Emulation and Control of Heating, Ventilation, and Air-Conditioning Systems

by

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ABSTRACT

The control of Heating, Ventilation, and Air Conditioning (HVAC) systems can lead to significant energy savings. A Building Energy Management System (BEMS) is one part of the building automation system and is responsible for indoor climate control, energy management, conditioning monitoring and more.

This thesis initializes the work on building an emulator for testing control strategies. A BEMS controller using optimal control strategies is developed. The controller is tested on a simulated HVAC system model, where a Transient Simulation Program (TRNSYS) is utilized.

The overall goal of the controller is for it to learn how to better control the HVAC system with the passage of time. To accomplish this several control algorithms are included. An intuitive control scheme is used during initial operation. Once sufficient information about the system has been gathered, optimal control is used instead.

The optimal control strategy is based on a total power formula which is represented in terms of a set of forcing functions and control variables. The formula, which is quadratic with respect to the control variables, is found automatically in the controller by using linear regression techniques. Equating the derivatives of the Jacobian with respect to the control variables to zero yields a set of predicted optimal control settings. If these settings violate any constraints, then this is adjusted for. A method that learns the constraints on the control variables is developed.

The controller is tested and an evaluation of the performance of the optimal control methodology is made. As difficulties are encountered when using the given control methodology, a detailed analysis of the predicted control settings, using different control schemes during initial operation, is performed. Comparisons of the results using different schemes show the importance of selecting smart intuitive control schemes.

One of the main findings of the study is that the power may be predicted acurately, but the optimal settings may not be correct. It is necessary that the control setting used during initial operation be varied sufficiently for all forcing functions so that the true optimum settings are included in the data used in the regression equation for the total power.

ACKNOWLEDGEMENTS

The completion of this thesis is not only the end of my masters studies, but it also marks the end of six years of studying in the United States. Over these years I have gotten to know people, from many different cultures and countries. It has been an incredibly rewarding experience, full of wonderfull memories. However, all good things must come to an end, and all I can do is to sit back, reflect, and think about everybody that became a part of me during this time of my life.

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Hasta la vista...see you later...and...på gjensyn Madison!

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NOMENCLATURE

Roman Symbols

AC	-	Air Conditioning
AHU	-	Air Handling Unit
BEMS	-	Building Energy Management System
c_p	-	specific heat
DA&C	-	Data Acquisition & Control
DDC	-	Direct Digital Control
f	-	vector of uncontrolled variables
F	-	Fraction
FORTRAN	-	programming language
h	-	convective heat transfer coefficient
HVAC	-	Heating, Ventilation, and Air Conditioning
HVACSIM+	-	HVAC Simulation plus other systems
I	-	hourly solar radiation

I/O	-	Input/Output
J	-	instantaneous operating cost
kW	-	kilowatts
kWh	-	kilowatt-hours
LMTD	-	Log Mean Temperature Difference
M	-	vector of discrete control variables
$\dot{m}$	-	mass flow rate
MHz	-	Megahertz
MW	-	Megawatts
n	-	number of observations
N	-	Number
NTU	-	Number of Transfer Units
Nu	-	Nusselt number
p	-	pressure
P	-	Power
PC	-	Personal Computer
$\dot{Q}$	-	heat flow rate
Re	-	Reynolds number
RMS	-	Root Mean Square
SHR	-	Sensible Heat Ratio of the building cooling load
T	-	Temperature
TMY	-	Typical Meteorological Year
TRNSYS	-	A Transient Simulation Program
TYPE	-	a TRNSYS subroutine
u	-	vector of continuous control variables

UA - overall heat transfer conductance

VAV - Variable Air Volume

x - predictor

$\widehat{X}$ - predictor matrix

y - response, measured or simulated value

$\widehat{y}$ - predicted response

$\widehat{Y}$ - response matrix

Greek Symbols

β - regression coefficient

$\widehat{\beta}$ - regression coefficient matrix

Δ - difference

ω - absolute humidity

η_o - overall surface efficiency

Additional Subscripts and Superscripts

a - air

amb - ambient

c - coil

c - cold

cap - capacity

coef - coefficients

comp - compressor

cw - chilled water

db	-	dry bulb
g	-	vector of equality constraints
h	-	hot
i	-	inlet condition
infl	-	infiltration
int	-	instantaneous
int	-	intuitive
IR	-	irradiation
lat	-	latent
meas	-	measured or simulated
min	-	minimum
o	-	outdoor condition
o	-	outlet condition
opt	-	optimum
pred	-	predicted
ref	-	refrigerant
s	-	static
sa	-	supply air
sens	-	sensible
set	-	set point
T	-	transposed vector (superscript)
tot	-	total
w	-	water
wb	-	wet bulb
z	-	zone

CHAPTER
ONE

INTRODUCTION

1.1 BACKGROUND

Over the past few years there has been an increasing worldwide awareness and interest in preserving our environment and conserving energy. At the same time an increasing number of people work in large building complexes that require significant amounts of space conditioning. The improvements in design, control, and maintenance of Heating, Ventilation and Air Conditioning (HVAC) systems can result in large energy savings. While all of the above will serve as the underlying motivation for this thesis, the focus will be on the cooling requirements of buildings.

A typical air conditioning system consists of one or more cooling towers, chillers, pumps, fans, and air handling units. Figure 1.1 shows a simplified schematic of a typical variable air volume (VAV) air conditioning system. Return air from the zones is mixed with fresh ventilation air in a mixing chamber to ensure good quality indoor air. The mixed air is then cooled and dehumidified in a cooling coil. The supply air fan provides the ventilation of the air through the different zones. In a variable air volume system the fan is adjusted so that the sensible loads of the building are met exactly. The warm mixed air is cooled by chilled water produced by the chiller (in the evaporator). The hot refrigerant in the chiller is cooled (in the condenser) by the water in the cooling tower loop. Finally, the hot water in the cooling tower loop is cooled through combined heat and mass transfer in the cooling tower, where heat is rejected to the environment.

Two temperatures that can be chosen as control variables are the chilled water and supply air set point temperatures, $T_{cw,set}$ and $T_{sa,set}$, respectively. The chilled water set point temperature determines the cooling requirements of the chiller while the supply air set point temperature determines the speed setting of the supply air fan. The implications of these two control variables on the overall system performance will be discussed in more detail below.

To reduce the overall operating costs of a HVAC system, close attention must be paid to both its design and control. The design of a HVAC system involves the selection of proper hardware, while the control issue involves, among other things, finding the optimal operation of the installed equipment.

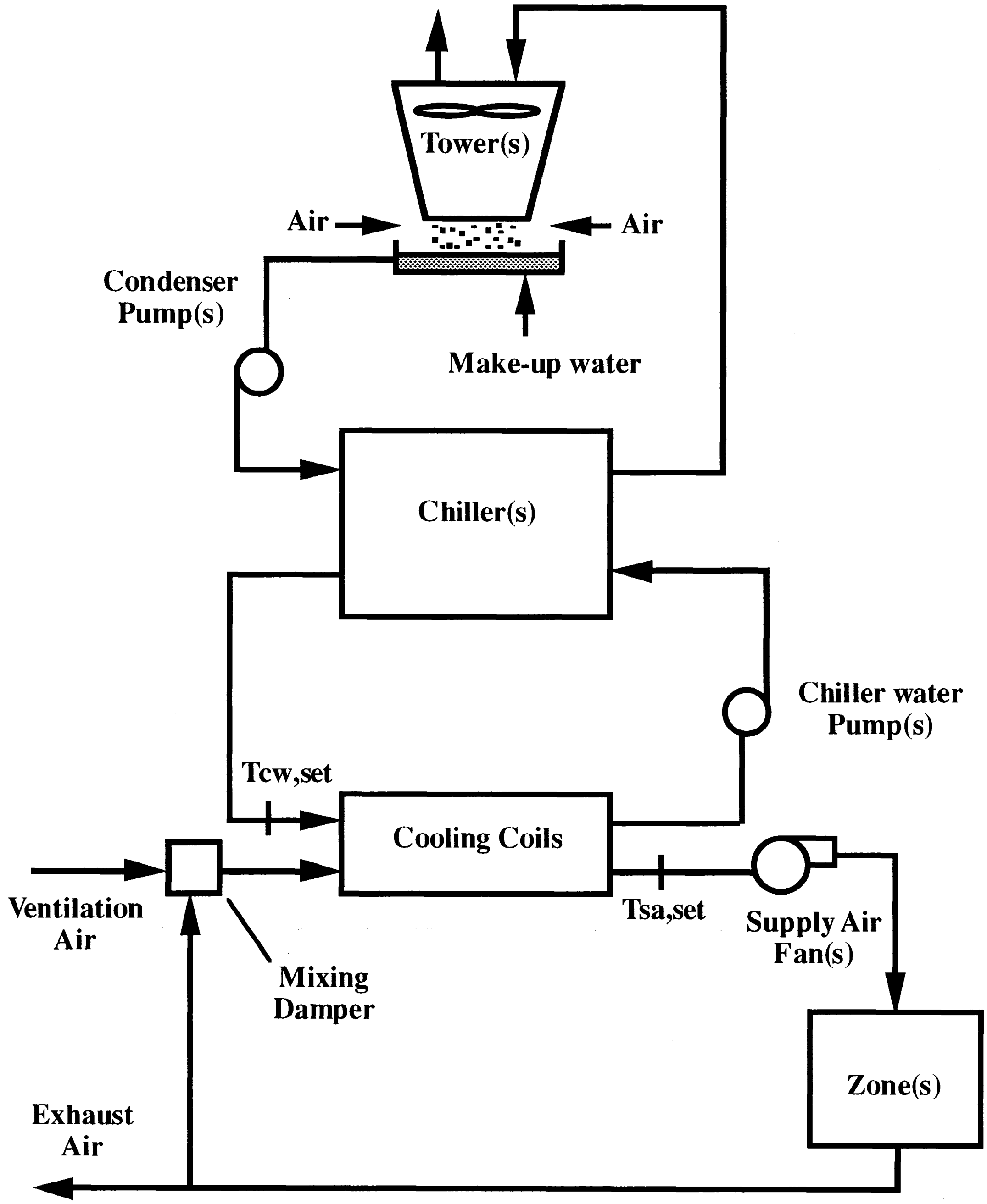

Figure 1.1 Schematic of a typical air conditioning system

In the design of a HVAC system there are many alternatives, some more favorable than others. The advent of new and reliable variable speed electric motors has opened up the door for more Direct Digital Control (DDC) of HVAC equipment. Treichler [1985] concluded that variable-speed pumping is economically attractive for both chilled water distribution and condenser water systems. Other studies have shown that using variable-speed instead of one-speed cooling tower fans can also decrease the total system power consumption (The Marley Cooling Tower Company). Furthermore, the most energy consuming components in a central cooling system, the centrifugal chillers, are more efficient when a variable-speed compressor is used (Braun [1988]).

In a central cooling system, such as the one described above, the principal power consuming components are: the cooling tower fan, the condenser pump, the chiller compressor, the chiller water pumps, and the supply air fan. To minimize the total system operational cost it is therefore important to implement intelligent control strategies. If the chilled water set point temperature is lowered, for example, the chiller cooling requirement is increased and consequently the chiller power consumption goes up. Similarly, if the supply air set point temperature is increased the supply air flow rate must also be increased and the supply air fan power consumption goes up. A method to control these two temperatures, or any other control variables, is therefore important. To implement these (and other) control strategies a Building Energy Management System (BEMS) can be used.

A Building Energy Management System is one part of the building automation system and serves as the controller of the building HVAC system (Hyvärinen, et. al. [1991]). The BEMS is responsible for indoor climate control, energy management, conditioning monitoring and more. This is achieved by using software, user-interface, and field devices (Kelly and May [1990]). The software can consist of supervisory control algorithms and/or DDC algorithms for local loop control. The field devices, such as actuators and sensors, are located in the vicinity of the equipment being controlled. The user-interface serves as the communication unit between the controller and the field devices. Control signals produced by the controller are sent, via the interface, to the actuators as digital or analog signals, depending on the type of actuator used. Response signals from the sensors are feed back to the controller, yielding closed loop control.

In general there are three possible approaches for developing and testing BEMS software: (1) Simulation, (2) Emulation, and (3) Field Testing (Wang [1992]). Figure 1.2 below, is a schematic of the three approaches for testing Building Energy Management Systems. The focus of this study will particularly be on emulation and simulation.

The simulation method provides convenient, flexible, low cost, and low time consuming testing of Building Energy Management Systems. Simulators include models for building and loads, HVAC systems, sensors, controllers, and supervisory control strategies. The main advantage of using simulation is that the general behavior of systems, over long periods of time, can be tested very quickly. (Long time periods also justifies the use of steady state models.) This also makes it possible to evaluate the long term energy saving potential of the BEMS control strategies. Studies by Braun [1988] and Pape [1989] showed that it is possible to represent the total system operational costs as a function of a set of independent control and uncontrolled variables. At any point in time it is possible to meet the cooling needs of a building with a number of different control variables, i.e., the chilled water and supply air set point temperatures, $T_{cw,set}$ and $T_{sa,set}$ of Figure 1.1. Therefore, there must also exist a set of optimal operation set points. This optimum can be found by minimizing the total operational cost function with respect to the independent control variables.

Emulation differs from simulation in that tests are run in real time. The advantage of using an emulator is that an actual system does not have to be built in order to test the real performance of the BEMS control strategies. Since an emulator includes an actual BEMS, dynamic models of simulated building and HVAC equipment must be used. Wang concluded that the emulation method is superior for testing the real BEMS facilities, while the simulation method is attractive for the testing and developing of BEMS control methodologies.

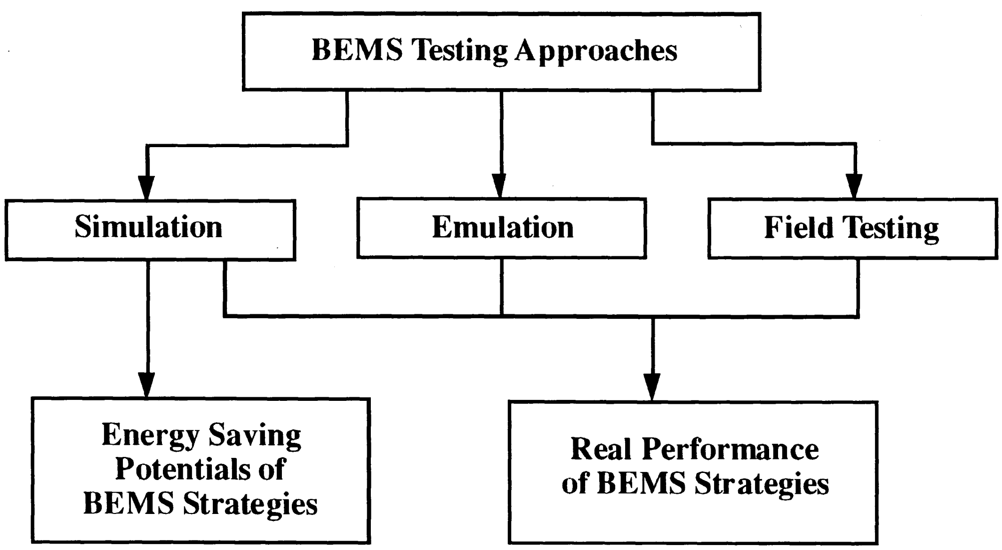

Figure 1.2 Testing Approaches for a Building Energy Management System

Field testing involves the testing of an actual BEMS on a physical building and HVAC system. As it might be imagined this type of testing is both expensive and time consuming. Field testing also has the potential problem of having sensors distorting signals. Furthermore, in field testing, it is difficult to determine if a particular algorithm yields optimal performance since the sequence of events cannot be repeated. However, if problems such as these can be minimized and a true testing site can be arranged, field testing does provide a very realistic setting for testing the real performance of BEMS control strategies.

1.2 OBJECTIVES

The objective of this research is to build an emulator to test controllers for a Building Energy Management System. The controller will have the capability to learn the performance characteristics of a building HVAC system with the passage of time. Both the building and the HVAC system and the controller will be represented as numerical simulation models. Several control strategies will be tested and developed. Specifically, the three main objectives of this research are to:

1. Build an emulator,
2. Build a BEMS controller using optimal control strategies, and
3. Test the controller on a building HVAC system model.

After having completed the above it will be possible to implement the new controller algorithms into an actual BEMS using emulation techniques.

1.3 SYSTEM DESCRIPTIONS

It is important to understand the difference between simulation and emulation. Emulators are generally divided into three distinct categories (Hyvärinen, et. al. [1991]):

1. **Artificial emulators** are simulators where all devices are represented as numerical simulation models.
2. **Testing (and training) emulators** include building and load models, a physical or numerically modeled HVAC system, and an actual BEMS.
3. **Field emulators** are used to replace the BEMS system in a real building.

Below follows two sections which describe emulation and simulation. The first section is a general description of a typical emulator used for evaluating a BEMS. The second section provides a more detailed description of the simulated building HVAC system used in this thesis to test and develop the BEMS controller.

