represented by several possible accurate simulations of the building's energy consumption. The accurate simulations are independent since if one simulation is correct, then the others are incorrect. The states of nature in the matrix can cover an infinite number of possible accurate simulations since numerous input parameters have high uncertainty; however, for simplicity, the developed matrix focuses on the parameters which most significantly affect the output, as was presented in the sensitivity analysis from Chapter 4. The decision maker has no control over these states of nature since it is unknown which input file is correct. The states of nature considered are the following [59]:

A. The input data (Chapter 2) is accurate and assumed to have been measured in the building, that is there are no errors in the input file. All other states of nature assume that there are some errors in measuring the required data.
B. The real glass conductance is 50% higher than the value used for case A.
C. The real glass conductance is 50% lower.
D. The actual lighting power density is 30% higher than A.
E. The lighting power density is 30% lower.
F. The equipment power density is 30% higher than the value for case A.
G. The equipment power density is 30% lower.
H. The cooling setpoint temperature is 1.1°C higher.
I. The cooling setpoint temperature is 1 1°C lower.
J. The heating setpoint temperature is 1.1°C higher.
K. The heating setpoint temperature is 1.1°C lower.
L. The fan power is 20% higher.
M. The fan power is 20% lower.
N. The chiller electric input ratio (ie. 1/COP) is 15% higher.
O. The chiller electric input ratio is 15% lower.

The outcomes or payoffs of the matrix can be represented by several parameters such as the cost savings for each energy conservation measure or design alternative ($, %), savings of energy consumption (kWh, %), payback period (years), or the benefit-cost ratio. In order to demonstrate the applicability of this method, a payoff matrix (Table 5.1) is developed where the outcomes are the annual energy cost savings ($), and the various selection criteria are applied to it.

Table 5.1 The payoff matrix of annual cost savings ($) for each alternative under several possible futures

ALT.	ANNUAL COST SAVINGS ($) POSSIBLE FUTURES														
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
NO ECM	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ECM 1	-287	-9	-212	-3	-391	-176	-216	-390	7	-22	-336	-281	-291	-277	-295
ECM 2	-109	215	-49	106	-426	-19	-62	-276	159	93	-214	-104	-115	-99	-118
ECM 3	-6153	-4308	-5424	-5951	-5660	-6104	-6133	-5135	-6667	-7076	-3165	-6136	-6158	-6153	-6290
ECM 4	4178	4007	2819	3494	4062	3976	3874	3679	4343	4763	4674	4529	3817	4645	3708
ECM 5	2442	2511	2829	3085	1378	2281	2550	2492	2627	2478	2410	2471	2413	2511	2373
ECM 6	5524	5367	5898	6731	3223	5109	5409	5232	5383	5376	5680	5594	5455	5688	5361
ECM 7	256	229	348	199	-20	195	107	247	129	124	132	262	251	266	247
ECM 8	3164	1072	4261	3015	1488	2984	3106	3611	2600	2862	4515	3371	2957	3451	2877
ECM 9	1406	1310	1415	1097	1353	1421	810	1620	1306	1952	1837	1501	1312	1557	1256
ECM I	6649	6232	5751	3945	5838	6450	6616	6468	6719	6964	7186	7022	6278	7176	6123
ECM II	689	195	2514	829	-881	621	129	657	-12	-986	3521	998	440	13[illegible]7	-1
ECM III	5847	5386	8132	5092	1870	6302	5019	5083	6519	4630	8538	6264	5490	6871	4824
ECM IV	10359	7643	12168	9250	6215	10794	9540	9717	10651	10039	11631	10775	9944	11215	9408

5.2 Analysis of the payoff matrix

Five evaluation criteria are used to analyze the various alternatives: Laplace criterion, maximin and maximax criteria, Hurwicz rule and minimax regret criterion. Through the use of these evaluation methods, the most profitable alternative is selected, regardless of the errors made in the simulation input file. The individual energy conservation measures (ECMs) and the groups of measures are evaluated separately so that a decision is made for each category.

Before the five evaluation criteria are applied to the matrix, several alternatives are eliminated through the principle of dominance; when the outcomes for the alternative I are dominated by those of another alternative II for every possible future, then the first alternative can be eliminated. Once the principle of dominance is applied to the payoff matrix for the individual and groups of ECMs separately, only ECMs 4 and 6 remain among the individual measures and only ECM IV remains among the groups of measures. Although this particular case is reduced to a very simplistic matrix, the alternatives are evaluated nonetheless, using the five criteria, in order to demonstrate a general approach for the selection of an alternative.

5.2.1 Laplace criterion

The Laplace criterion is based on the theory of insufficient reason, consequently, each possible future is given an equal probability of occurrence. To evaluate the alternatives using this criterion, the average payoff, or in this case the average annual cost savings, is calculated for each design alternative, and the alternative with the highest average payoff is selected. The results show alternative ECM IV as the best alternative with a value of $9 956.60 and ECM 6 among the individual measures with a value of $5 402.00, while ECM 4 averages only $4 037.87.

5.2.2 Maximin criterion

The maximin criterion is based on a very pessimistic view of the future. It is assumed that the state of nature with the smallest outcome will result for each alternative. Therefore, the smallest outcome is determined for each alternative, and from these, the alternative with the highest payoff is selected. The results show group ECM IV is the highest overall with a value of $6 215.00, and ECM 6 is higher than ECM 4, with a value of $3 223.00 over a value of $2 819.00 for ECM 4.