1.3.1 EMULATION

An emulator for Building Energy Management System applications consists of a computer-based simulation of a building and its mechanical system connected to an actual BEMS (May and Park, [1985]). It can be used to replace the entire HVAC system, or the emulator software can be interfaced with selected pieces of physical HVAC hardware. The emulator is connected to the BEMS in place of the regular BEMS sensors and actuators. The BEMS, through its supervisory and/or direct digital control algorithms, then controls the simulated HVAC system as if it were an actual system. At the same time the emulator evaluates the performance of the BEMS in terms of the energy consumed by the simulated building and its HVAC system, the indoor air quality maintained in the simulated space, the response time, accuracy of control, etc. Figure 1.3 is a schematic of a typical emulator for a BEMS. Chapter 2 contains a more detailed discussion of emulators for building HVAC applications.

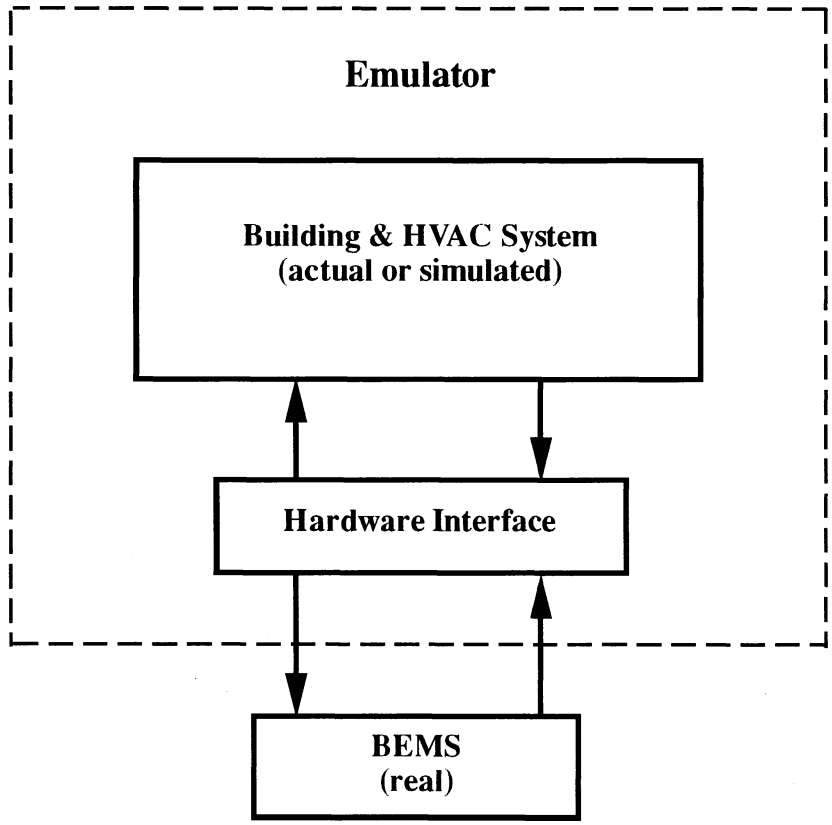

Figure 1.3 Schematic of an Emulator

1.3.2 SIMULATION

Simulation involves the mathematical modeling of actual systems which follow a given set of physical laws. Simulation provides a convenient and economical method to evaluate systems before they actually have been built. In simulation either dynamic models, steady state models, or both dynamic and steady state models can be used, depending on the problem at hand.

The program used in this study to simulate the complete building HVAC system is the Transient System Simulation Program TRNSYS (Klein, et. al. [1988]). This modular program consists of different subroutines, which mathematically model the performance of the system components. The subroutines are written in the computer language FORTRAN. Originally TRNSYS was developed as a simulation program for solar energy systems, but other components for energy systems have been included. The program provides great flexibility because it readily allows the user to create new models or to modify old ones. Once all the components needed have been selected, they are linked together to form a complete system model. A TRNSYS *simulation deck* organizes and connects all the inputs and outputs together, much in the same manner as the pipes and wires of an actual system would be connected together.

In order to observe the system behavior with the passage of time a set of forcing functions, such as the ambient conditions, must be provided. Weather data from a Typical Meteorological Year (TMY) can be used to test the given system over a wide range of conditions for many different locations in the U. S. A. The duration of the simulation must be specified by the user. For each time step the inputs to all of the components must converge within a specified tolerance. Because the dynamic behavior of the equipment used in the system can be neglected, the steady state models in TRNSYS are suitable.

Figure 1.4 is a schematic of the information flow in the simulated building, HVAC system, and BEMS controller used in this research. The way it works is as follows: Ambient conditions including the dry bulb temperature, absolute humidity, wind speed, and global solar radiation, are read from a TMY file. This information is then passed on to the building model which, along with the heat gains from people and equipment, generates the total cooling requirement of the zones. At the same time information on dry bulb and wet bulb temperatures is passed on to the cooling tower in the HVAC system. A BEMS controller controls the variable speed supply air fan, the variable speed chiller water pump, and sets the constant speed cooling tower fan and condenser pump. The total fraction of outdoor air is usually set to be constant. The controller also passes on information about the supply air set point temperature, which determines the cooling required in the cooling coil; and the chilled water set point temperature, which determines the chiller requirements. A local loop controller is employed in order to reach simulation convergence around the cooling coil. (See Section 3.2.4 for more details on the local loop controller.) As the simulation progresses, the BEMS controller continuously records and stores the operation set points, weather variables, system performance, and any other important information in a data base. Based on an optimal control scheme, a pair of new supply air and chilled water set point temperatures are calculated and sent back to the system.

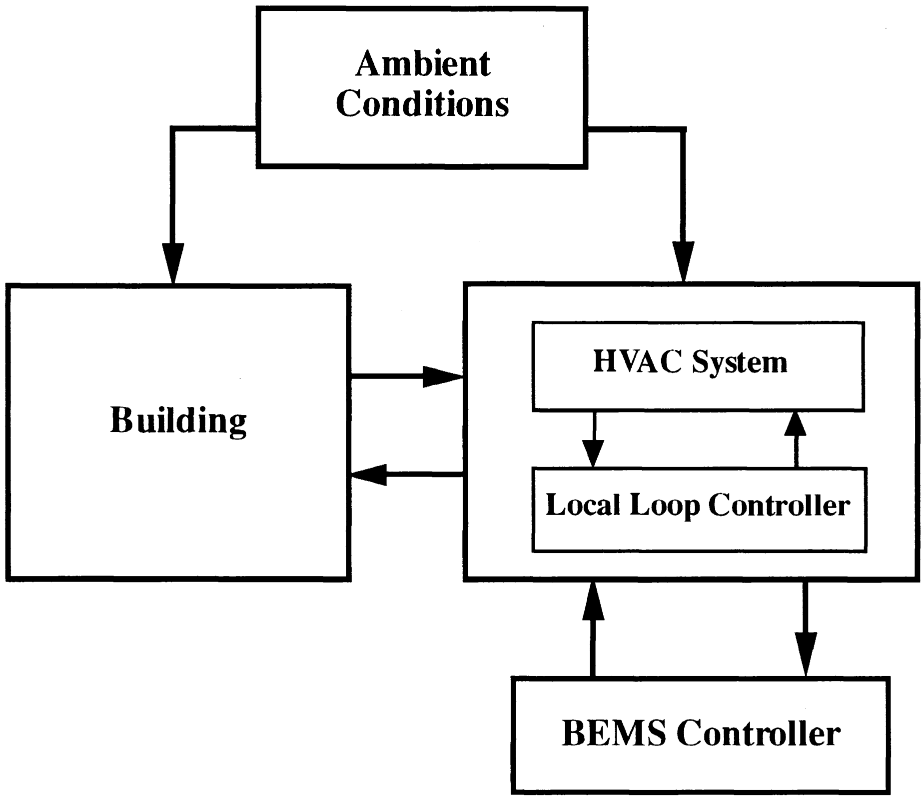

Figure 1.4 Information flow diagram of the simulated building, HVAC system with local loop controller, and BEMS controller

The TRNSYS library contains many standard components and some of them were used in this work. A few of the subroutines, such as the local loop controller, electric motor, and flow converter were developed by Pape. The BEMS controller was a component developed particularly for this research. Appendix B lists the source code of the BEMS controller.

The sizing of the equipment used in the representative system considered in this research was done by Pape, who followed the procedures as discussed in ASHRAE handbooks [1987, 1988] and other publications (e.g. McQuiston and Parker [1982]). The order of the general methodology used to select HVAC equipment was the following:

1. The cooling coil(s) of the air handling unit(s),
2. The fan(s) of the air handling units,
3. The chiller water pump(s),
4. The chiller(s),
5. The cooling towers including their fan(s),
6. The condenser pump(s), and
7. The electric motors for the driven devices.

1.4 ORGANIZATION

The work of this thesis is divided into five chapters. After the introduction chapter follows Chapter 2, which discusses emulators for HVAC applications. Chapter 3 is a presentation of the development and verification of the simulation models used in this thesis; However, the particular focus of the chapter will be to describe the development of the BEMS controller algorithms. Chapter 4 presents the results from various tests and control strategies performed on the controller. Conclusions and recommendations are given in Chapter 5.

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CHAPTER
TWO

HVAC SYSTEM EMULATION

This chapter discusses the subject of HVAC system emulation. First, an introduction describing the general concept of emulation is presented. The structure of emulators for building HVAC systems is not predetermined, but depends on the testing needs and objectives. Section 2.2, discusses some of the different uses of emulators and how they typically are structured. Then, in Section 2.3, follows a more detailed description of the equipment needed in emulation . HVAC emulation is a relatively new science, but some research has been done in the field. Section 2.5, presents some examples of emulators that have been built up to now. The chapter is summarized in Section 2.5.

2.1 INTRODUCTION TO HVAC SYSTEM EMULATION

Emulation of building HVAC systems is a relatively new science. It involves using numerical simulation models of a building and its mechanical system, as well as using actual pieces of HVAC equipment. The emulator could be used to test selected pieces of HVAC hardware, such as boilers, chillers, pumps, fans, or Building Energy Management System controllers. When using an emulator to test BEMS controllers it is not necessary to know the exact structure of the algorithms used in the BEMS in order to evaluate how well they perform. This is clearly an advantage since BEMS controllers usually are proprietary.

A great deal of research effort has over the past years been spent on simulation of HVAC systems; these models are best used for dimensioning real HVAC systems and optimizing their general behavior. However, simulation does not always provide a realistic image of the physical system. Therefore, in the future emulators are believed to serve as the *link* between simulated models and actual systems. Hence, an emulator may be utilized to test a BEMS for any type of building HVAC system for which a simulation model is available.

2.2 USES OF EMULATORS

Over the past few years there has been an increasing interest in using emulators to create an artificial setting for testing HVAC systems and/or pieces of HVAC equipment. Building emulators are suitable for use in testing; product development; training; pre-tuning of automation equipment; studying of fault diagnostics; and dynamic and steady-state loading, testing, and performance measurements of actual process equipment (Emulation News [1993]). The sections below describe some of the possible uses of emulators.

2.2.1 TESTING OF PROCESS EQUIPMENT

An emulator for testing actual pieces of HVAC equipment, consists of a simulated building, an interface, and the physical device which is to be tested (Wang [1992]). The simulated part of the system both provides and requires numerical data, while the real devices provide and require physical (electrical) signals. In order to establish a dialog between the simulated and the physical part an interface must be used.

Let us consider the testing of a chiller using an emulator. The idea of testing a boiler using an emulator was first studied by Laitila et. al. [1991], but the basic principle can easily be extended to the testing of a chiller (or any other piece of HVAC equipment). In this case the interface of the emulator is to convert the water outlet temperature of the chiller to a numerical value that can be used in the simulated system. The return water temperature, which is calculated numerically in the simulation program, is converted and supplied back to the chiller.

Figure 2.1 shows the structure of an emulator for testing the chiller in a central cooling plant for a building. As it can be observed, the interface consists of two parts: An Input/Output (I/O) interface, and a heat exchanger system. The I/O unit converts the

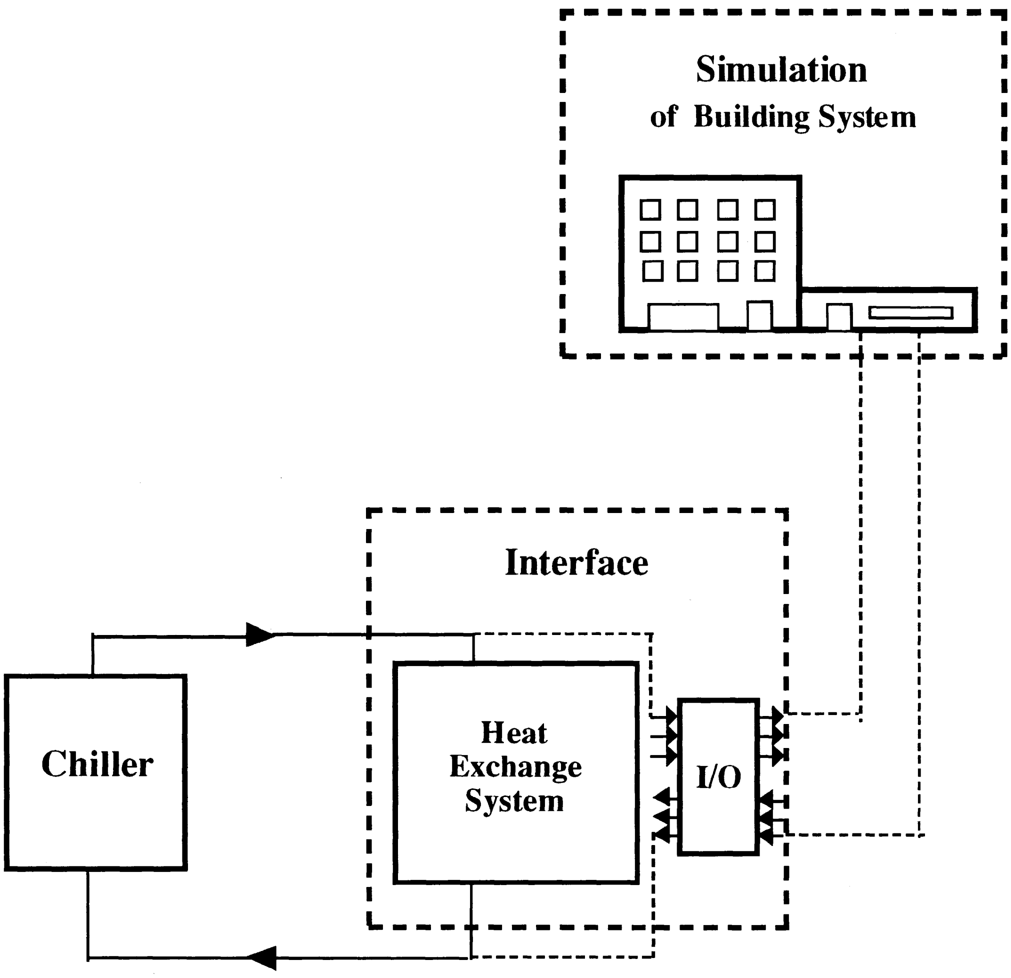

Figure 2.1 Structure of an emulator for testing the chiller in a central cooling plant for a building

electrical signals from the sensors into numerical data, and is then supplied to a simulated building. Similarly, the I/O unit converts the return water temperature into electrical signals, which determines the set-point temperature of the heat exchange system. The heat exchange system heats up the return water to the set-point provided by the simulation. This emulator set-up may be used to test either the chiller performance, or the control algorithms of the chiller.

2.2.2 BEMS TESTING

An emulator for testing a Building Energy Management System consists of a simulated building HVAC system, an interface, and an actual BEMS (Nusgens [1991]).

In an actual modern building HVAC system the digital control system, or BEMS, receives information about the system variables (temperatures, flow rates, etc.) from the sensors which convert the physical signals into electrical signals. These electrical signals are registered by the BEMS and used to compute further control action demands. The BEMS controls the system by sending analog or digital signals to the actuators, depending on the type of actuation equipment being used. There are also situations where the BEMS sends both analog and digital signals to the actuators.

If an emulator is used to test a BEMS, the actual sensors and actuators are replaced by simulation models. In this case the emulator generates electrical signals which replace those that would have been provided by the real sensors. The electrical control signals generated by the real BEMS are sensed by the emulator and used as inputs to the simulated actuator models.

An interface is used in order to provide the necessary communication between the simulated building HVAC system and the real BEMS. The interface converts the digital signals from the simulated sensors into analog (or digital) signals for the BEMS, and converts analog (or digital) signals for the simulated actuators. Figure 2.2 is a schematic of an emulator used for testing a BEMS.

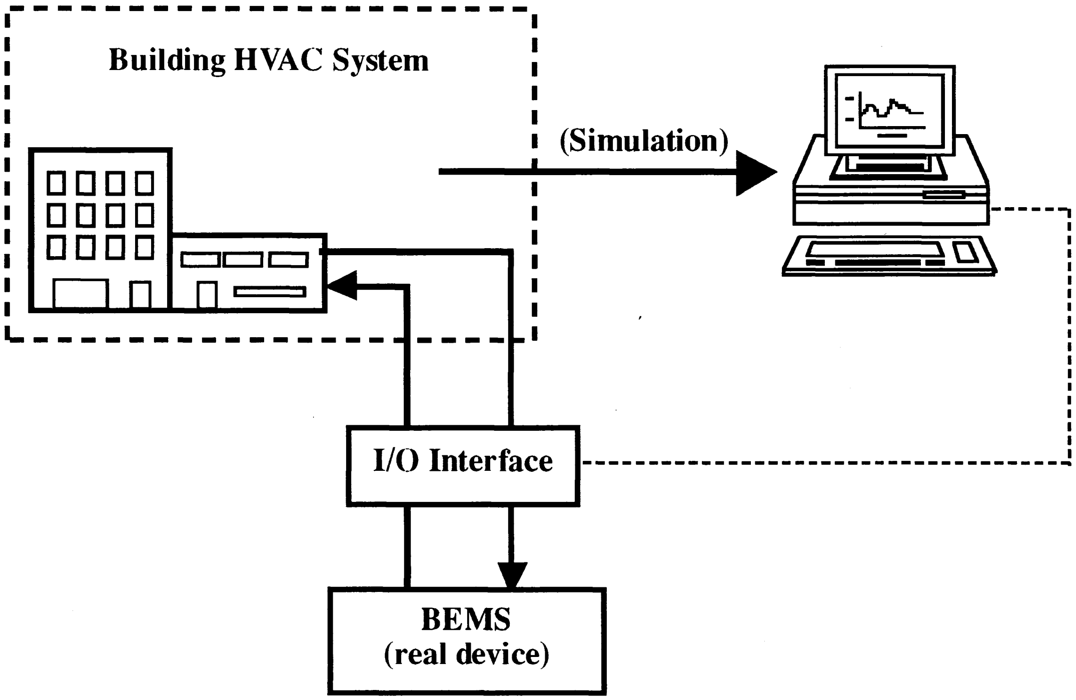

Figure 2.2 Schematic of an emulator for testing a BEMS

2.2.3 OTHER USES OF EMULATORS

In addition to testing of HVAC hardware equipment or Building Energy Management Systems, emulators can also be utilized in a wide range of other HVAC applications.

They might, for example, be used for training BEMS operators. In this case there would be no danger or fear of damaging actual HVAC equipment.

In climates where there are two distinctively different seasons, tuning of the HVAC controllers in order to ensure efficient operation is necessary. The tuning of the controllers can be made quicker and easier by pre-tuning the controller with the emulator. Although the pre-tuning parameters from the emulation probably have to be modified before they are used in a real building, they are at the same time more likely to be closer to the right values than a set of guessed parameters.

Another very important area of emulators is to assist in product development and debugging of new BEMS control algorithms. Emulators of the future, will probably become the *link* between testing control strategies in simulation and testing of the same strategies in actual test buildings.

2.3 HARDWARE AND SOFTWARE FOR BEMS TESTING

The hardware needed to test a BEMS using an emulator involves the selection of computers and communication interfaces. Furthermore, to run the building emulator, software for the simulated building HVAC system, software for the communication interface, and real time management and indication (graphics) is needed. The next two sections discusses some of the considerations that have to be made when selecting hardware and software.

2.3.1 HARDWARE

When selecting the type of computer hardware to be used in a BEMS emulator, such as the one illustrated in Figure 2.2, one has the choice of using one or two computers. In the one computer system the simulation of the building and the HVAC system, the communication with the BEMS, the real time graphical monitoring, and any other tasks are performed on the one single computer. In the two computer system the tasks are shared by two computers, where one computer is usually used to simulate the building systems while the other one is mainly used to manage the communication interface.

In the selection of computers there is no particular advantage of using two computers as opposed to one. Actually, a system using two computers might have the disadvantages of being complex and slow, and there might be problems with data transfer delay. However, regardless of which design is chosen, it is necessary for the computers used in the BEMS emulation to provide:

1. Sufficient computation speed,
2. A communication port (or possibilities to install an I/O interface),
3. Graphics possibilities, and
4. Sufficient storage space.

The communication interface used to build the emulator must have the capability to handle either analog or digital signals, and must in general meet the following requirements:

1. I/O signals are concordant with I/O of the BEMS,
2. Acceptable conversion accuracy, and
3. Sufficient conversion speed.

There are several methods of designing the emulator Data Acquisition and Control (DA&C) system (Peitsman and Nicolaas [1990]). To perform the task, internal bus products, such as a computer plug-in I/O board which is connected directly to the Personal Computer (PC) bus, are often used. External bus products, such as distributed I/O or DA&C systems, can also be used. These stand-alone DA&C systems are connected to the computer via standard communication channels.

Some of the advantages of using stand-alone DA&C systems is that they are generally very flexible and can consequently be placed close to the field signals if necessary. They also have a large storage capacity and therefore have the possibility of *off-loading* some of the data collecting tasks from the host computer. The disadvantages of the stand-alone systems are their slow speed and relatively high costs compared to the plug-in boards. The plug-in I/O boards, on the other hand, have the advantages of high speed, low cost, and small size. However, the disadvantage of the I/O boards is that they have a more limited number of available input and output slots compared to the stand-alone DA&C systems.

2.3.2 SOFTWARE

To operate the building emulator, software for the simulated building HVAC system, the communication interface, the real time management, and real time information indication (graphics) is needed. These different types of software are described in the sections below.

2.3.2.1 Simulation Software

The software for the building HVAC system includes simulation models that describe the different system components. Two possible programs that can be used to simulate the models are TRNSYS (A Transient Simulation Program) and HVACSIM+ (HVAC Simulation plus other systems). When testing the BEMS controller algorithms it is very important that the simulation models accurately describe the energy behavior and give realistic dynamic responses of the control loops. In order to validate the component models, one can compare them to experimental results or catalog data from manufactures. Furthermore, since emulation time must always be smaller than or equal to a real time (see section 2.3.2.3 for more details on real time management), it is important to keep computation speed of the simulated models as quick as possible.

2.3.2.2 Communication Software

The purpose of the communication software is to operate the I/O interfaces in such a manner that the information exchange between the numerical simulation model and the real BEMS goes smoothly and correctly. The software for operating the I/O interface may be self-developed subroutines or commercially available software packages or drivers. If the latter option is chosen, one needs to ensure that the software available is compatible with the simulation software, and that the computation speed is sufficiently high.

Another important task for the communication software is to convert the nature (pressure, voltage, digital, etc.) of the signals between the computer and the BEMS, while at the same time taking into consideration the quantitative relationship between the signals. For example, when sending a thermo-physical value (such as temperature) to the BEMS, the computer must inform the interface about what level of electrical signal (voltage, current etc.) corresponds to what temperature.

2.3.2.3 Real Time Management Software

Since the emulator might be used to test an actual piece of equipment, such as an actual BEMS, the simulation of the system must be run in real time, and the selection of real time management software becomes necessary. An example of real time management scheduling of an emulator is shown in Figure 2.3 (Wang [1992]) and is discussed below.

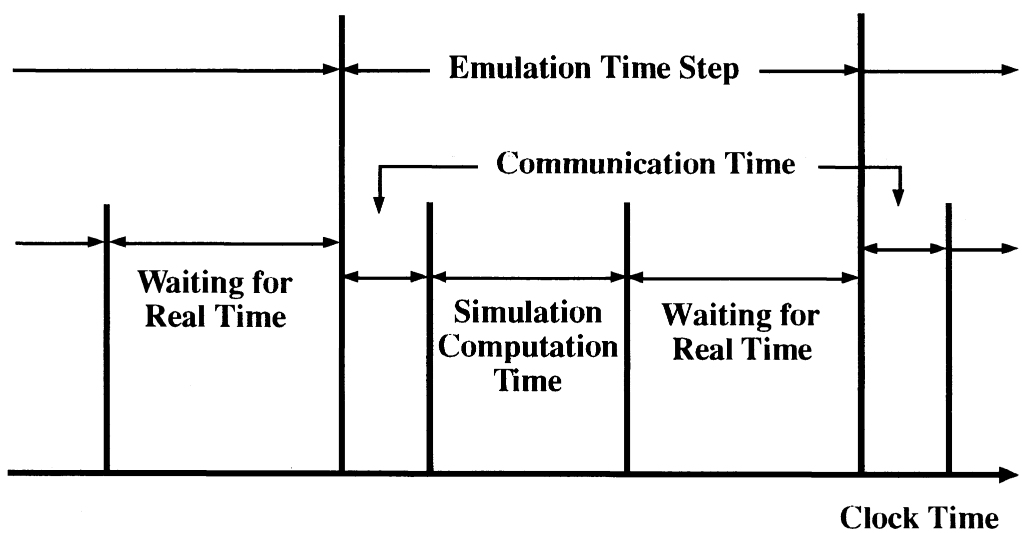

Figure 2.3 Real Time Scheduling of an Emulator

As seen in the figure one emulation time step consists of three time phases:

1. Simulation calculation time,
2. Communication time, and
3. Waiting for real time.

The purpose of the waiting phase is to slow the emulation time down to real time. This slowing down of time is necessary because the actual pieces of HVAC hardware (e.g. chillers or BEMS controllers), are designed to operate in real time, i.e., actual clock time. Thus the waiting time allows actual devices to be integrated with simulated components. Then, as the next emulation time step begins, the computer sends the required variables of the simulated system to the BEMS and receives the control demands from the BEMS via the hardware interface. The time it takes to perform this task, is referred to as the communication time. The next time phase is the simulation time, i.e., the time it takes to compute the responses of the simulated system. Finally, the computer will wait until real time, or clock time, is reached.

2.3.2.4 Real Time Graphics Software

As it is important to observe the behavior and performance of the emulator with the passage of time, software for real time graphics becomes necessary. Graphical display makes it possible for the user to view variables, such as set point temperatures, flow rates, system power consumption, Coefficient of Performance (COP), and much more. Any extremely abnormal behavior, errors, or visually obvious faults can then easily be detected and the emulation can be stopped. Using graphical display might therefore both enhance the user's understanding of what is physically happening in the emulation, and make him or her more efficient.

2.4 EXAMPLES OF PREVIOUS RESEARCH

Over the past few years there has been an increasing worldwide interest in emulators for HVAC applications. The International Energy Agency (IEA) Annex 17 project is an international research effort with the goal of sharing the latest results, experiences, developments, and utilizations of emulators. So far six countries have been involved in Annex 17. These are: Belgium, Finland, France, The Netherlands, United Kingdom, and United States of America. This section provides a short summary of the structure and equipment used in these six different building emulators.

The University of Liège (Belgium) emulator consists of a 386 micro-computer (33 MHz) with a math coprocessor and an I/O interface (Nusgens and Wang [1991]). The computer runs the simulation, the graphics, and manages the I/O interface; while the I/O interface links the simulated system and the BEMS to be tested. The simulation program used is TRNSYS.

The Centre Scientifique et Technique du Bâtiment (France) emulator employs a multi-tasking workstation and a data acquisition and control system (Vaezi-Nejad and Hutter [1990]). The use of the multi-tasking workstation facilitates the change of parameters while the simulation is running. However, the configuration is expensive compared to PC implementations. The simulation program used is HVACSIM+.

The Technical Research Centre of Finland (VTT) emulator consists of two computers and a field device interface (Kärki and Piira [1991]). The computer manages both the simulation of the building system and the communication interface. The other computer is used to observe the emulation in the form of graphics, process diagrams, etc. The simulation program used is TRNSYS.

The TNO (The Netherlands) emulator employs one 386 micro-computer with a math coprocessor and an analog device (Peitsman and Kruk [1991]). The simulation of the building system, management of communication, and real time graphics, are all performed by one computer. The simulation program used is TRNSYS.

The Oxford University (U.K.) emulator uses a workstation for the simulation and a single-board computer based I/O interface (Haves, et. al. [1991]). The microcomputers are programmed in an extension of PASCAL that supports the real time execution , multi-tasking, and communication. The simulation program used is HVACSIM+.

The National Institute of Standards and Technology (U.S.A.) emulator employs a data acquisition and control system, two personal computers (Kelly, et. al. [1991]). One computer runs the simulation while the other one manages the communications. The simulation program used is HVACSIM+.

2.5 CHAPTER SUMMARY

In this chapter it was demonstrated that using an emulator for Heating, Ventilation, and Air Conditioning applications can be a very convenient and flexible way to develop, test, and tune HVAC equipment. The concept of using emulators to develop and test BEMS controllers is of particular interest for this thesis, as it provides the motivation for continuing the work on HVAC control methodologies. Over the most recent years, there has been an increasing worldwide interest in emulators. Particular interesting are the research efforts on emulators for testing Building Energy Management Systems, which were done in the framework of The International Energy Agency Annex 17 program.

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CHAPTER

THREE

DEVELOPMENT OF THE HVAC EMULATOR

This chapter describes the development of the HVAC emulator used to develop and test the controller algorithms for a BEMS. In Section 3.1, a brief introduction on what is involved in the development of the emulator is presented. It is important that the models of the building and HVAC system employed in testing of the controller depict the performance of an actual system accurately at some appropriate level. It is also important to properly define how detailed the analysis should be. Some guidelines on what type of models one might consider for studies such as this, along with a description of the specific types used in this study, are discussed in Section 3.2. The general concept of HVAC controls, and the control of the simulated system, are described in Sections 3.3

and 3.4, respectively. The actual modeling of the BEMS controller, which is the crux of this thesis, is presented in Section 3.5. A chapter summary is found in Section 3.6.

3.1 INTRODUCTION TO DEVELOPMENT OF THE HVAC EMULATOR

In the previous chapter it was established that simulation techniques can be used to emulate a building HVAC system in order to develop BEMS controller algorithms, which later can be implemented into an actual controller. Therefore, a representative HVAC system, such as the one displayed in Figure 1.1 of Chapter 1, was simulated. The Transient System Simulation program - TRNSYS- was used for this task.

The modeled system consists of a multi-zone building, six air handling units (AHU) with one set of cooling coils and variable speed supply air fans each, six main water loops with one variable speed pump each, one chiller with a maximum capacity of 560 tons, and one cooling tower with one constant speed fan and one constant speed condenser pump.

To maintain the building within comfort limits at all times and for all kinds of weather conditions, a BEMS that is responsible for both the local and supervisory control is introduced. The local control involves ensuring proper mixing of ventilation air with return air from the zones, adjusting the stream flow rates on the variable speed supply air fans and main water loop pumps, and operating the cooling tower fan and condenser pump. All of the pumps and fans are set so that the cooling load at the operating set points always are met. The supervisory part of the controller manages the system measurements and data collection (similarly to an actual DA&C system), and sets the operating supply air and chilled water set point temperatures based on a particular control strategy. The goal of this chapter is to demonstrate that a controller, which collects information on the system performance for various operating conditions and set points and learns how to optimally control the system with the passage of time, can be developed.

3.2 MODELING OF THE BUILDING AND HVAC SYSTEM

This section briefly describes the building and HVAC models used to test the controller. All of the models are TRNSYS subroutines that have already been developed and tested. For further details on these models, a TRNSYS manual should be sought.

3.2.1 WEATHER GENERATION

The weather that drives the simulation in this project was based on a Typical Meteorological Year (TMY). TMY data is available for a number of locations in the United States, and is derived from long-term data. The hourly meteorological data used in this particular study includes information about the month of the year, hour of the month, direct normal solar radiation, global solar radiation on a horizontal surface, dry bulb temperature, humidity ratio, and wind speed. Since the focus of this research is simplified to cooling and ventilation for a summer season, a relatively warm and humid climate was desirable. Nashville, Tennessee had these characteristics, and was thus chosen as the weather system forcing function.

In order to convert the insolation data, which is the total solar radiation on a horizontal surface over the previous hour, into a desirable form, a solar radiation processor subroutine must be employed. The TRNSYS TYPE 16 radiation processor, which has the capability to interpolate radiation data; calculate several quantities related to the position of the sun; and estimate insolation on up to four surfaces of either fixed or variable orientation, was therefore used for this task.

3.2.2 THE BUILDING MODEL

In most instances building models are developed because it is desired to learn something about the general cooling and heating energy requirements of a building. Well designed building models can assist engineers and architects in designing more energy efficient buildings. Entrepreneurs (particularly in Germany) have demonstrated that the TRNSYS TYPE 56 Multi-zone building model, may be a viable simulation tool when investigating the possible energy savings in buildings that are still only on the planning and design stage. In the process of designing more energy efficient buildings, this type of interactive work between engineers, architects, contractors, etc., will become increasingly more important.

If it is important to describe the building in great detail, the model mentioned above is recommended. However, if the purpose is solely to obtain a load profile, as was the case in this research, then a simpler model can be used. For this particular study a HVAC system had already been designed and sized for a maximum cooling capacity of 560 tons, or about 2 MW. Continuously variable building cooling loads were desired, but the internal details of how they were arrived at were not important. Therefore, only a simple building model, the TRNSYS TYPE 19 Detailed zone model, was employed.

In TYPE 19 the walls, ceilings, and floors are modeled according to the ASHRAE transfer function approach. The model also has provisions for windows and walls. The effects of both short-wave (solar) and long-wave radiation both inside and outside the structure are considered. Thermal capacitance effects are calculated from an energy balance on the zone air plus any furnishings. The rate of internal moisture gain calculation is based on the addition of moisture due to the ventilation and infiltration air streams.