5.2.3 Maximax criterion

Opposite to the principle of the maximin criterion, the maximax criterion is based on an extremely optimistic view of future events. It is assumed that the future will produce the highest outcome for each alternative, and the alternative with the maximum outcome is selected. The results show ECM 6 will yield a higher cost savings than ECM 4 with values of $6 731.00 over $4 763.00, while ECM IV results in the largest savings overall with a value of $12 168.00.

5.2.4 Hurwicz criterion

In light of the extreme nature of the maximin and maximax criteria, the Hurwicz criteria allows for a compromise between these two extremes. The decision-maker can evaluate an index of optimism (α) to represent any level of optimism between a value of 0, which represents the most pessimistic view, and 1, which represents the most optimistic view. The following equation is used to select the best alternative for any value of α between 0 and 1 [58]:

$$\textit{best alternative} = \max_i(\alpha[\max_i P_{ij}] + (1-\alpha)[\min_i P_{ij}]) \quad (5.1)$$

where: P_{ij} is the payoff for the i^{th} alternative and the j^{th} possible future.

A graph can be drawn showing the payoff for any value of α between 0 and 1, thereby clearly identifying the best alternative for various situations. In a general case, different alternatives may be the best choice for different values of the index of optimism, α. Figure 5.1 shows that alternative 2 would be preferred if the decision maker is more pessimistic (ie. $\alpha < \alpha_{CR}$) and the alternative 1 would be preferred if the decision maker is more optimistic (ie. $\alpha > \alpha_{CR}$). In the present case, however, the choice is simple since ECM 6 shows a larger payoff than ECM 4, irrespective of α, and ECM IV shows a higher payoff than ECM 6.

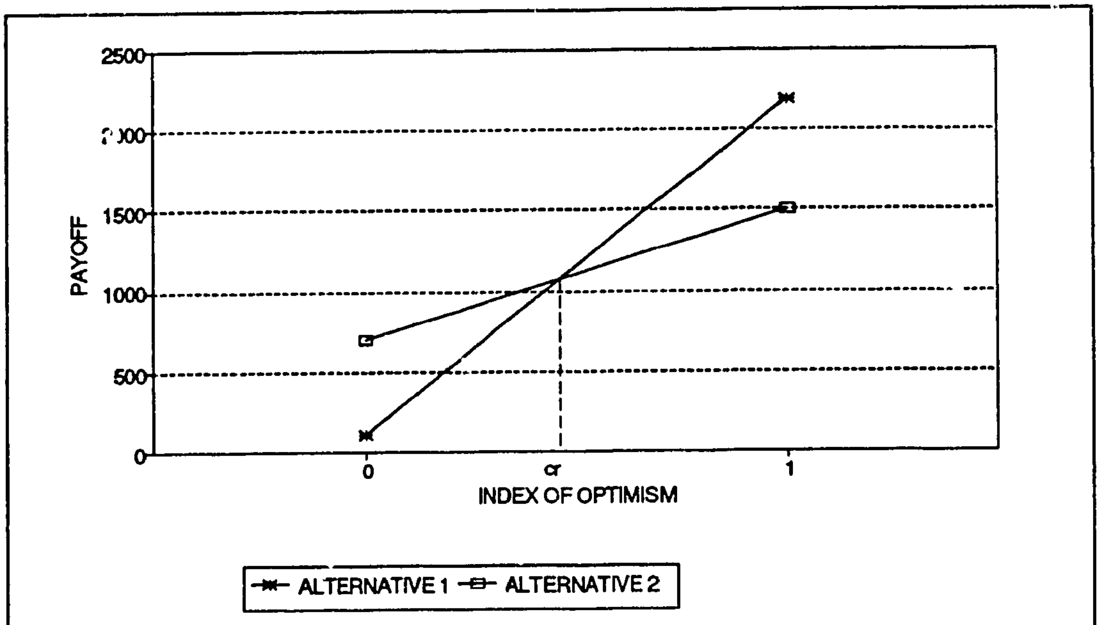

Figure 5.1 Application of Hurwicz criterion in a general case

Figure 5.2 presents the minimum and maximum cost savings for each alternative, which also corresponds to the most pessimistic and optimistic views of the possible futures. The largest range of cost savings occurs for ECM III and ECM IV, which indicates that they are very sensitive to the quality of the input data. Consequently, some inaccurate input data could lead to large errors in the estimate of cost savings, even though, for this case, this sensitivity would not change the decision in the selection of ECMs.