In the design of the emulator it is only necessary to model one room, since it is assumed that the building can be approximated by identical levels, consisting of one room per level. The floor and ceiling can be treated as intercore partitions, as it is assumed that every room in the building is at the same temperature at all times. Figure 3.1 is a simple schematic of the modeled zone. The window in the room is facing south. Also, as indicated in the figure, there are zone heat flows due to the solar radiation, ambient conditions, machines and equipment, number of occupants, and lighting. The summation of these heat flows yields the total sensible cooling load of the zone. The zone humidity ratio is allowed to float between a maximum and a minimum limit. If the calculated humidity ratio falls outside these limits, then the humidification or dehumidification energy required to maintain the desired humidities is output. Otherwise, the latent load is zero.

After the modeling of the zone was completed, the maximum cooling energy requirement during the summer for that individual zone was found. With this information it was possible to scale up the cooling load so that it resembled that of a large multi-zone building, for which the HVAC system was originally designed. Similarly, the ventilation flow, or the supply air flow rate, provided by the HVAC system was scaled down by the same factor.

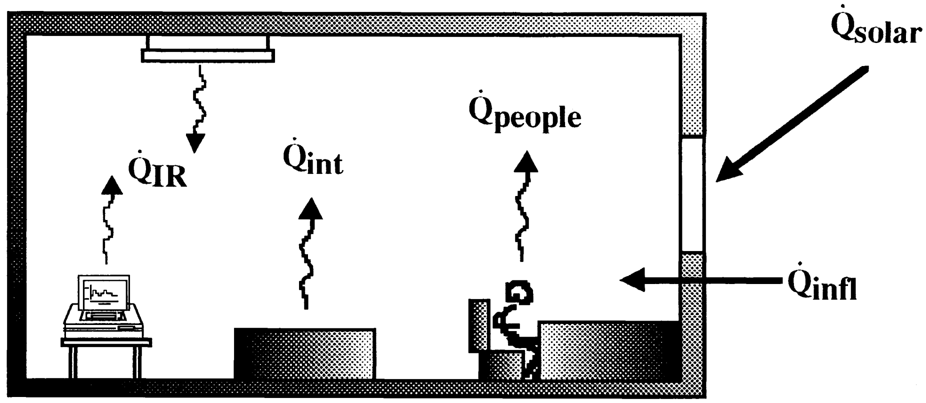

Figure 3.1 Schematic of the simulated zone and its energy flows

3.2.3 THE HVAC EQUIPMENT COMPONENTS

The HVAC equipment components utilized in the system simulations consist partly of standard TRNSYS subroutines. These include:

1. TYPE 51 Cooling Tower,
2. TYPE 52 Cooling Coil,
3. TYPE 53 Parallel Chiller, and
4. TYPE 3 Pump or fan

In addition, several electric motors and flow controllers were employed (Pape [1989]). The electric motor models operate either at constant or variable speed. The flow converters were necessary because several air handling units were used. In the flow converters, the sum of the water flow rates through the coils are set equal to the water flow through the evaporator of the chiller while the flow from the chiller is divided into equal flows for the air handling units. In this study, six air handling units were employed.

3.3 CONTROL OF HVAC SYSTEMS

HVAC system are usually sized to meet the maximum building heating and cooling loads for which they were designed. However, from a functional standpoint, the air conditioning system will seldom operate at these maximum design capacities, and thus controls are needed. The closing of a valve in a water line, in order to reduce the flow rate, might be one type of such controls.

Local control systems for HVAC systems have many important assignments, and must therefore be robust, reliable, and easy to maintain. In general, they must have the capability to:

1. Regulate the HVAC system so that comfortable (and required standard) conditions are maintained in the occupied space,
2. Operate the equipment efficiently, and
3. Protect the equipment and building from damage and the occupants from injury.

The basic elements of a local control system are shown in Figure 3.2, where the controlled condition, e.g., a temperature, is perceived by a sensor and converted into a pneumatic pressure or voltage, which in turn is compared to a pressure or voltage representing the desired condition, such as a set point temperature (Jones and Stoecker [1986]). If the two signals do not match, the actuator repositions a valve, damper, or similar device that has the potential of changing the temperature.

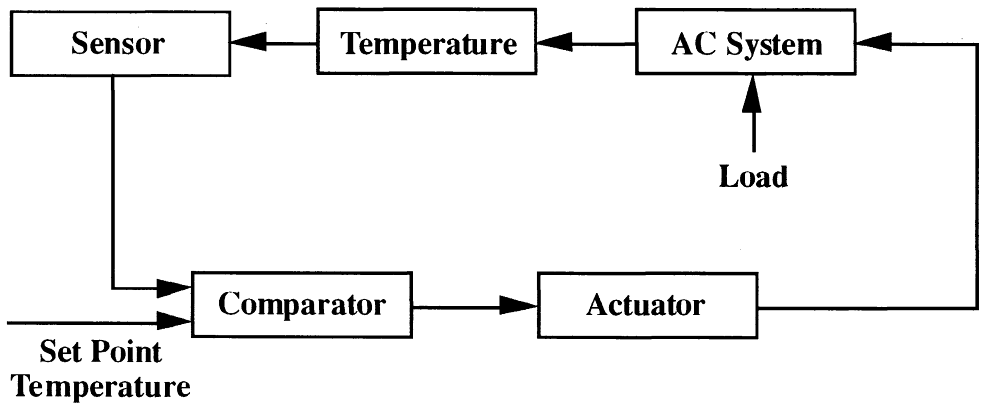

Figure 3.2 Basic elements in a local control system

In an actual HVAC system various types of sensors, actuators, and other hardware can be installed. These include: (1) Pneumatic, (2) Electric, (3) Electronic, and (4) Direct

Digital (DDC). The standard type of control systems that have been used and are still being used in large building systems today, are essentially pneumatic while electric systems have traditionally been used in smaller buildings. Hybrid systems, where the sensors and transmission of signals may be electric or electronic while the final force at the actuator is pneumatic, is also fairly common. However, over the most recent years the arrival of new and more reliable DDC systems are gradually replacing the more traditional pneumatic and electric control systems (American Auto Matrix Incorporation). And in more modern buildings DDC systems are convenient to use when interfacing the HVAC system with the BEMS.

The introduction of digital control of HVAC systems has set the scene for more usage of computer based controls, which also presents the opportunity to acquire large amounts of data on the air conditioning system. Valuable information, such as total system power consumption with corresponding flow rates, temperatures, pressures, and ambient conditions, can therefore easily be stored, analyzed, and applied in future control strategies. With the correct approach, this could possibly be done automatically in a BEMS controller.

3.4 CONTROL OF THE SIMULATED HVAC SYSTEM

As mentioned above, it is important to operate an air conditioning system as cost effectively as possible. The control of the simulated HVAC of this study involves the implementation of a set of supervisory and local loop control algorithms. The purpose of the two sections below, is mainly to provide a transition between the previous research and development of optimal control strategies, and the work of this thesis, which deals more with the implementation and testing of these strategies.

3.4.1 SUPERVISORY CONTROL

The control of the simulated HVAC system is presented in Figure 3.3 and discussed below. A BEMS controller is responsible for both the local loop and supervisory control of the system. The supervisory part of the controller involves several aspects. Outside air temperature and humidity, T_{amb} and ω_{amb}, are sensed. The ratio of mixing outside and return air, $F_{o,set}$, is set by the controller, depending on the amount of fresh air desired. Also set in the controller are the supply air temperature out of the cooling coil, $T_{sa,set}$, and the chilled water temperature out of the evaporator of the chiller, $T_{cw,set}$. These two set point temperatures are determined from either an intuitive or optimal control strategy, and will be discussed in more detail below. In addition, measurements of the supply air temperature, humidity, flow rate, and static pressure; T_{sa}, ω_{sa}, $\dot{m}_{sa}$, and p_s, respectively, are made. The zone temperature and humidity, T_z and ω_z, are also measured.

The local control of the simulated system involves adjusting various flow rates so that the control set point temperatures are met. As indicated in Figure 3.3, the controlled variables are

1. $T_{sa,set}$ - the supply air set point temperature,
2. $T_{cw,set}$ - the chilled water set point temperature, and
3. $T_{z,set}$ - the zone set point temperature.

The manipulated variables that need to be adjusted so that these set point temperatures are maintained are

1. $\dot{m}_{cw}$ - the chilled water mass flow rate,
2. $\dot{m}_{ref}$ - the refrigerant mass flow rate, and
3. $\dot{m}_{sa}$ - the supply air mass flow rate.

In this study only the influence of the supply air and chilled water set point temperatures on the system performance will be considered. The zone temperatures are for simplicity held constant, as it was assumed that all the zones required the same amount of cooling. The cooling tower fan and the condenser pump speeds, which are both set by the controller, were also held constant.

Another important assumption that can be made in simulation studies such as this is that the local control systems can be treated as steady-state models. Thus, it is assumed that all the calculated equipment settings are accommodated in every hour of the simulation (or any other user specified simulation time step). An example of this is found in the refrigeration cycle, where the expansion valve is regulated with perfect accuracy so that the chilled water set point temperature is reached at all times.

In summary, the following assumptions and simplifications were made:

(1) constant cooling tower fan and condenser pump speeds

(2) constant mass fraction of outdoor air and zone temperatures

(3) equal load on all six air handling units

(4) steady state operation

(5) perfect local loop control.

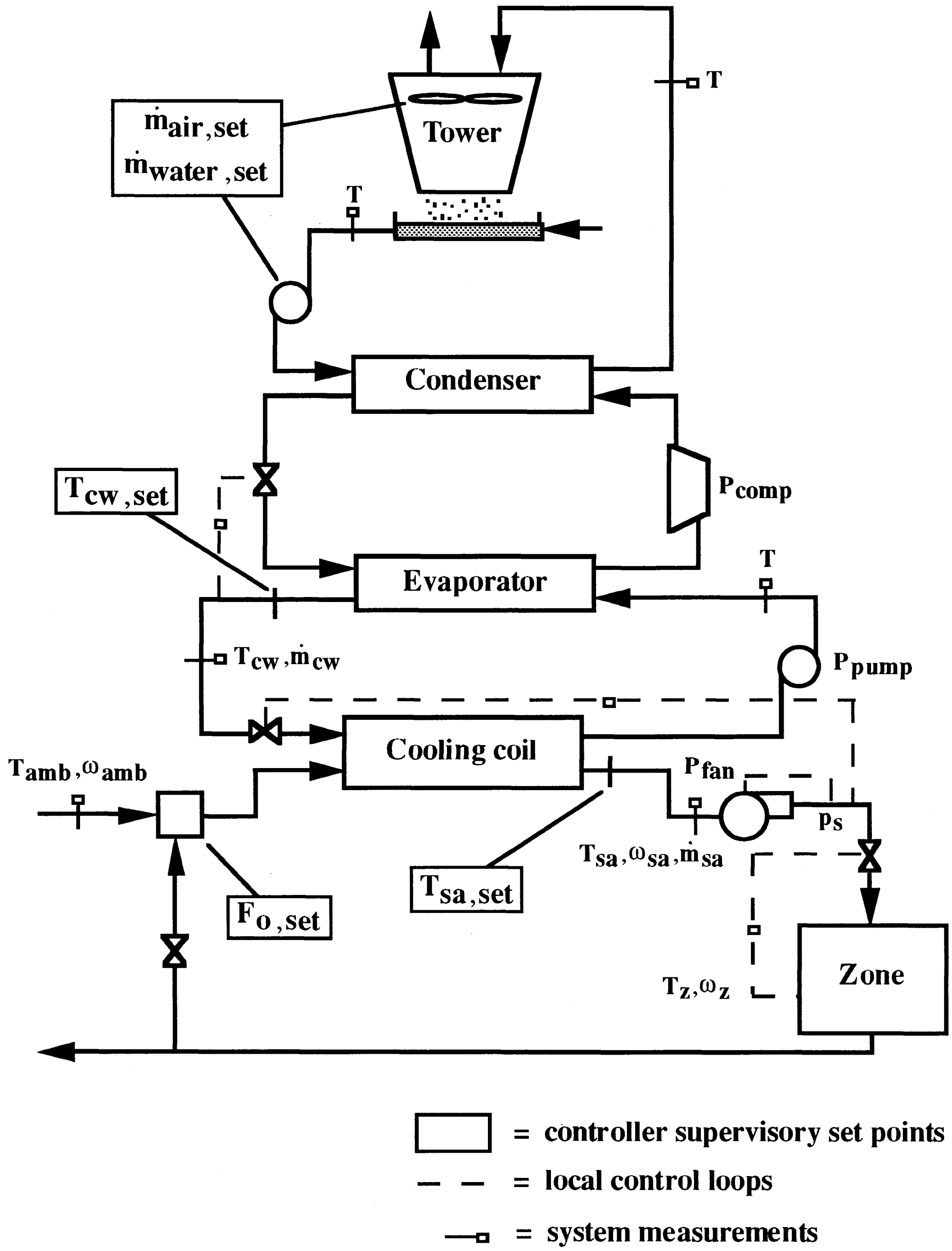

Figure 3.3 Control of the simulated HVAC system

3.4.2 LOCAL LOOP CONTROL

The local loop controller for the cooling coil used in the simulations of this study has little to do with local control in an actual system, but is included merely for simulation convergence purposes: The cooling coil component requires all the stream variables as inputs while all the exit stream variables are calculated and provided as outputs. However, as the desired air temperature out of the cooling coil, $T_{sa,set}$, is set by the BEMS controller a feedback local loop controller must be employed.

Figure 3.4 is a block diagram demonstrating the decision process and information flow for the cooling coil simulation problem. The required mass flow rate of the air is calculated from the room and supply air set point temperatures, the heat gain from the supply air fan, and the sensible building load. For a given set of ambient conditions, the coil inlet humidity and coil air outlet (i.e., supply air) temperature and humidity are evaluated. The calculated air supply temperature is then compared to the supply air set point temperature. If the temperatures are not equal (i.e., not within a specified tolerance), the water mass flow rate through the coil is changed. A secant method is used to reach quick convergence between these two temperatures. Once convergence has been reached, a new room humidity is evaluated in the zone, and a new coil air inlet humidity is evaluated and input to the cooling coil. It should be noted here that close attention must be paid to the system initial conditions and to the capacitance effects of the zone. Actually, it was found that for the zone to reach steady state behavior, a *stabilizing period* of about 48 hours was necessary.

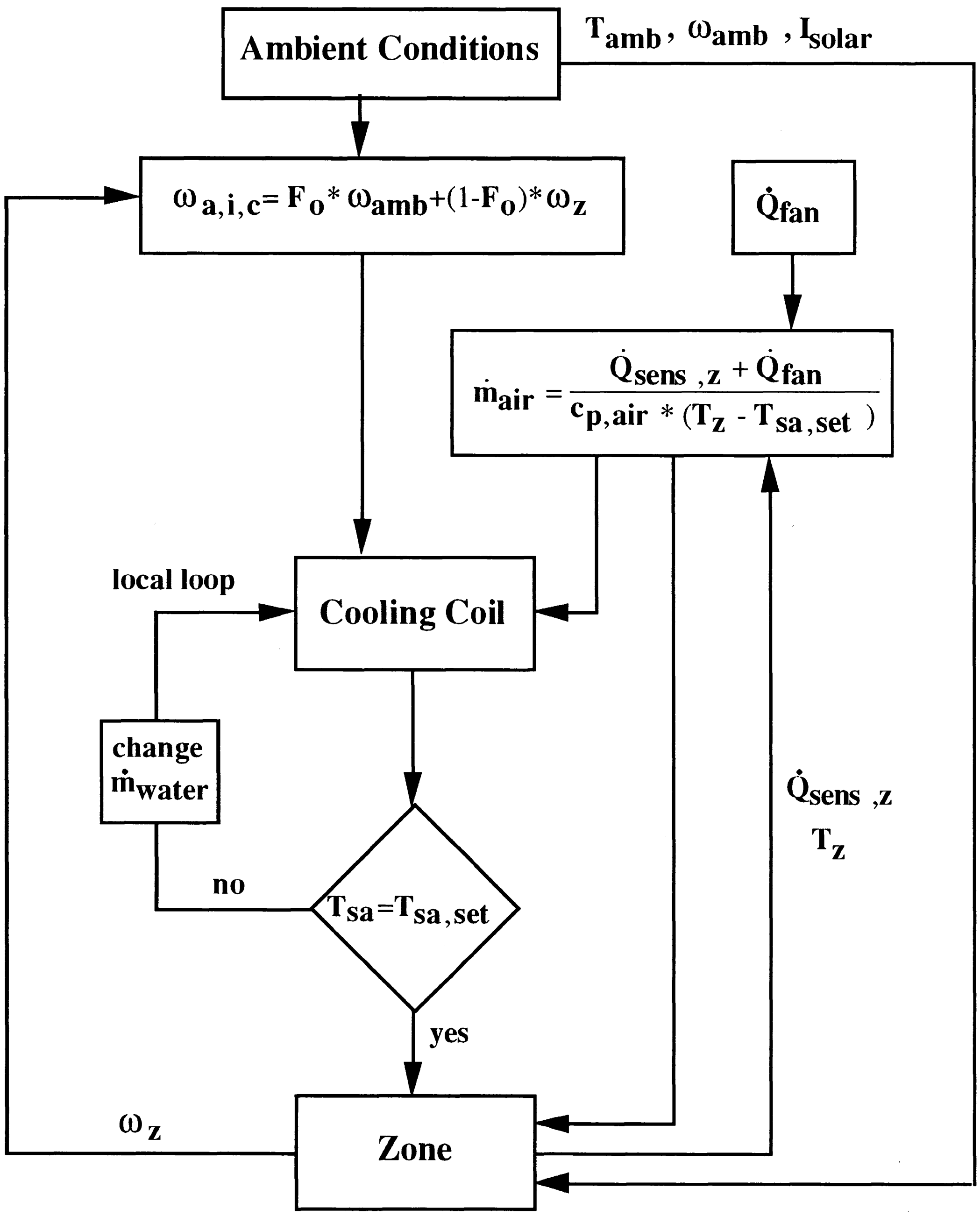

Figure 3.4 Information block diagram of the decision process and information flow around the cooling coil

3.5 MODELING OF THE BEMS CONTROLLER

The sections below describe the modeling of the Building Energy Management System controller developed for this thesis. In Section 3.5.1, the general concept of the control of the simulated HVAC system is presented. Section 3.5.2 illustrates the possible energy savings associated with *smart* control strategies. Next, in Section 3.5.3, follows a brief description of an intuitive control scheme. The theory behind an optimal control methodology is explained in Section 3.3.4. Sections 3.3.5 to 3.3.7, discuss the implementation of the optimal control strategies into the BEMS controller.

3.5.1 GENERAL CONCEPT OF THE CONTROLLER

Many control strategies employed in air conditioning systems today are quite simple. The reason for this is that many engineers still yearn for simple control systems that are easy to understand and maintain. However, to achieve good control of the space condition while at the same time keeping the total operating costs at a minimum, a BEMS controller can be utilized.

The basic idea behind the smart controller developed in this research is that the controller is able to *learn* how to better operate the system as time goes by. To complete this task several control strategies were considered. In this study a control strategy is understood as the way in which the controlled variables, i.e., the supply air and chilled water set point temperatures, are set. Initially, before a control is established, a start-up control scheme, using a simple and fairly conventional control strategy was used, and is referred to as *intuitive control.*

The BEMS controller uses intuitive control for a specified system *learning period.* The learning period is referred to as the period when the controller is learning about the behavior and characteristics of the system. When sufficient information about the system performance has been learned, a regression is performed and, based on optimal control ideas, a new set of control variables are found. This *on-line* collecting, handling, analyzing, and processing of data, continues automatically until the end of the simulation period. Figure 3.5 demonstrates the logic of the on-line controller during the simulation progress.

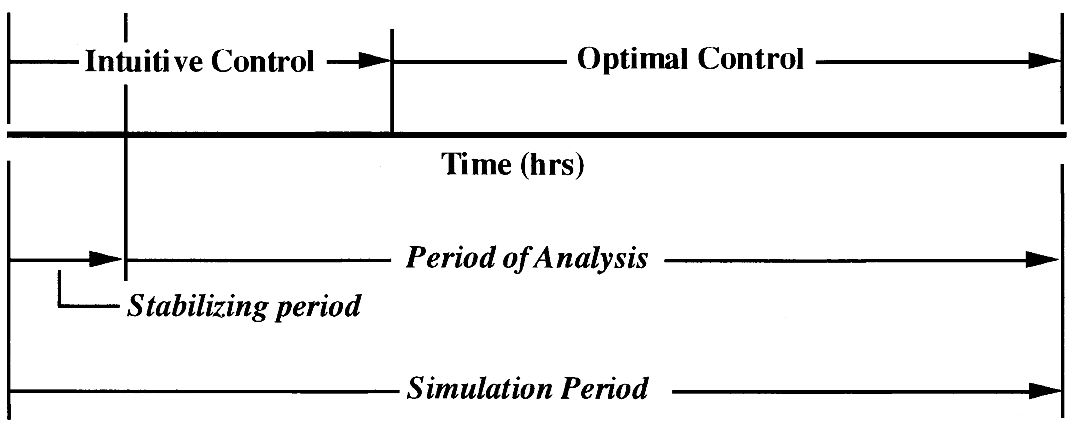

Figure 3.5 Controller strategy during simulation progress

3.5.2 ILLUSTRATION OF SYSTEM PERFORMANCE

In order to properly model the controller it is necessary to have an understanding of how a typical HVAC system, such as the one simulated in this study, behaves under different control set point temperatures and forcing functions. The forcing functions are the ambient wet-bulb temperature, total building cooling load, and sensible heat ratio of the building load; or T_{wb}, Load, and SHR, respectively.

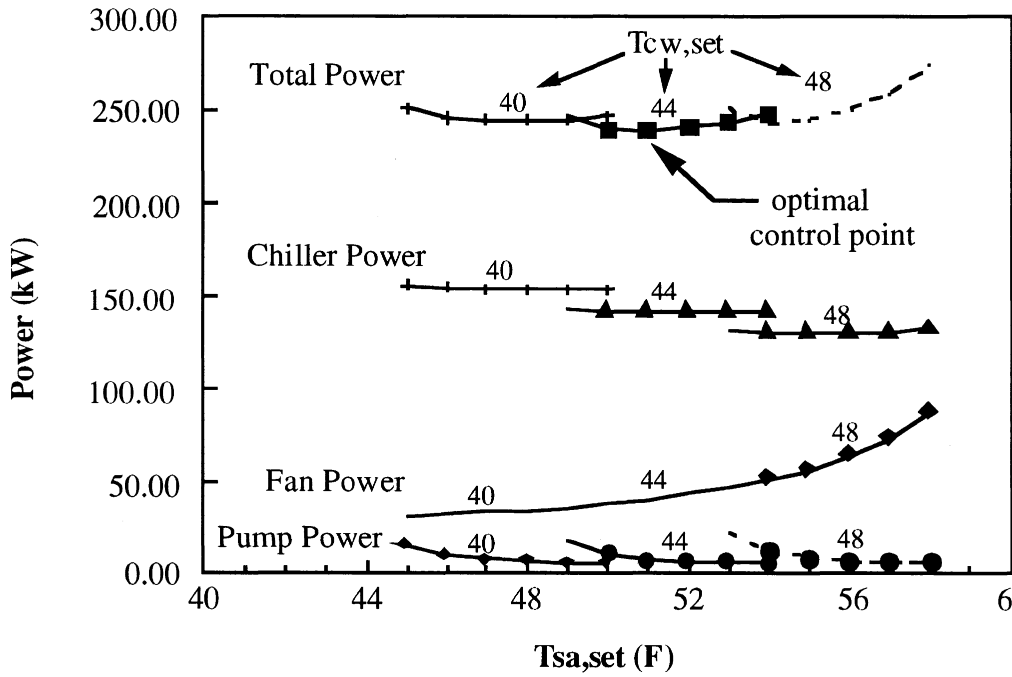

Figure 3.6 Components and total system power as a function of the supply air and chilled water set point temperatures

Figure 3.6 is an illustration of how the total system power, air handling unit fan power, chiller power, and main water loop pump power of the HVAC system varies for different set point temperatures (Pape[1989]). The power consumptions of the cooling tower fan and condenser pump are constant for all conditions, and are therefore not included in the figure. A fixed set of forcing functions (T_{wb} = 65 °F, Load = 300, SHR = 0.8) were used. As seen from the figure, there exists an optimal combination of set points at around a $T_{cw,set}$ of 44 °F and a $T_{sa,set}$ of 51 °F, which minimizes the total power consumption of the system. This illustration is important for the understanding of the following discussion.

3.5.3 INTUITIVE CONTROL

As it was demonstrated above, there exists an optimum set of control variables that minimizes the total system power consumption. In order to obtain this optimum, a data base with information about the system performance under various operating conditions must first be gathered. This is termed the learning period. Since there are many ways to operate the system in the learning period, a control scheme needs to be set up. An intuitive control scheme, similar to one used by operators of actual HVAC installations, was employed. Figure 3.7 describes the main features of the intuitive control scheme and is described below.

The intuitive control works is set up as follows: Five basic operating set-points were established. These include:

1. $T_{sa,low,set}$ - low end supply air set point temperature,
2. $T_{sa,high,set}$ - high end supply air set point temperature,
3. $T_{cw,low,set}$ - low end chilled water set point temperature,

4. $T_{cw,high,set}$ - high end chilled water set point temperature, and
5. $F_{cap,set}$ - fraction of total chiller capacity set point.

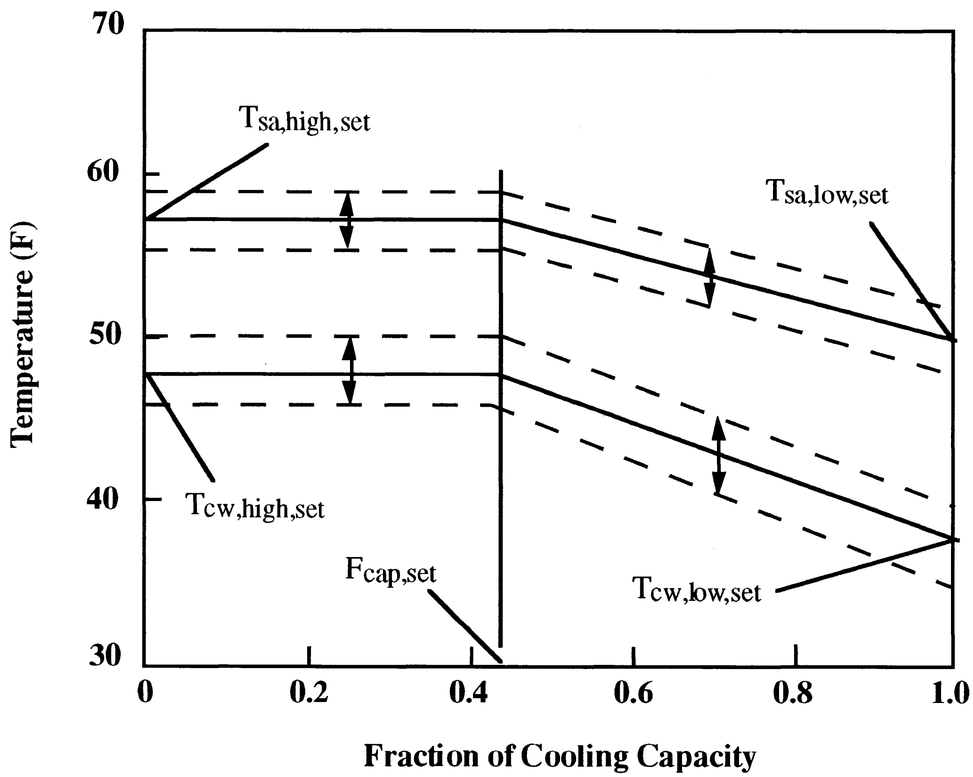

Figure 3.7 Intuitive control scheme

The $T_{sa,low,set}$ and $T_{sa,high,set}$ are essentially the minimum and maximum supply air set point temperatures the system may operate at while the $T_{cw,low,set}$ and $T_{cw,high,set}$ are the minimum and maximum chilled water set point temperatures. The $F_{cap,set}$ is the ratio between the total building load and the maximum chiller capacity (560 tons). If, during operation, the ratio of the building load to the capacity is larger than the $F_{cap,set}$, then the control set point temperatures are lowered automatically. The basis for this linear control scheme at high loads is based on the experience that the control variables can be expressed as linear functions of the forcing functions. The reasons for this will become more clear from the succeeding sections. However, it also makes sense from a more practical point of view, because as the building load increases, colder air must be ventilated through the zones in order to meet the load. By the same token, colder chilled water is required to meet the load at the cooling coils.

Another important consideration, when initially arranging the intuitive control scheme, is the fact that there exists a minimum temperature difference between the $T_{sa,set}$ and $T_{cw,set}$, that one can operate the system at (Tuzson [1992]). This is because of the heat transfer limitations of the cooling coils. Therefore, the set point temperature difference is always kept relatively far away from this minimum, and is increased at higher loads. The determination of the system temperature constraints will be discussed below.

Finally, as it was desirable to learn how the system performed for a relatively wide range of operating set points, the possibility of varying the control scheme slightly from day to day was also built into the controller. The dashed lines in Figure 3.7 indicates this variation.

3.5.4 OPTIMAL CONTROL METHODOLOGY

A methodology for controlling HVAC systems which determines the independent control variables, T_{cw} and T_{sa}, that minimize the instantaneous cost of operating chilled water systems was developed by Braun [1988]. The determined values do not represent the absolute minimum, but values very close to the optimum, and is therefore termed near-optimal control. An overall empirical cost function for the total power consumption of the cooling plant used in this study was developed by Pape [1989]. The near-optimal control algorithms employed in this thesis were based on the above work, and is for convenience referred to as optimal control.

3.5.4.1 System Operating Cost Function

In the vicinity of the optimal control points, the total system power consumption may be approximated with a quadratic function of the continuous control variables and the uncontrolled variables. The total power curve of Figure 3.6 illustrates this quadratic behavior. The following generic function may be used to represent the total system instantaneous operating cost:

$$J(f,M,u) = u^T\widehat{A}u + \widehat{b}^T u + f^T\widehat{C}f + \widehat{d}^T f + f^T\widehat{E}u + \widehat{g} \tag{3.1}$$

where $\widehat{A}$, $\widehat{C}$, and $\widehat{E}$ are coefficient matrices, $\widehat{b}$ and $\widehat{d}$ are coefficient vectors, $\widehat{g}$ is a scalar, superscript T denotes the transposed vector, and

J = instantaneous operating cost

M = vector of discrete control variables

u = vector of continuous control variables

f = vector of uncontrolled variables

In this study the discrete control variables are the relative supply air fan and main water loop speeds and the number of operating chillers, pumps, and fans. The independent control variables are the supply air and chilled water temperatures (T_{sa}, T_{cw}) while the uncontrolled variables consist of the ambient wet bulb temperature, building load, and sensible heat ratio (T_{wb}, Load, SHR).

3.5.4.2 Optimal Control Algorithm

A solution for the optimal control vector of equation (3.1) that minimizes the cost may be determined analytically by applying the first order condition for a minimum. The derivatives of the Jacobian of the quadratic function for power with respect to the control variables is equated to zero:

$$\frac{\partial J(f,M,u)}{\partial u} = 0 \tag{3.2}$$

Solving for the optimal values for the continuous control variables yields

$$u^* = k + Kf \tag{3.3}$$

where,

$$k = -\frac{1}{2}\hat{A}^{-1}\hat{b}$$

$$K = -\frac{1}{2}\hat{A}^{-1}\hat{E}$$

Assuming that there are no constraints on the controlled variables, the system cost can be computed as

$$J^* = f^T \theta f + \sigma^T f + \tau \tag{3.4}$$

where,

$$\theta = K^T \widehat{A} K + \widehat{E} K + \widehat{C}$$
$$\sigma = 2K\widehat{A}k + K\widehat{b} + \widehat{E}k + \widehat{d}$$
$$\tau = k^T \widehat{A} k + \widehat{b} k + g$$

The control using equation (3.3) results in a minimum cost only if the Hessian of the cost function is a positive-definite matrix, i.e., $\widehat{A}$ of equation (3.1) is a positive-definite. If this condition holds and equation (3.1) accurately depicts the operating costs, then the optimal continuous control variables vary as near linear functions of the uncontrolled variables.

In general, a different linear relationship applies to each feasible combination of discrete control modes. However, in this study only one type of system was analyzed, i.e., only one set of discrete control variables existed, and thus only one cost formula needed to be developed. The above analysis does not include bounds and constraints on the continuous control variables and this problem is discussed below.

After the coefficients of equation (3.1) have been determined empirically, the derivatives with respect to the controlled variables can be computed in order to obtain a set of linear control laws. The total operating cost, J, can be represented by $P_{formula}$ and the continuous control variables, u, can be represented by $T_{cw,set}$ and $T_{sa,set}$. Hence, from equation (3.2), the derivatives of the quadratic power formula with respect to the chilled water and supply air temperature can be taken, and the following two equations can be solved analytically to yield the optimal set point temperatures:

$$\frac{\partial P_{formula}}{T_{cw,set}} = 0 \tag{3.5}$$

$$\frac{\partial P_{formula}}{T_{sa,set}} = 0 \tag{3.6}$$

According to equation (3.3), the set point temperature equations can be written as:

$$T_{sa,set,opt} = g_1(T_{wb}, \text{Load}, \text{SHR}) \tag{3.7}$$

$$T_{cw,set,opt} = g_2(T_{wb}, \text{Load}, \text{SHR}, T_{sa,set,opt}) \tag{3.8}$$

These two unbounded set point temperature are linear functions of the forcing functions due to the assumption of the quadratic dependence of power on these variables.

3.5.5 MATHEMATICAL DESCRIPTION OF REGRESSION

The coefficients in equation (3.1), which depend on the discrete control variables, i.e., the various operating modes, need to be determined empirically. To complete this task a least square linear regression technique was employed.