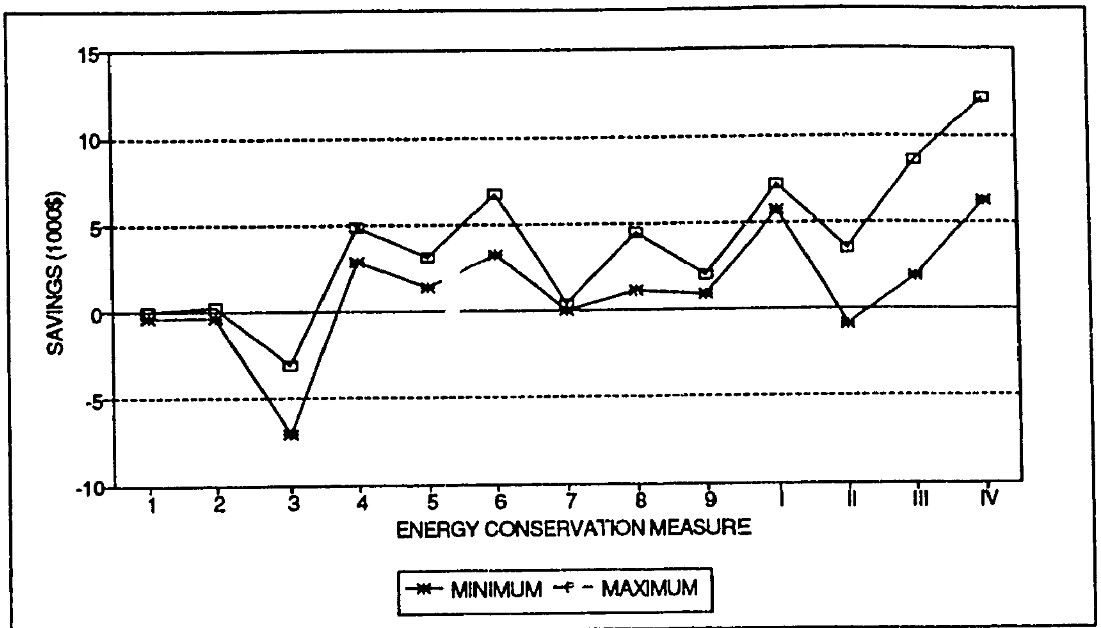

Figure 5.2 Range of savings for each alternative

5.2.5 Minimax regret criterion

The principle of the minimax regret criterion is to minimize the regret which would result from choosing an alternative which does not result in the maximum payoff. This is accomplished by first developing a regret matrix (Table 5.2), completed by calculating the difference between the maximum payoff which could have been obtained for a given future and the payoff for the alternative chosen. The maximum regret which could occur for any possible future is determined for each alternative, and the minimum among these is selected. The regret values for each alternative are calculated as the difference between the overall maximum payoff (ie. ECM IV) and the payoff for a particular alternative (ie. ECMs 4 and 6) for each state of nature. From the regret matrix, it is found that ECM 6 is a better choice over ECM 4, with a maximum regret of $6 270.00 over $9 349.00.

Table 5.2 Regret matrix

ANNUAL COST SAVINGS ($)															
ALT.	POSSIBLE FUTURES														
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
ECM 4	6181	3636	9349	5756	2153	6818	5666	6038	6308	5276	6957	6246	6127	6570	5700
ECM 6	4835	2276	6270	2519	2992	5685	4131	4485	5268	4663	5951	5181	4489	5527	4047

5.3 Payoff matrix for payback period and benefit-cost ratio

In order to accurately predict the cost benefit of an energy conservation measure, the cost of implementation must be taken into consideration. As previously discussed in Chapter 2, several indices can be calculated to present the benefits over time of an initial investment. For this particular case, two indices are chosen: 1) the payback period, which represents the number of years needed to recover the initial cost through the annual energy savings, and 2) the benefit-cost ratio, which takes into account inflation and interest over the amortization period (equations 2.1 and 2.2).

As mentioned previously, the usual threshold for the payback period is approximately three years; whereas, the benefit-cost ratio must be greater than one in order to be acceptable. When the payoff matrix is defined for the payoffs represented by the payback period and another by the benefit-cost ratio, similar trends are observed. ECMs 1, 2, 3, and II are eliminated due to dominance since they show a very long or negative payback period and a very small benefit-cost ratio. In addition, since measures ECM 4, 5, 6, 7, and group ECM I, do not require any initial investment they are recommended. The payoff matrices for the remaining alternatives, ECM 8, 9, III, and IV, are presented in Tables 5.3 and 5.4 for the payoffs represented as payback period and benefit-cost ratio, respectively. Among the individual alternatives, ECM 8 shows better results than ECM 9; however, ECM IV dominates over all alternatives, which leads to the obvious conclusion that it is the best alternative.

Table 5.3 Payback period payoff matrix

PAYBACK PERIOD (YRS)															
ALT.	POSSIBLE FUTURES														
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
ECM 8	1.7	4.9	1.2	1.7	3.5	1.8	1.7	1.5	2.0	1.8	1.2	1.6	1.8	1.5	1.8
ECM 9	3.9	4.2	3.9	5.0	4.1	3.9	6.8	3.4	4.2	2.8	3.0	3.7	4.2	3.5	4.4
ECM III	1.8	2.0	1.3	2.1	5.7	1.7	2.1	2.1	1.6	2.3	1.3	1.7	2.0	1.6	2.2
ECM IV	1.0	1.4	0.9	1.2	1.7	1.0	1.1	1.1	1.0	1.1	0.9	1.0	1.1	1.0	1.1

Table 5.4 Benefit-cost ratio payoff matrix

BENEFIT-COST RATIO															
ALT.	POSSIBLE FUTURES														
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
ECM 8	1.4	0.5	1.9	1.3	0.7	1.3	1.4	1.6	1.2	1.3	2.0	1.5	1.3	1.5	1.3
ECM 9	0.6	0.6	0.6	0.5	0.6	0.6	0.3	0.7	0.6	0.8	0.8	0.6	0.6	0.7	0.5
ECM III	1.3	1.2	1.8	1.1	0.4	1.4	1.1	1.1	1.4	1.0	1.9	1.4	1.2	1.5	1.1
ECM IV	2.3	1.7	2.7	2.0	1.4	2.4	2.1	2.1	2.3	2.2	2.5	2.4	2.2	2.4	2.1

5.4 Conclusions

A payoff matrix was used in order to determine the most profitable energy conservation measure, given several possible correct input files for the energy simulation program. Although for this case the solution is simplistic, the proposed method of selection could be extended to consider other possible errors and a larger or more complex variety of energy conservation measures. This method of decision making under uncertainty can ensure that the most beneficial alternative will be recommended regardless of the input file.

CHAPTER 6
CONCLUSIONS AND RECOMMENDATIONS

The research presented focused on the validation of simulation software used to predict the energy performance of buildings. The need for a validation procedure which could be applied to energy simulation software was defined and the outcome of the study was presented.

6.1 General conclusions

The review of past research in the field of energy simulation software validation revealed a need for a systematic approach to this problem. The validation techniques recently developed by such groups as the Solar Energy Research Institute, the Building Research Establishment, and the Commission of European Communities PASSYS team have shown great downfalls in terms of ease of applicability as well as efficiency. The focus has been on validating the software by researchers rather than techniques which could be applied by the consultants to test the results themselves. Furthermore, there has been a lack of research on commercial buildings due to the complexity involved in modelling HVAC systems.

The research project stemmed from a study of the BESA-Design software which revealed the need for a systematic approach to the validation process. Consequently, a procedure was designed which integrates two well-known validation techniques, namely the empirical validation using measured utility data and the inter-model comparison, with other techniques focusing on particular aspects of the program. In the first part, the program's ability to estimate the energy consumption of an existing commercial building was determined, as well as its ability to predict the cost savings associated with various energy conservation measures. This study showed some discrepancies; however, the presence of program errors, or the nature of such errors, could not be concluded without further investigation.

The second part consisted of several small tests and analyses which, together, ensured an overall validation of the simulation results. The first technique involved a group of tests which evaluated the model's response to an instantaneous change in outdoor temperature, in terms of indoor temperature and heating and cooling loads. An increase and decrease in outdoor temperature were simulated, and the effect of these were analyzed. The simulated indoor temperature response was compared to the predictions from a mathematical model for one perimeter zone as well as for an entire floor. The time constant of the building was also calculated using the simulation results, the mathematical model, and a simplified analytical method. The results showed some discrepancies, particularly in the slow initial response seen in the simulation results which was attributed to thermal storage effects.

Specific program algorithms, such as the economizer control and the calculation of the cooling load, were compared to the predictions from a HVAC modelling toolkit developed by ASHRAE. The modelling tool consists of short subroutines which perform simplified calculations for secondary HVAC systems. The hourly values from the simulation were used as input for the toolkit program and the results were compared. The economizer controls, including the dry-bulb temperature and the enthalpy economizers, were found to be modelled in the same manner for both cases. A program error was detected in the calculation of the air humidity ratio which exceeded the saturation point. Most importantly, the effect of the humidity ratio error on the latent cooling load was found to be significant on hot and humid days.

A sensitivity analysis was also performed which was divided in two sections: (1) elimination parametrics, where certain parameters were given input values which, in essence, eliminated the parameter from the simulation; and (2) coefficients of influence, where the value of the parameter was varied with a positive and negative increment and the effect on the results was shown in terms of various indices. This test identified which parameters had the greatest influence on the simulated energy consumption and cost results: the U-value of the windows; the percent window area; the lighting power density; the heating and cooling setpoints; the size of supply, return and exhaust fans; and the supply air temperature. Once the sensitivity of certain parameters is determined, extra attention can be given to estimating these values for the input file in order to ensure accurate results.

The last test consisted of simulating a simplified model of the building with no windows, no internal gains or electrical loads, no infiltration, and no HVAC system. This model was simulated with user-defined design-day weather data in order to regulate the outdoor conditions. The model's complexity was increased incrementally, parameter by parameter, to identify any anomalies in the model's response. In this manner, the detection of the source of the problem was facilitated. The results of this test showed the inability of the software to simulate a building with no heat losses but having an operational HVAC system. Furthermore, an error was found which sets the temperature supply air to the minimum temperature specified by the user even when the return air temperature is lower than the supply air temperature setpoint and no heating is available.

One of the greatest advantages of energy simulation software is in performing detailed energy analyses for recommending energy conservation measures. However, due to the uncertainty involved in estimating the values of the required input parameters, the predicted savings may not be realised once these measures are implemented. In order to prevent this occurrence, a payoff matrix model was used to determine the most profitable alternative given the possibility of several correct input files. The matrix was evaluated using various criteria, so that a final recommendation could be made.

In summary, this procedure was able to detect not only the presence of programming errors but also the nature of such errors. The program as a whole was tested in addition to specific algorithms, in order to detect general programming errors that could occur during the transferring of data, for example. A systematic approach, which could be adopted by any user, was developed to evaluate the simulation results. With this knowledge, the user can better understand the significance of the results and be more cautious in recommending certain energy conservation measures.

6.2 Contributions

Due to the great potential for building energy simulation software to be used for detailed energy analyses, particularly in light of the proposed energy code, a procedure was developed for the validation of these programs. The study discussed made an attempt to facilitate the verification and validation procedure for energy consultants and designers who are using building energy simulation software. The contributions presented in this work are summarized as follows.

Empirical validations of two building energy simulation programs

The energy simulation programs BESA-Design, MICRO-DOE 2.1D, and MICRO-DOE 2.1E were subjected to an empirical validation using a large commercial building. Through this conventional validation technique, some program limitations and discrepancies were discovered.

Inter-model comparison of two building energy simulation programs

The output from the programs was compared in order to identify any disagreements between the results. This validation technique, often used in validating new software, proved to be insufficient in identifying any program errors.

Development of a systematic approach to software validation

A procedure was developed which does not necessitate any large expenses or time commitments, and can therefore be used by energy consultants as well as designers, in order to determine the accuracy of their simulations. Several tests and analytical verifications were defined, through which program errors can be detected.