The number of possible coefficients in terms of the controlled and uncontrolled variables in the quadratic equation for each set of discrete control modes is

$$N_{coef} = N_u^2 - \frac{N_u(N_u-1)}{2} + N_u + N_f^2 - \frac{N_f(N_f-1)}{2} + N_f + N_f N_u + 1 \tag{3.9}$$

where N_u is the number of continuous controlled variables and N_f the number of uncontrolled variables. In this study there are two controlled variables ($T_{sa,set}$, $T_{cw,set}$) and three uncontrolled variables (T_{wb}, Load, SHR), thus 21 coefficients need to be determined.

The exact model of the quadratic power formula has the form

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_{n+1} x_1^2 + \ldots + \beta_{2n+1} x_1 x_2 + \ldots \tag{3.10}$$

where y is the response, x_i are the predictors, β_i are the regression coefficients, and n is the number of variables in the equation (n=5 in this case). A second order least squares linear regression estimates the β_i's with b_i's and predicts

$$\hat{y} = b_0 + b_1 x_1 + b_2 x_2 + \ldots + b_{n+1} x_1^2 + \ldots + b_{2n+1} x_1 x_2 + \ldots \tag{3.11}$$

where $\hat{y}$ is the fitted or predicted value.

The coefficients can be estimated using the matrix equations:

$$\hat{Y} = \hat{X}\hat{\beta} \tag{3.12}$$

where the matrices are arranged as

$$\hat{Y} = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_N \end{bmatrix}, \quad \hat{X} = \begin{bmatrix} 1 & x_{11} & x_{21} & \cdots & x_{11}^2 & \cdots & x_{41}x_{51} \\ 1 & x_{12} & x_{22} & \cdots & x_{12}^2 & \cdots & x_{42}x_{52} \\ & \vdots & & & \vdots & & \vdots \\ 1 & x_{1N} & x_{2N} & \cdots & x_{1N}^2 & \cdots & x_{4N}x_{5N} \end{bmatrix}, \text{ and } \quad \hat{\beta} = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \beta_{N_{coef}} \end{bmatrix}$$

and N is the number of data sets collected (can not be less than 21 in this case).

After some matrix manipulation and rearranging, the coefficients matrix can be solved analytically by (Cheney and Kincard [1985])

$$\hat{\beta} = \left(\hat{X}^T\hat{X}\right)^{-1}\left(\hat{X}^T\hat{Y}\right) \tag{3.13}$$

where,

$\hat{X}^T$ = transpose of $\hat{X}^T$

$\left(\hat{X}^T\hat{X}\right)^{-1}$ = inverse of $\left(\hat{X}^T\hat{X}\right)$

In this study the 5 predictors used in equation (3.9) were T_{wb}, Load, SHR, $T_{cw,set}$, and $T_{sa,set}$ while the response was the total system power consumption.

As it may be anticipated from equation (3.11), the values of the coefficients depend strongly on the number of data sets (i.e., sets of predictors and corresponding response) used in the regression. The amount of data to be regressed is directly related to the length of the learning period: The longer the learning period the more data becomes available. The issue of an optimal learning period length will be investigated in the next chapter.

Another interesting problem that was encountered, was that the results from the regression were significantly affected by the format of the numerical input data. It was discovered that only data which had been rounded off (in this case the data was rounded off to the fourth decimal), gave *good* results, i.e., reasonable estimated coefficients. The reason for this was that in many instances the difference between the data from hour to hour was fairly small. This was especially true for the hour to hour difference between the operating set point temperatures used during intuitive control. Hence, if the set points included in the regression were not rounded off, they would always have an effect on the regression while if they were rounded off they did not. It was also necessary to perform all of the regression calculations in double precision.

An example of the accuracy of the regression is shown in Figure 3.8 below, where the results are from a 3 week period of analysis. The plot shows the power predicted by equation (3.11) versus the total power of all the simulated HVAC system components.

The root mean square, which is evaluated from

$$\mathrm{RMS} = \sqrt{\frac{\sum_{i=1}^{N} \left(\hat{y}_i - y_i\right)^2}{(N-1)}} \tag{3.14}$$

was 1.746 kW, or about 0.6% of the average value of the power. Thus, it seems that the developed quadratic formula accurately describes the total power consumption of the modeled system. Furthermore, the RMS is an important check on the exactness of the regression, and is therefore included as one of the BEMS controller output variables.

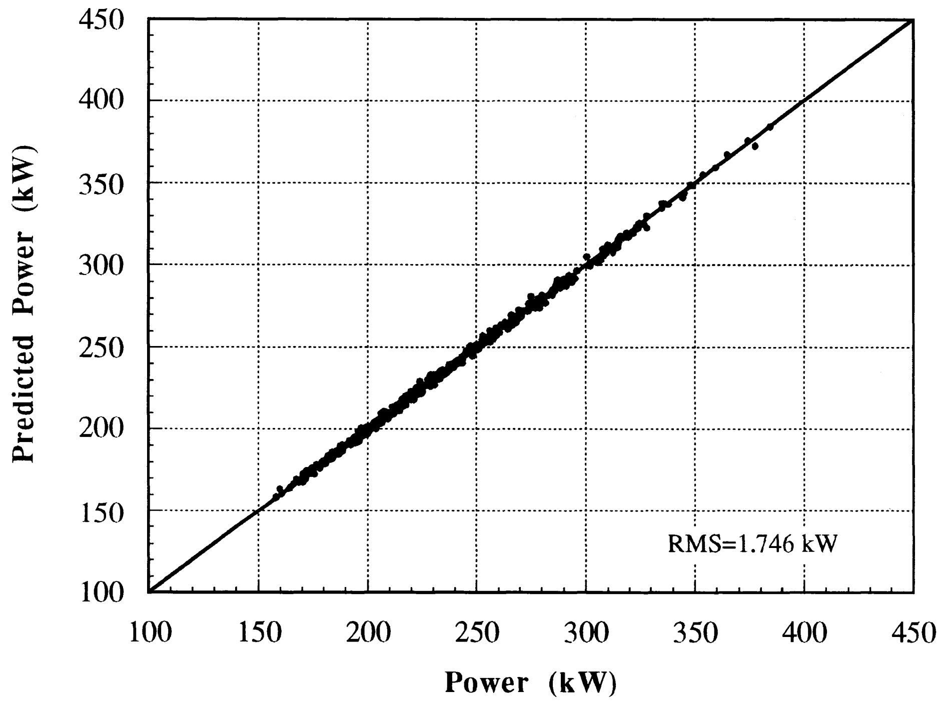

Figure 3.8 Predicted Power versus Model Power

3.5.6 SYSTEM TEMPERATURE CONSTRAINTS

In the optimal control methodology it is assumed that there are no constraints on the control variables. However, this is not the case in an actual system. In the cooling coil, for example, there exists a set of very real temperature limits. The chilled water set point temperature, for instance, must allow for sufficient dehumidification and prevent freezing in the evaporator tubes. In addition, there also exists a minimum temperature difference between the supply air and chilled water set point temperatures to transfer the required heat flow, due to the finite size of the heat exchangers.

All of the above constraints are included in the controller. Recommended upper and lower operating chilled water temperatures of 55 °F and 38 °F, respectively, were selected. The other constraint included in the controller was found by forcing the system to a minimum temperature difference. However, this *experimental* procedure is most realistic for simulation studies, such as this, because it involves testing the HVAC system over a wide range of conditions, including some which may be very hard on the equipment. Therefore, a more indirect approach, which focuses on learning the behavior and performance of the cooling coil on-line, was developed. The two sections below describe these two different cooling coil analysis'.

3.5.6.1 *Experimental* Cooling Coil Analysis

The temperature difference constraint is a function of the cooling coil, which requires a minimum temperature difference between the supply air and chilled water set point temperatures (Tuzson [1992]). In order to quantify this constraint, the simulation model was run over a variety of operating conditions. In each run, the supply air temperature was incrementally decreased while the chilled water temperature was increased until the load could not be met. This procedure was repeated for various building loads and sensible heat ratios. Since the ambient wet-bulb temperature proved to have no significant effect on the results, the constraint could be estimated as

$$\Delta T_{min} = a_0 + a_1 * SHR + a_2 * Load \tag{3.15}$$

The results of this curve fit is shown in Figure 3.9, where the temperature difference predicted by equation (3.15) are indicated by the dots and the straight line represents perfect prediction. The predicted minimum temperature difference was within approximately 0.5 °F. It is also seen that equation (3.15) is a fairly conservative estimation because it actually under predicts the constraint slightly, and was for this reason included in the controller.

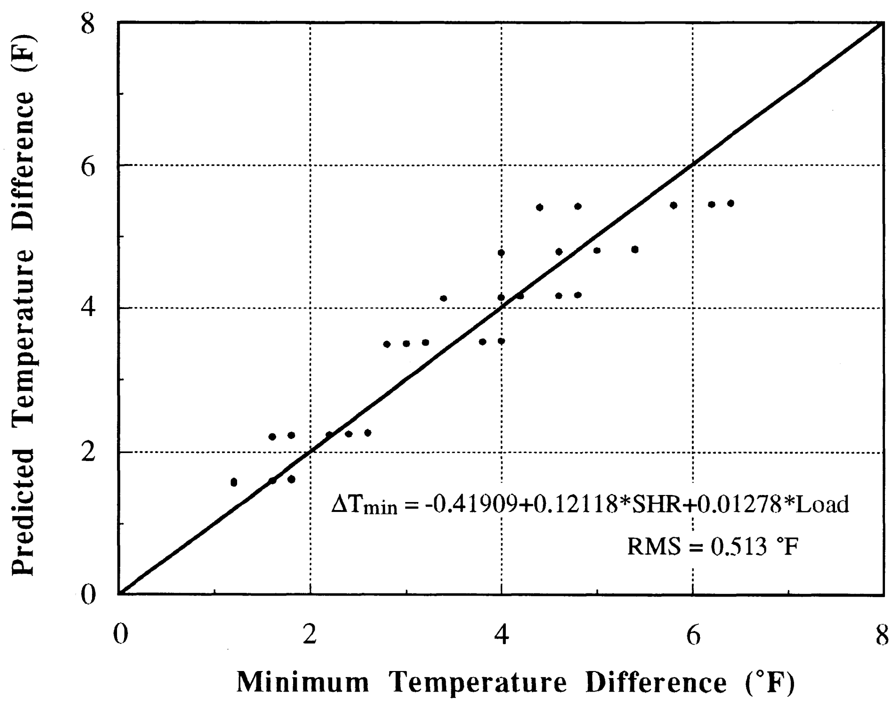

Figure 3.9 Predicted Minimum Temperature Difference versus Minimum Temperature Difference

3.5.6.2 On-line Cooling Coil Analysis

A smart BEMS controller must have the capability to learn, on-line, the characteristics of the cooling coil over time. This becomes particularly important in HVAC systems where such performance characteristics are not readily available from manufacturers or other sources. Therefore, an analysis of the cooling coil was performed to ascertain the requirements for inclusion in a BEMS. The analysis was performed with constructed data, but the procedure would be the same if actual weather is used.

It was found that the cooling coil can be analyzed in two different modes: (1) A sensible mode, and (2) a combined sensible and latent mode. In the sensible mode heat transfer is assumed to occur on a completely dry cooling coil while in the combined mode heat transfer occurs on a partially wet and dry coil. As it has been demonstrated by Braun, et. al. [1989], the effectiveness of the cooling coil can be estimated (within 5% compared to a detailed analysis) by assuming the entire coil to be either wet or dry. Hence, a sensible cooling coil analysis can be performed. It has also been demonstrated that as the number of passes in a heat exchanger increases beyond about four, the performance of a cross-flow heat exchanger approaches that of a counter-flow. This information makes it possible to use either the log mean temperature difference (LMTD) method or the effectiveness-NTU method as a basis for the cooling coil analysis.

By assuming the cooling coil to be completely dry, it is possible to determine the overall heat transfer conductance, UA, by using a relatively straight forward heat exchanger approach. In general the overall heat transfer coefficient may be written as (Incropera and DeWitt [1990])

$$\frac{1}{UA} = \frac{1}{(\eta_o hA)_c} + \frac{1}{(\eta_o hA)_h} \tag{3.16}$$

where c and h refer to the hot and cold fluids (air and water in this case), respectively, η_o is the overall surface efficiency or temperature effectiveness of a finned surface, and h is the convective heat transfer coefficient. The conduction resistance and fouling factors were neglected.

For turbulent flow through the coils the Nusselt number, Nu, is approximately proportional to the Reynolds number, Re, raised to the power of 0.8. Analogously, the heat transfer coefficients for the air and water side can be expressed as

$$h_a \approx \dot{m}_a^{0.8} \tag{3.17}$$

$$h_w \approx \dot{m}_w^{0.8} \tag{3.18}$$

Substituting equations (3.17) and (3.18) into equation (3.16), and rearranging yields

$$UA_{pred} = \frac{c_0 \left(\dot{m}_a \cdot \dot{m}_w\right)^{0.8}}{c_1 \dot{m}_a^{0.8} + c_2 \dot{m}_w^{0.8}} \tag{3.19}$$

where c_1 and c_2 are constants and c_0 the product of c_1 and c_2. For a given set of UA, $\dot{m}_a$, and $\dot{m}_w$'s, these constants can be found by utilizing non-linear regression techniques. The "measured" (in this case measured means outputs from the various simulation components) UA value can be found from

$$UA_{meas} = \left(\frac{LMTD}{\dot{Q}_{coil}}\right)_{meas} \tag{3.20}$$

where the cooling coil heat transfer rate, $\dot{Q}_{coil}$, and LMTD, both can be obtained from the simulation. (The UA is only a function of the air and water inlet and output temperatures, all of which can be converted to simulation outputs).

Several *off-line* experiments were performed to test the UA prediction model of equation (3.19). Figure 3.10 below, which is one example of one such experiment, demonstrates the accuracy of the UA model. The figure shows that the model of equation (3.1) predicts the measured UA of equation (3.20) very well, although there is some bias present. The same pattern of the bias was found for other curve fits using different sets of data.

In an on-line situation, the controller would have to collect information on the cooling coil air and water mass flow rates, inlet and outlet stream temperatures, and heat transfer rate. With this information an expression for UA, in terms of the supply air and chilled water mass flow rates, can be found using equation (3.19) in the recommended approach above. A critical UA, evaluated from the maximum supply air and chilled water flow rates, must then be calculated. For a pair of optimal set point temperatures, the LMTD can be computed and the controller can predict the coil heat transfer rate. The maximum possible heat transfer rate for the given set of stream flow and temperature conditions (i.e., the conditions at that instant in time) can also be calculated. If the predicted coil cooling load is greater than that of the maximum possible load, some kind of control action must be taken: Either the supply air temperature must be set higher, or the chilled water lower. This procedure must be repeated for every time step, and the UA prediction expression needs to be updated continuously, so that the minimum temperature difference constraint can be treated properly.