Use of this approach to validate MICRO-DOE 2.1E

The developed procedure was used to validate a recently updated version of a widely accepted energy simulation software. The validation identified several errors present in the software and particularly focused on the validation of the heating, ventilating and air-conditioning equipment.

Use of decision models under uncertainty to evaluate energy conservation measures

A payoff matrix was used to evaluate the most profitable energy conservation measure given several possible futures as to the correct input file. The model can be used to ensure the accuracy of the predicted cost savings even though several input variables in the simulated model may be associated with high uncertainties.

6.3 Recommendations for further research

Although a methodology has been developed and applied, there are still numerous areas of this field which need to be considered. Some of these are described as follows.

Development of an evaluation spreadsheet

The tests which were described in the validation methodology can be incorporated into a spreadsheet which would allow the user to introduce the simulation results and the calculations would be performed automatically. Graphs could be set up in the spreadsheet to facilitate the analysis. Diagnostic comments could also be included to inform the user of possible program errors.

Testing of other HVAC algorithms in DOE-2.1E

The methodology developed was only applied to two types of HVAC systems, namely a central variable-air-volume system and a rooftop constant-volume system. Other equipment such as heat pumps, water-cooled condensers, dual-duct systems and various control mechanisms have not been tested. In order to ensure the applicability of the MICRO-DOE2.1E software under any conditions, these must also be verified.

REFERENCES

1. R. D. Judkoff, "Validation of Building Energy Analysis Simulation Programs at the Solar Energy Research Institute", Energy and Buildings, Vol. 10, 1988, pp. 221-239.

2. D. Wortman, B. O'Doherty, and R. Judkoff, "The Implementation of an Analytical Verification Technique on Three Building Energy Analysis Codes: SUNCAT 2.4, DOE 2.1, and DEROB III", Proceedings of the Solar Engineering Conference, Reno, Nevada, April 27 - May 1 1981, pp. 268-276.

3. R. D. Judkoff, "International Energy Agency Building Simulation Comparison and Validation Study", Building Energy Simulation Conference, Seattle, 1985, pp. 264-272.

4. E. Allen, D. Bloomfield, N. Bowman, K. Lomas, J. Allen, J. Whittle, and A. Irving, "Analytical and Empirical Validation of Dynamic Thermal Building Models", Building Energy Simulation Conference, Seattle, 1985, pp. 274-280.

5. A. D. Irving, "Validation of Dynamic Thermal Models", Energy and Buildings, Vol. 10, 1988, pp. 213-220.

6. D. P. Bloomfield, "Evaluation Procedures for Building Thermal Simulation Programs", Proceedings of the Building Simulation Conference, 1989, pp. 217-222.

7. S. Ostergaard Jensen and R. van de Perre, "Tools for Whole Model Validation of Building Simulation Programs - Experience from the CEC Concerted Action PASSYS", Proceedings of the Building Simulation Conference, 1991, pp. 547-552.

8. S. Ostergaard Jensen, "Empirical Whole Model Validation - Case Study: the PASSYS Reference Wall", Proceedings of the Third International Conference of the International

Building Performance Simulation Association, Adelaide, Australia, August 16-18 1993, pp.335-341.

9. Q. T. Ahmad and S. V. Szokalay, "Thermal design tools in Australia - a comparative study of TEMPER, CHEETAH, ARCHIPAK, and QUICK", Proceedings of the Third International Conference of the International Building Performance Simulation Association, Adelaide, Australia, August 16-18 1993, pp.351-357.

10. P. A. Strachan, "Procedures for Scaling and Replication by Simulation", Proceedings of the Third International Conference of the International Building Performance Simulation Association, Adelaide, Australia, August 16-18 1993, pp.343-349.

11. N. Ramdani and Y. Candau, "Empirical Model Validation of Dynamic Buildings Energy Simulation Models Using Linear Analysis Tools", CISS - First Joint Conference of International Simulation Societies Proceedings, Zurich, Switzerland, August 22-25 1994.

12. P. Strachan and J. A. Clarke, "Towards an Interactive Model Validation Facility", Proceedings of the Building Simulation Conference, 1991, pp. 563-569.

13. J. P. Waltz, "Practical Experience in Achieving High Levels of Accuracy in Energy Simulations of Existing Buildings", ASHRAE Transactions, 1992, Part 1, pp.606-617.

14. D. P. Bloomfield, K. J. Lomas, and C. J. Martin, "Assessing programs which predict the thermal performance of buildings", BRE Information Paper, Building Research Establishment, 1992.

15. A. Gadgil, D. Goldstein, R. Kammerud, and J. Mass, "Residential Building Simulation Model Comparison Using Several Building Energy Analysis Programs", The 5th National Passive Solar Conference, University of Massachusetts, October 19 - 26, 1980, pp. 187-190.

16. J. G. F. Littler, "Comparison of Passive Solar Design Methods", Proceedings of the 2nd International Passive and Low Energy Architecture Conference, Crete, Greece, June 28 - July 1, 1983, pp. 597-602.

17. W. L. Carroll, "Annual Heating and Cooling Requirements and Design Day Performance for a Residential Model in Six Climates: A Comparison of NBSLD, BLAST-2, and DOE-2.1", ASHRAE / DOE, ORNL Conference, Florida, December 1989, pp. 697-721.

18. G. K. Yuill and C. P. Wray, "An Approach to the Verification of Simple Building Energy Analysis Computer Programs", ASHRAE Transactions, 1987, Part 1, pp. 417-433.

19. M. Zaheer-Uddin, D. Seth, and P. Fazio, "Inter-model Comparisons between Three P.C. Programs and BLAST", Energy and Buildings, Vol. 13, 1989, pp. 210-216.