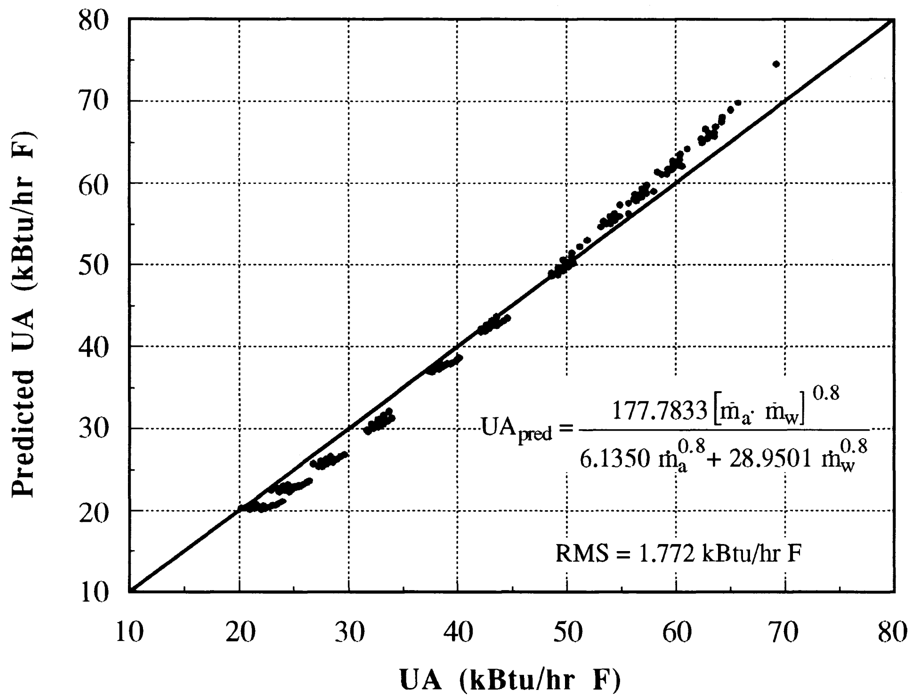

Figure 3.10 Predicted versus measured overall heat transfer conductance

3.5.7 DESCRIPTION OF THE CONTROLLER ALGORITHMS

This section provides a more detailed description of the algorithms used in the BEMS controller. The controller works as follows: Before anything is known about the behavior of the system an intuitive control scheme is set up. As time goes by information

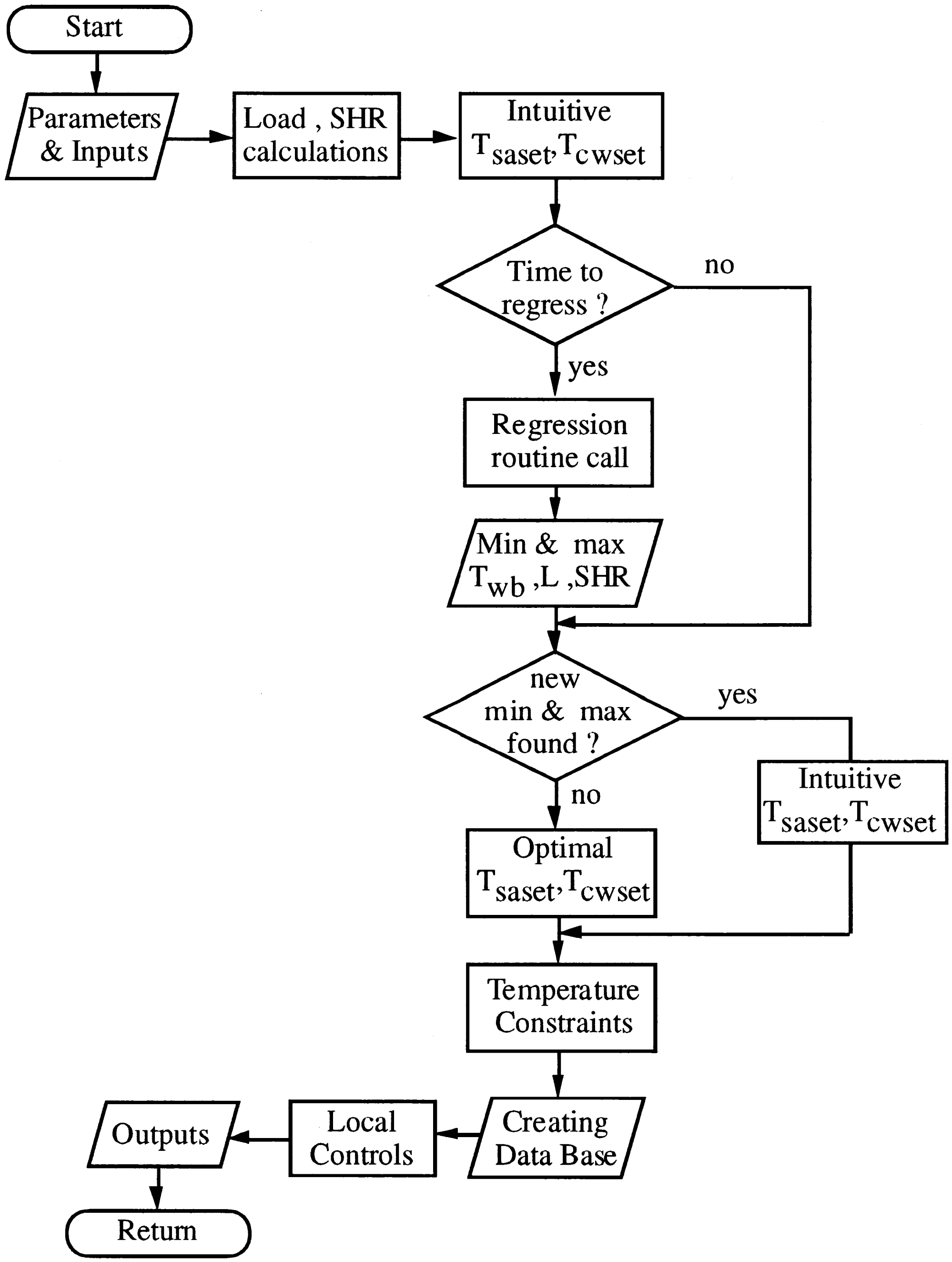

Figure 3.11 Information flow and decision processes in the BEMS controller

about the uncontrolled variables, control variables, and total system power consumption is collected, stored, and arranged in a data base so that it can be used at a later time. At the end of a specified *learning period* a regression is performed automatically in the controller, producing the coefficients for the linear control laws. As the simulation continues more data is collected, the data base is up-dated, new regressions are performed, and new control laws are continuously found. A diagram of the information flow and decision process in the controller is shown in Figure 3.11 and is discussed below.

First, all of the parameters and inputs are read in (the parameters are only read in the first call of the simulation). Then the total building cooling load and SHR are calculated from:

$$\text{Load} = \dot{Q}_{sens,z} + \dot{Q}_{lat,z} \tag{3.16}$$

$$\text{SHR} = \frac{\dot{Q}_{sens,z}}{\text{Load}} \tag{3.17}$$

where $\dot{Q}_{sens,z}$ and $\dot{Q}_{lat,z}$ are the sensible and latent building loads output from the zone model.

The first decision the controller makes involves setting up the intuitive control strategy or not. If the time (simulation time) is less than the initial learning period time, then intuitive control is used to calculate the control variable set points ($T_{cw,set}$ and $T_{sa,set}$).

The second decision to be made is when to regress the *data* (T_{wb}, Load, SHR, $T_{cw,set}$, $T_{sa,set}$, and P_{tot}) which has been collected in the learning period. The regression can be performed at every new hour after the learning period, or at any other specified time interval. Output from the regression routine are the 21 coefficients of the quadratic power formula, which makes it possible to estimate the powers and consequently the RMS of the regression. The minimum and maximum forcing functions (T_{wb}, Load, and SHR) encountered in the regression are also registered.

The third decision involves deciding on what type of control to use, optimal or intuitive control. If a set of forcing functions, outside the minimum or maximum range, are encountered during the optimal control period, then intuitive control is used instead. The reason for this is that the quadratic power formula is at best valid in the range of forcing functions that it was initially based on. However, if this is found to disturb the system the other option, which is to stick with optimal control regardless of the conditions encountered, can be used.

Once the control variable set points have been established, a check is made to see if any of the temperature constraint discussed above are violated. If so these are adjusted for according to the approaches discussed in Section 3.5.6.

The last task in the supervisory part of the controller is to organize and/or update the *data* which is to be used in the next hour of the simulation. This organization depends on the regression mode that has been selected. In the first mode all of the new data points are added to the old data base, which was created during the initial learning period. This results in an increasing data base. In the second mode only a limited, or fixed, number of data sets are stored in the data base. For every new set of data added to the end of the data base, one is removed from the beginning, and a sliding data base is created.

In the local controls part of the controller the calculation of the supply air flow rate through the conditioned space is evaluated from:

$$\dot{m}_{air} = \frac{\dot{Q}_{sens,z} + \dot{Q}_{fan}}{c_{p,air}\,(T_z - T_{sa,set})} \qquad (3.18)$$

where $\dot{Q}_{fan}$ is the sensible heat gain from the electric motor of the supply air fan, $c_{p,air}$ is the specific heat of air, and T_z is the zone temperature. The temperature and absolute humidity of the air entering the cooling coil are evaluated from

$$T_{a,i,c} = T_z\,(1-F_o) + T_{amb}\,F_o \qquad (3.19)$$

$$\omega_{a,i,c} = \omega_z\,(1-F_o) + \omega_{amb}\,F_o \qquad (3.20)$$

where T_{amb} is the ambient temperature, ω_z and ω_{amb} are the absolute humidities of the combined zones and the ambient, and F_o is the mass fraction of outdoor air in the supply air stream. (See Section 3.4 for more details).

Finally, the controller outputs all the variables required by the simulated building and HVAC components.

3.6 CHAPTER SUMMARY

In this chapter the development of the HVAC emulator used to develop and test the control algorithms for a BEMS was discussed. Models for a representative building and

HVAC system were simulated using TRNSYS. TMY data was used as the weather forcing function.

Local and supervisory control ideas were discussed and implemented in a BEMS controller. The concept of having a controller that is able to learn how to better operate the HVAC system with the passage of time was introduced. To achieve this two control strategies were required: (1) Intuitive control, and (2) optimal control.

Intuitive control consists of a relatively simple scheme based on the operator's past experience on how to control the system, and is used during a specified learning period. Optimal control involves minimizing the overall operational costs of the system. To achieve this a quadratic power formula that describes the total system power consumption in terms of a set of forcing functions and control variables must be found. A method to collect, organize and regress the data, and to obtain the coefficients of the power formula automatically (or on-line), was developed.

Setting the derivatives of the power function with respect to the control variables to zero and solving yields a set of equations which determine the optimal values for the continuous control variables. However, depending on the accuracy of the power formula, the control variables might violate various temperature constraints. A methodology that involves the handling of these temperature constraints was developed, and included in the controller. Results from testing the developed BEMS algorithms are presented in the next chapter.

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CHAPTER
FOUR

TESTING OF THE BEMS CONTROLLER

In this chapter the testing of the BEMS controller is described. Results from several simulations were used to analyze the performance of the controller and the applicability of the control ideas developed in Chapter 3. An introduction to the testing of the controller, including an overview of the simulations performed, are presented in Section 4.1. During the learning period of the controller it is necessary to generate a data base with information on the HVAC system performance over a wide range of operating control settings so that the total system power consumption can accurately be described. To achieve this, two different control approaches were investigated. These are described in Section 4.2. A more extensive analysis of the two control approaches is presented in Section 4.3. The discoveries made here with regards to the control settings is the essence of this research. A comparison of the performance of the two control approaches are presented in Section 4.4. The main results and findings of this chapter are summarized in Section 4.5.

4.1 INTRODUCTION TO TESTING OF THE BEMS CONTROLLER

The final objective of this study is to test the BEMS controller algorithms on the simulated building and HVAC system. Specifically, the optimal control methodology described in Chapter 3 will be tested. The results from these tests will be discussed and analyzed.

Numerous simulations were run in order to better understand how the optimal control methodology could be built into an actual BEMS controller. Some of the simulation attempts made were more successful than others. The following is a summary of the findings and short comings:

1. **Learning period length:** The length of the initial learning period was found to be important; as the learning period increases more data points (i.e., sets of T_{wb}, Load, SHR, $T_{cw,set}$, $T_{sa,set}$, and P_{tot}) are made available. Thus a more accurate quadratic power formula relationship, valid for a wide range of forcing functions (T_{wb}, Load, SHR), can be found. Testing of short learning periods (i.e., 1 to 4 weeks) demonstrated that it was always possible to fit a curve through the data points. However, the corresponding control settings ($T_{cw,set}$

and $T_{sa,set}$) derived from the power formula were not always realistic. Testing of long learning periods, on the other hand, yielded more realistic control settings.

3. Frequency of regression: Initially the on-line regression was performed only every one or two weeks. This gave rise to problems with unrealistic control settings. However, it was discovered that in order to achieve smooth transitions between the various control laws, the regression needed to be performed every hour. By doing this the coefficients of the power formula did not vary too much from hour to hour, and neither did the control settings. Examples of the stabilizing of the coefficients during optimal control are found in Appendix C.

3. Sliding learning period: The concept of having a sliding data base of a fixed length was also tested. The slider was set up so that for every new data point added to the end the data base, one data point was removed from the beginning. The advantage of this is that only the most recent forcing functions are remembered by the controller. However, the disadvantage is that when data is removed valuable information might be lost. If a slider is to be used, a method on how to recognize *good* data points must first be developed. A *good* data point would then be defined as one that includes new information about the system and does not duplicate old data.

4. Cells: The load is the uncontrolled variable with the single most significant effect on the system operating costs. Therefore, the idea of dividing the data base into cells, depending on the magnitude of the load, was investigated. But, this approach was unsuccessful. The reason for this was that the amount of data available at high and low loads was insufficient, and as a result unrealistic control settings were obtained were obtained from the regression. However, the idea of using cells might be a good one if only *good* data is stored in the cells. This would also eliminate the problem of having a number of data sets with very similar data. (In an actual system the forcing functions change very slowly, and a large number of data sets are located in the same region, or cells, and are therefore redundant.)

From the above it is clear that there are many factors that affect the performance of the controller. Therefore, a scenario that provided the most ideal situation for testing the controller was set up: The longest possible initial learning period of 12 weeks with an increasing data base (where the data base was up-dated with data taken with new optimal control settings) was selected. A stabilizing period of 48 hours allowed the system to reach steady state. Intuitive control was used during the initial learning period. The

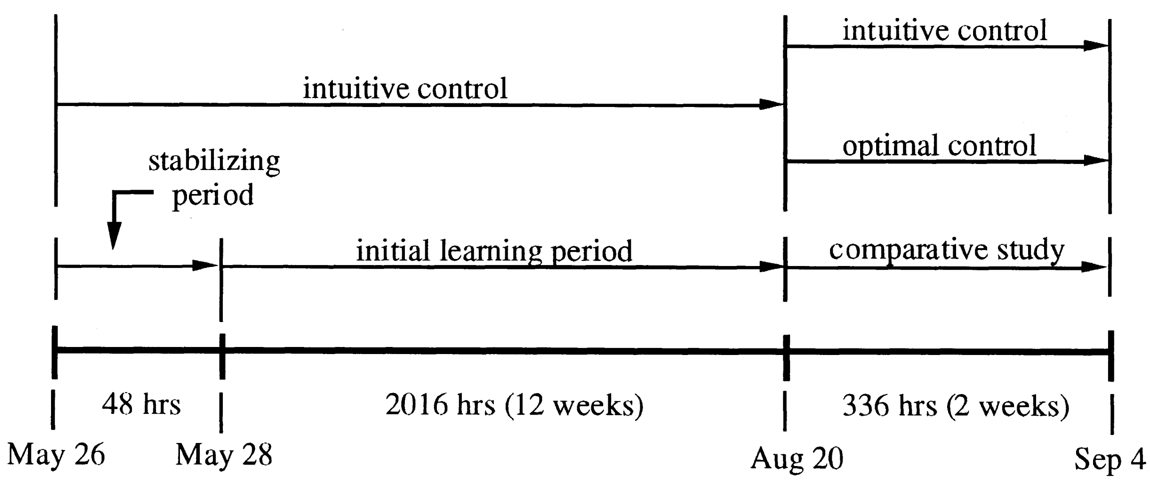


Figure 4.1 Schematic of simulation progress

regression was performed every hour during the optimal control period. Figure 4.1 illustrates the simulation progress. For all of the simulations TMY data for Nashville, Tennessee was used.

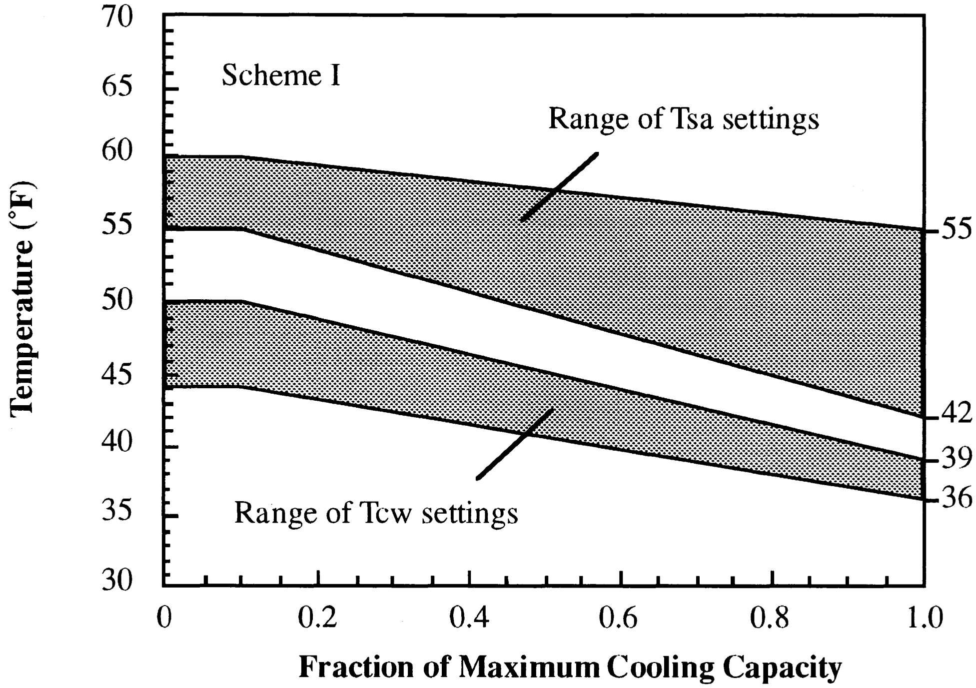
4.2 EXAMPLE OF TWO CONTROL APPROACHES

This section provides a description of the intuitive control schemes used during the initial learning period, a validation of the regression used to obtain the quadratic power formula, and a comparison of the power curves for different loads and intuitive control schemes.