20. R. Zmeureanu, P. Fazio, and F. Haghighat, "Analytical and Inter-program Validation of a Building Thermal Model", Energy and Buildings, Vol. 10, 1987, pp. 121-133.

21. R. Judkoff, D. Wortman, C. Christensen, B. O'Doherty, D. Simms, and M. Hannifan, "A Comparative Study of Four Passive Building Energy Simulations: DOE-2.1, BLAST, SUNCAT-2.4, DEROB III", The 5th National Passive Solar Conference, University of Massachusetts, October 19 - 26, 1980, pp. 126-130.

22. S. J. Irving, "Energy program validation: conclusions of IEA Annex 1", Computer Aided Design, Butterworth and Co. Ltd., U.K., Volume 14, 1982, pp. 33-37.

23. G. K. Yuill & Associates Ltd., Verification of the BLAST Computer Program for Houses - A Research Report, Energy, Mines and Resources Canada, Building Energy Technology Transfer Program Publication No. 83.05, 1983.

24. F. Y. Sorrell, T. J. Luckenbach, and T. L. Phelps, "Validation of Hourly Building Energy Models for Residential Buildings", ASHRAE Transactions, 1985, Part 2B, pp. 77-86.

25. F. Arumi-Noe, "Field Validation of e DEROB/PASOLE System", 3rd National Passive Solar Conference, San Jose, January 11 - 13, 1979, Vol. 3, pp. 152-157.

26. F. Bauman, B. Andersson, W. L. Carroll, R. Kammerud, and N. E. Friedman, "Verification of BLAST by Comparison with Measurements of a Solar-Dominated Test Cell and a Thermally Massive Building", Proceedings of the Solar Engineering Conference, Reno, Nevada, April 27 - May 1, 1981, pp. 9-307.

27. W. B. May, Jr. and L. G. Spielvogel, "Analysis of Computer-Simulated Thermal Performance of the Norris Cotton Federal Office Building", ASHRAE Transactions, 1981, Part 1, pp. 1207-1221.

28. T. Alezera and L. Hovander, "Validation of an Hourly Microcomputer Building Energy Analysis Program", ASHRAE Transactions, 1985, Part 2B, pp. 99-108.

29. L. F. Goldberg, "A Comparative Validation of the Long Term Energy Consumption Predictions of Five Residential Building Energy Simulation Programs in a Heating Climate", Building Energy Simulation Conference, Seattle, August 1985, pp. 282-289.

30. J. A. Heidell and Z. T. Taylor, "Comparison of Empirically Measured End-Use Metered Data with DOE 2.1 Simulations", Building Energy Simulation Conference, August 1985, pp. 0-5.

31. S. C. Diamond and B. D. Hunn, "Comparison of DOE-2 Computer Program Simulations to Metered Data for Seven Commercial Buildings", ASHRAE Transactions, 1981, Part 1, pp. 1222-1231.

32. G. C. Corson, "Input-Output Sensitivity of Building Energy Simulations", ASHRAE Transactions, 1992, Part 1.

33. J. A. Clarke, "Assessing Building Performance by Simulation", Building and Environment, Volume 28, No. 4, October 1993, Pergamon Press, pp. 419-427.

34. ADS Groupe-Conseil Inc. "Évaluation des effets énergétiques combinés des mesures d'économie dénergie. Bâtiment de type: grand édifice à bureaux". Prepared for Hydro-Québec. December 1992.

35. Architectural Glass Products. The Right Glass. PPG Canada, Inc., #08810 PPG, Optical and Thermal Performance Data.

36. ASHRAE Handbook of Fundamentals, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, Georgia, U.S.A. 1989.

37. M. Kaplan and P. Canner, "Guidelines for Energy Simulation of Commercial Buildings. Final." Kaplan Engineering. Prepared for Bonneville Power Administration. Commercial Technology Section - RMCB, Portland, Oregon, U.S.A. March 1992.

38. "CIBSE Guide Volume A - Design Data", The Chartered Institution of Building Services Engineers, London, 1986.

39. Building PULSE. Version 1.2. Building Energy Analysis Program. User's Guide. Scanada Consultants Limited. Toronto, Ontario, 1993.

40. ASHRAE Standard 90.1-1989. "Energy Efficient Design of New Buildings Except Low-Rise Residential Buildings". American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, Georgia, U.S.A. 1989.

41. S. Silberstein and R.A. Grot, "Air Exchange Rate Measurements of the National Archives Building". ASHRAE Technical Data Bulletin. Infiltration and Air Leakage. American Society of Heating Refrigeration and Air-Conditioning Engineers, Inc. Atlanta, Georgia, U.S.A. June 1985.

42. "Split System Air Conditioners", The Trane Company, DS S/S-1 1076, June 1977, pp 13,15,22,25,35,36.

43. "Single-Package Rooftop Units - Product Data", Carrier Heating and Cooling, Form 50C,D-1PD, 1985.

44. R. Zmeureanu and P. Fazio, "Analysis of the energy performance of office buildings in Montreal in 1988". Energy and Buildings, vol. 17, 1991, pp.63-74.

45. R. Zmeureanu, L. Pasqualetto, and S. DePani, "Empirical Validation of the BESA-Design Energy Analysis Software", CISS - First Joint Conference of International Simulation Societies Proceedings, Zurich, Switzerland, August 22-25, 1994, pp. 714-718.

46. R. Ménard and CMA Chalifour, Marcotte et Associés inc. (1992) "Guide de l'analyse énergétique". Hydro-Québec, Direction Approvisionnement de l'Exploitation.

47. R. O. Lewis, Independent Verification and Validation - A Life Cycle of Engineering Process for Quality Software, John Wiley and Sons, Inc., New York, 1992.

48. "DOE-2 Reference Manual Part 1, Version 2.1", Group WX-4, Program Support, Los Alamos Scientific Laboratory, Los Alamos, New Mexico. Prepared for the U.S. Department of Energy. May 1980.

49. N. B. Hutcheon, G. O. P. Handegord, Building Science for a Cold Climate, Construction Technology Centre Atlantic Inc., 1989, p.166.

50. F. C. Winkelmann, B. E. Birdsall, W. F. Buhl, K. L. Ellington, and A. E. Erden, "DOE-2 Supplement Version 2.1E", Energy and Environment Division, Lawrence Berkeley Laboratory, University of California, and J. J. Hirsch and S. Gates, Hirsch and Associates, California, November 1993.

51. R. Zmeureanu, L. Pasqualetto, and Frédéric Bilas, "Comparison of Cost and Energy Savings in an Existing Large Building as Predicted by Three Simulation Programs", Proceedings of the Building Simulation Conference, University of Wisconsin at Madison, August 1995.

52. A.W. Pratt, Heat Transmission in Buildings, John Wiley and Sons, New York, U.S.A., 1981, pp. 121-155.

53. F. Keith and M. S. Bohn, Principles of Heat Transfer, Fourth Edition, Harper and Row, Publishers Inc., New York, U.S.A., 1986, pp. 96-101.

54. M. J. Brandemuehl, HVAC-2-TOOLKIT, A Toolkit for Secondary HVAC System Energy Calculations, prepared for and published by The American Society of Heating, Refrigerating and Air-Conditioning Engineers, 1993.

55. F. C. McQuiston and J. D. Parker, Heating, Ventilating, and Air Conditioning Analysis and Design, 3rd edition, John Wiley and Sons, U.S.A., 1988, p.211.

56. R. Shuttleworth, Mechanical and Electrical Systems for Construction, McGraw-Hill Publishing Company, U.S.A, 1983, p.455.

57. D. M. Griffiths, K. J. Anderson, "Commercial Building/System Characteristics Sensitivity Analysis", Proceedings of ACEEE 1994 Summer Study on Energy Efficiency in Buildings, Panel 5 Commissioning, Operation, and Maintenance, American Council for an Energy-Efficient Economy, pp. 5.105-5.112.

58. W.J. Fabrycky and G.J. Thuesen, Economic Decision Analysis, Prentice-Hall Inc., New Jersey, 1974, pp. 252-259.

59. L. Pasqualetto, R. Zmeureanu, "Application of Decision Models under Uncertainty to the Selection of Energy Conservation Measures", Proceedings of Indoor Air Quality, Ventilation and Energy Conservation in Buildings, 2nd International Conference, Montreal, May 1995, pp. 583-590, winner of the "Best Poster Presentation" for the Energy Conservation Session.

APPENDIX A
WEATHER DATA EDIT FILE

The weather file was edited on an hourly basis for the simulations of perturbations in the outdoor environment using the file described below. The first line of values and each alternating line thereafter, indicates the month, day and hour for which the weather file is being edited. Each column of numbers on the line following the month, day and hour specification refers to different weather data (the value -999 indicates that the original value in the weather file is not modified): 69.7 is the wet-bulb temperature (°F), 72.0 is the dry-bulb temperature (°F), 68.8 is the dewpoint temperature (°F), -999 indicates no change in the value for barometric pressure (inches of Hg), 0.0 is the wind velocity (knots), 10.0 is the cloud amount (a factor from 0 to 10), -999 indicates no change in the cloud type (an index equal to either 0, 1 or 2 depending in the type of clouds), -999 shows no change in the wind direction, 0 is the total horizontal solar radiation (Btu/hr·ft²) and the last 0 is the direct normal solar radiation (Btu/hr·ft²).

```
EDIT
30-BITNORMAL
  1    8    1
 69.7  72.0  68.8 -999.   0.0  10.0   -999  -999    0     0
  1    8    2
 69.7  72.0  68.8 -999.   0.0  10.0   -999  -999    0     0
  1    8    3
 69.7  72.0  68.8 -999.   0.0  10.0   -999  -999    0     0
  1    8    4
 69.7  72.0  68.8 -999.   0.0  10.0   -999  -999    0     0
  1    8    5
 69.7  72.0  68.8 -999.   0.0  10.0   -999  -999    0     0
  1    8    6
 69.7  72.0  68.8 -999.   0.0  10.0   -999  -999    0     0
 .
 .
 .

  1    9   12
```

```
69.7  72.0  68.8 -999.   0.0  10.0   -999  -999    0     0
   1     9    13
 -5.0  -4.0  -5.9 -999.   0.0  10.0   -999  -999    0     0
   1     9    14
 -5.0  -4.0  -5.9 -999.   0.0  10.0   -999  -999    0     0
   1     9    15
 -5.0  -4.0  -5.9 -999.   0.0  10.0   -999  -999    0     0
   1     9    16
 -5.0  -4.0  -5.9 -999.   0.0  10.0   -999  -999    0     0
   1     9    17
 -5.0  -4.0  -5.9 -999.   0.0  10.0   -999  -999    0     0
 .
 .
 .

   1    21    23
 -5.0  -4.0  -5.9 -999.   0.0  10.0  -999  -999    0     0
   1    21    24
 -5.0  -4.0  -5.9 -999.   0.0  10.0  -999  -999    0     0
 -999
LIST
PACKED  1987  -999    1    12
STAT
END
```

APPENDIX B

FORTRAN PROGRAM FOR MATHEMATICAL MODEL

The program used to calculate the values from the heat transfer equation is listed here. A simple approach of trial and error is first used to determine the values for α_1 and α_2 by assuming a value and comparing the two sides of the equation. Once these values are determined, they are placed directly into the heat transfer equation.

```
      PROGRAM EQUATN
*
*
      IMPLICIT NONE
      INTEGER  I
*
      REAL  HI,HO,HS,L,K1,K,V1,C1,BI,BO,BS,C,V,A,BETA,BE2,
    +   ARALPH(10),T1,T2,T3,T4,T5,S1,S2,S2A,S2B,S3,
    +   S4,S5,S5A,S5B,S6,S7,S8,S8A,S8B,S(48),ALPHA1,ALPHA2,
    +   SS(48),AL1SQ,AL2SQ,T,ALPHA,TRIGHT,DIFF,DIFF2,TAU
*
        CHARACTER ANSWER
*
      DATA ARALPH/10*0.0/
*
*      The values of the heat transfer coefficients are defined as follows:
*
*
      HI=1.47
      HO=1.114
      HS=1.307
*
*      The wall thickness is taken as unity and the thermal diffusivity, thermal
*      conductivity, ventilation heat loss rate and thermal capacity are defined *
       as follows:
```

```
*
*
      L=1.0
      K1=0.7576
      K=0.02706
      V1=0.0
      C1=14.89
*
      BI=(HI*L)/K1
      BO=(HO*L)/K1
      BS=(HS*L)/K1
      C=(C1*K)/(L*K1)
      V=(V1*L)/K1
      A=1.0+(1.0/BI)+(1.0/BO)
      BETA=(BS*(BI+V))/(C*(BI+BS+V))
*
*       A value of ALPHA is chosen starting from 0.001 and the equation is applied
*       to determine if the two sides of the equation are equal.  The value of
*       ALPHA is increased and the two sides of the equation are compared until
*       a solution is found.  At this point, the increment is decreased until the
*       solution is within satisfactory precision.
*
*
       ALPHA=1.674
             PRINT*, 'TRIGHT        ALPHA'
      DO 40 I=1,50
        T1=C*(ALPHA**4)*(((V+BS)*(BI+BO))+(BI*BO))
        T2=BS*(ALPHA**2)*((V*(BI+BO))+(BI*BO))
        T3=C*(ALPHA**4)*(BI+BS+V)
        T4=(ALPHA**2)*((C*BI*BO*(V+BS))+(BS*(V+BI)))
        T5=V*BI*BO*BS
        TRIGHT=((T1-T2)/(T3-T4+T5))/(TAN(ALPHA))
        PRINT*, TRIGHT, ALPHA
             ALPHA = ALPHA + 0.0001
   40  CONTINUE
*
*       In order to end the program when the values of ALPHA1 and ALPHA2 are
*       not yet determined, this IF statement is included:
*
*
         PRINT*, 'DO YOU WANT TO END THE PROGRAM?'
         READ*, ANSWER
         IF ANSWER.EQ.Y GO TO 100

*       The values of α obtained by trial and error are now input directly:

      PRINT*, 'ENTER ALPHA1 AND ALPHA2'
      READ*, ALPHA1,ALPHA2
```

```
*
*     T represents the time in hours after the change in temperature.
*
*
      T=1.0
      DO 50 I=1,48
*
      AL1SQ=ALPHA1**2
      AL2SQ=ALPHA2**2
      TAU=K*T/(L**2)
*
*     The equation is separated into several sections in order to simplify it.
*
*
      S1=((BS-C*AL1SQ)*AL2SQ)/(BS*(1+V*A)*(AL2SQ-AL1SQ))
      S2A=V*BI*(BS-C*AL1SQ)*(COS(ALPHA1)+(BO/ALPHA1)*SIN(ALPHA1))
      S2B=C*BO*(BI+BS+V)*(BETA-AL1SQ)
      S2=1.0+(S2A/S2B)
      S3=EXP(-AL1SQ*TAU)
      S4=((BS-C*AL2SQ)*AL1SQ)/(BS*(1+V*A)*(AL2SQ-AL1SQ))
      S5A=V*BI*(BS-C*AL2SQ)*(COS(ALPHA2)+(BO/ALPHA2)*SIN(ALPHA2))
      S5B=C*BO*(BI+BS+V)*(BETA-AL2SQ)
      S5=1.0+(S5A/S5B)
      S6=EXP(-AL2SQ*TAU)
      S7=(V*(BS**2))/(C*BETA*((BI+BS+V)**2))
      BE2=SQRT(BETA)
      S8A=BI*((BS-C*BETA)**2)*(BI+BS+V)*(COS(BE2)+(BO/BE2)*SIN(BE2))
      S8B=BO*(BS**3)*(1.0+V*A)*(1.0-(BETA/AL1SQ))*(1.0-(BETA/AL2SQ))
      S8=(1.0+S8A/S8B)*(EXP(-BETA*TAU))
*
*     The sections of the equation are integrated in order to arrive at the solution.
*     The values for each hour are saved in an array and printed to the screen.
*
*
      S(I)=1.0-(S1*S2*S3)+(S4*S5*S6)-(S7*S8)
*
      T=T+1.0
      PRINT 47, I, S(I)
 47   FORMAT (1X,'FOR T= ',I2,'   FRACTION= ',F6.4)
 50   CONTINUE
100   END
```