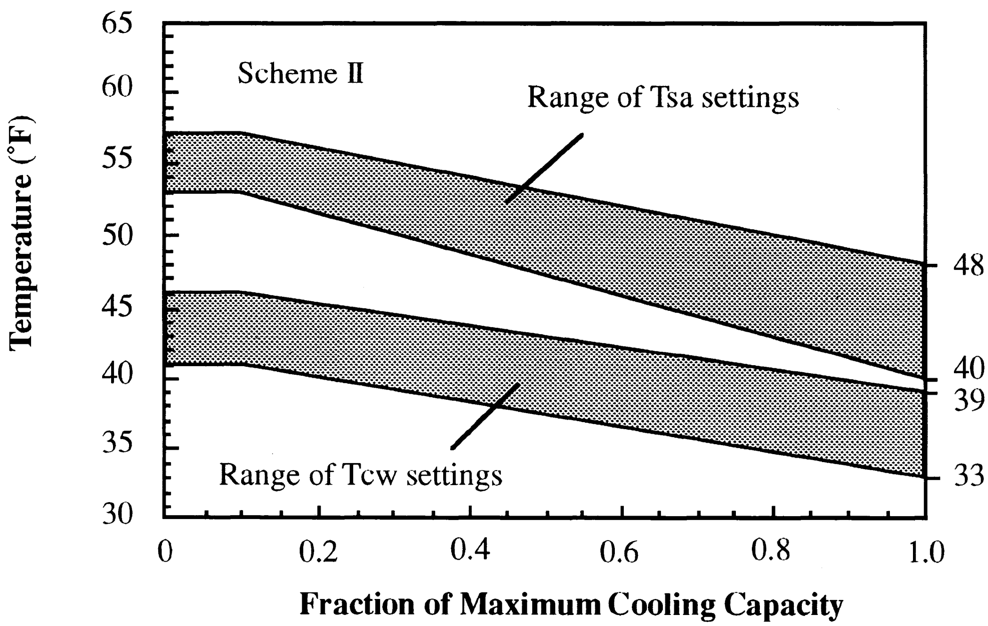
4.2.1 OVERVIEW OF INTUITIVE CONTROL SCHEMES

The purpose of the intuitive control is to vary the control variables for a number of different forcing functions so that the optimal control settings can eventually be found. In order to obtain data useful for a regression, it is necessary that the control settings are varied over a range. As it will become clear from the following discussions, the ability to predict the optimal control settings depend heavily on the type of intuitive control selected during the initial learning period.

Figures 4.2 (a) and (b) show the range of the supply air and chilled water set point temperatures ($T_{cw,set}$ and $T_{sa,set}$) as a fraction of the maximum cooling capacity for intuitive control schemes I and II, respectively. As seen from the figures, the ranges of $T_{cw,set}$ and $T_{sa,set}$ in scheme I are in general higher than in scheme II. Furthermore, the



(a)



(b)

Figure 4.2 Range of supply air and chilled water control settings as a function of the fraction of maximum cooling capacity: (a) Scheme I and (b) scheme II range of $T_{sa,set}$ in scheme I is wider than the range in scheme II while the opposite is true for the range of $T_{cw,set}$. Seven different sets of high and low settings for the chilled water and supply air temperatures (see Figure 3.7) that were varied each day, were selected for each scheme. This produced some day to day variation in the control settings. The $F_{cap,set}$, fraction of capacity set point was always 0.1 and the set point temperatures were always selected so that the minimum temperature difference between the control settings was never violated.

4.2.2 VALIDATION OF CURVE FITS

An evaluation of the quadratic power formula curve fits is important in order to understand how well the power is predicted for different intuitive control schemes. The form of the calculated quadratic power formula used in this study was:

$$
\begin{aligned}
P_{formula} = {} & b_1 + b_2\,T_{wb} + b_3\,Load + b_4\,SHR + b5\,T_{cw} + b_6\,T_{sa} + b_7\,T_{wb}\,T_{wb} \\
& + b_8\,Load\,Load + b_9\,SHR\,SHR + b_10\,T_{cw}\,T_{cw} + b_{11}\,T_{sa}\,T_{sa} \\
& + b_{12}\,T_{wb}\,Load + b_{13}\,T_{wb}\,SHR + b_{14}\,T_{wb}\,T_{cw} + b_15\,T_{wb}\,T_{sa} \\
& + b_{16}\,Load\,SHR + b_{17}\,Load\,T_{cw} + b_{18}\,Load\,T_{sa} + b_{19}\,SHR\,T_{cw} \\
& + b_20\,SHR\,T_{sa} + b_{21}\,T_{cw}\,T_{sa}
\end{aligned}
\tag{4.1}
$$

The calculated coefficients of the power formula for scheme I and II are listed in Table 4.1. The table shows that both the numerical magnitudes and signs of the coefficients varied significantly, depending on which scheme was used.

Table 4.1 Calculated coefficients

Coefficient	Scheme I	Scheme II
1	1232.30033	- 11326.79366
2	19.85042	13.85185
3	- 4.97265	4.30337
4	1156.84592	1237.10469
5	- 130.30569	474.42841
6	42.58082	9.16575
7	- 0.02837	- 0.03836
8	0.00249	0.00104
9	- 392.04887	- 627.65858
10	4.77068	- 3.30225
11	1.84174	0.94458
12	0.01294	0.01716
13	- 10.78384	- 12.05256
14	- 0.05140	- 0.27667
15	- 0.10301	0.22265
16	2.48098	2.58083
17	0.10427	- 0.09299
18	- 0.06118	- 0. 07653
19	- 30.34205	- 25.24007
20	19.55749	22.24806
21	- 5.35542	- 2.91797

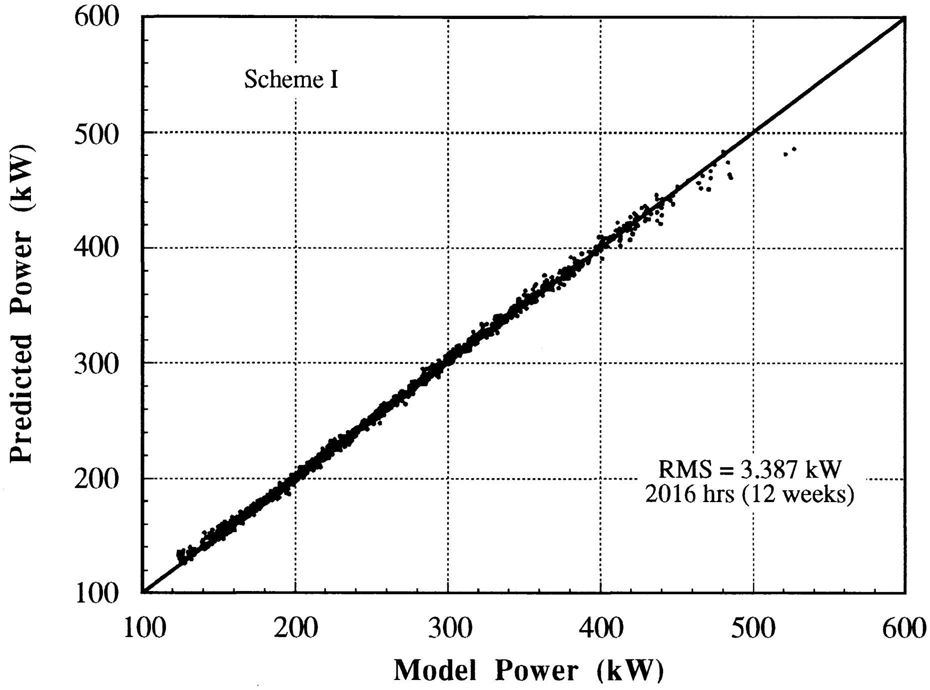


Figure 4.3 Predicted power versus model power, scheme I

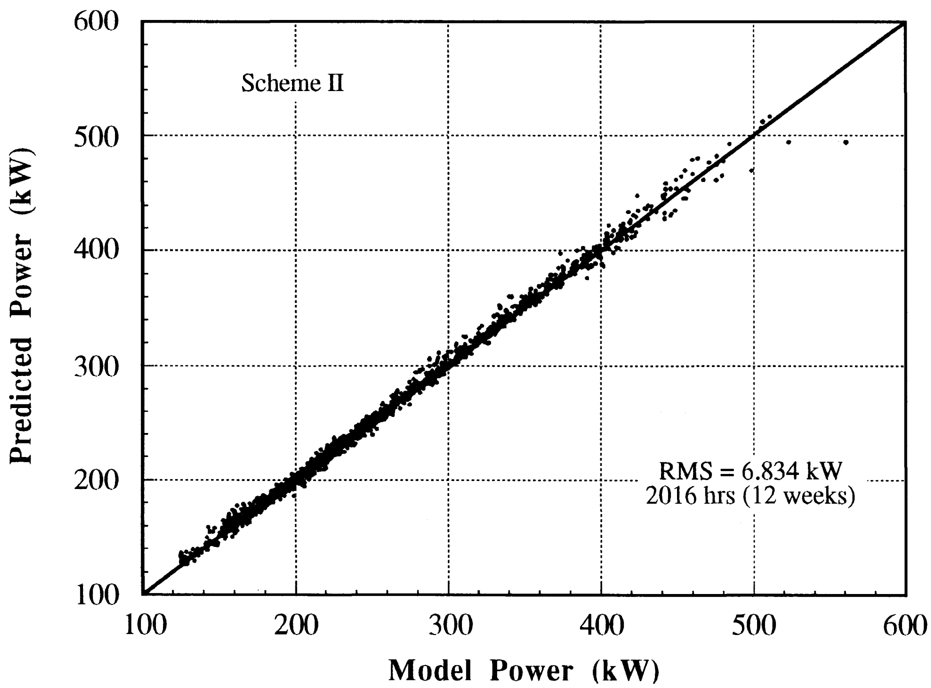


Figure 4.4 Predicted power versus model power, scheme II

Figures 4.3 and 4.4 show the predicted versus model power for intuitive control scheme I and II, respectively Both figures show that the data were accurately fitted to the power formula. In scheme I the RMS (root mean square) was 3.387 kW, or about 1% of the average total power consumption, while in scheme II the RMS was 6.834 kW, or about 2% of the total power. However, the formula is less accurate in predicting high powers because fewer data points are available for high loads. Thus it appears that the accuracy of predicting the power is not significantly affected by the selected intuitive scheme.

4.2.3 COMPARISON OF CURVE FITS

In search of the *true* optimum control settings of the simulated HVAC system, it is first necessary to fully understand the behavior of the system for a fixed set of forcing functions. Figures 4.5 through 4.8 show the total power consumption as a function of the control variables for a medium and high load for each of the two intuitive control schemes. The first set of forcing functions (T_{db} = 77.9 °F, T_{wb} = 69.5 °F, Load = 300 tons, and SHR = 0.849) occurred on June 8 while the second set (T_{db} = 88.5 °F, T_{wb} = 75.3 °F, Load = 452.7 tons, and SHR = 0.781) occurred on June 11. The formula power curves were derived from equation (4.1) using the coefficients of Table 4.1 while the *true* power curves were found by running the simulation models for various control settings.

From Figures 4.5 and 4.6 it is seen that the predicted and true power curves match better at a medium loads than at high loads. Furthermore, for both the medium and high load situation, the agreement between the curves is best at low chilled water and supply air

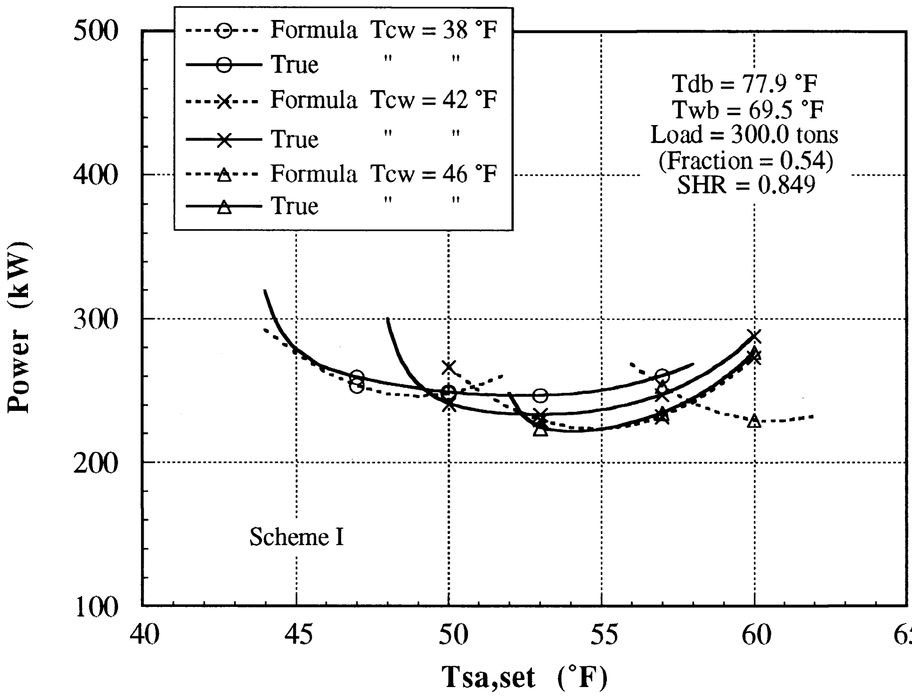


Figure 4.5 Formula and true power for a medium cooling load, scheme I

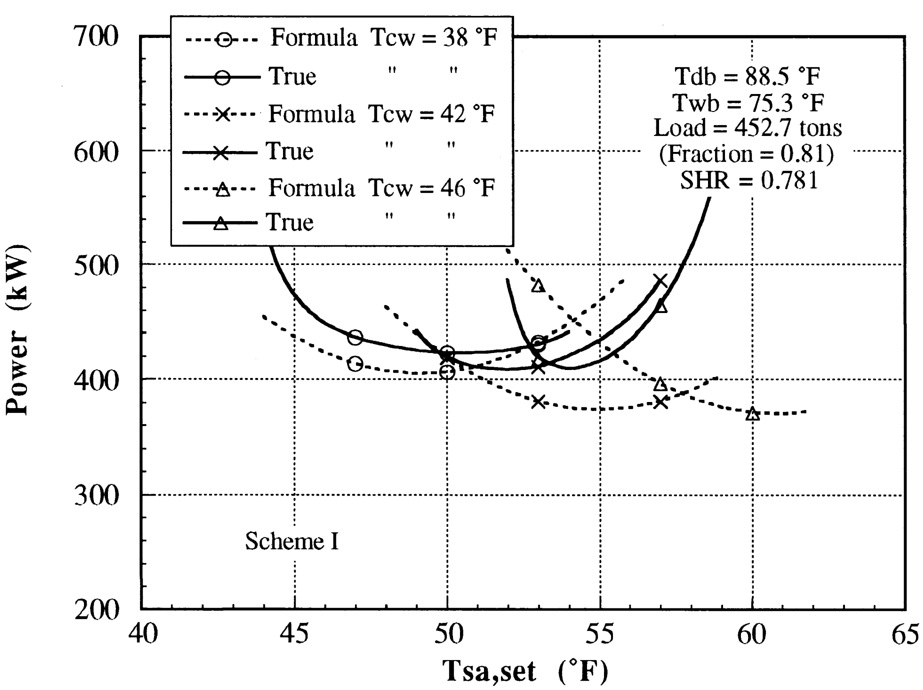


Figure 4.6 Formula and true power for a high cooling load, scheme I

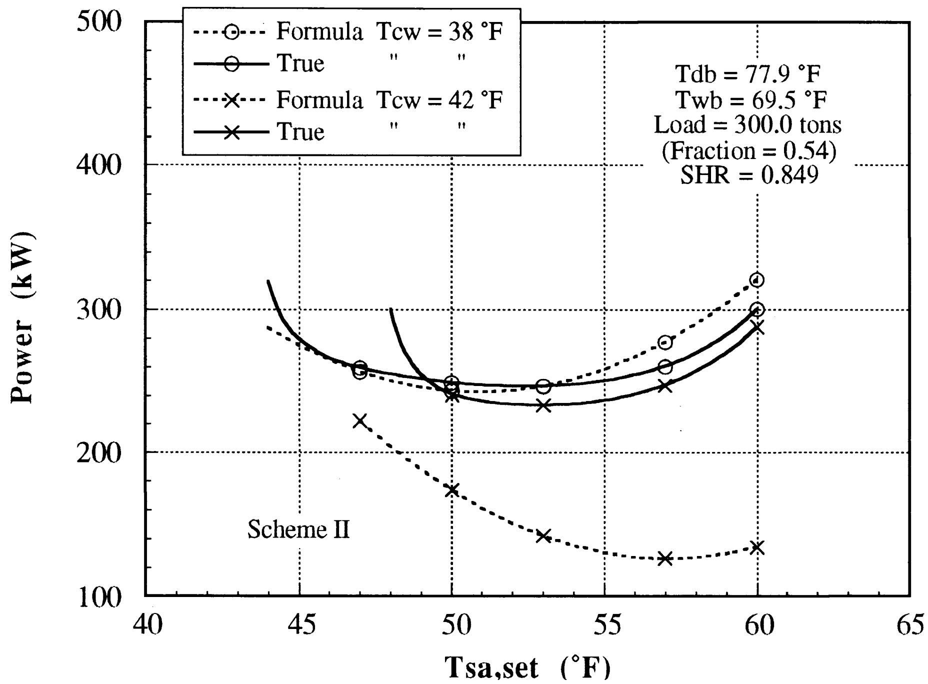


Figure 4.7 Formula and true power for a medium cooling load, scheme II

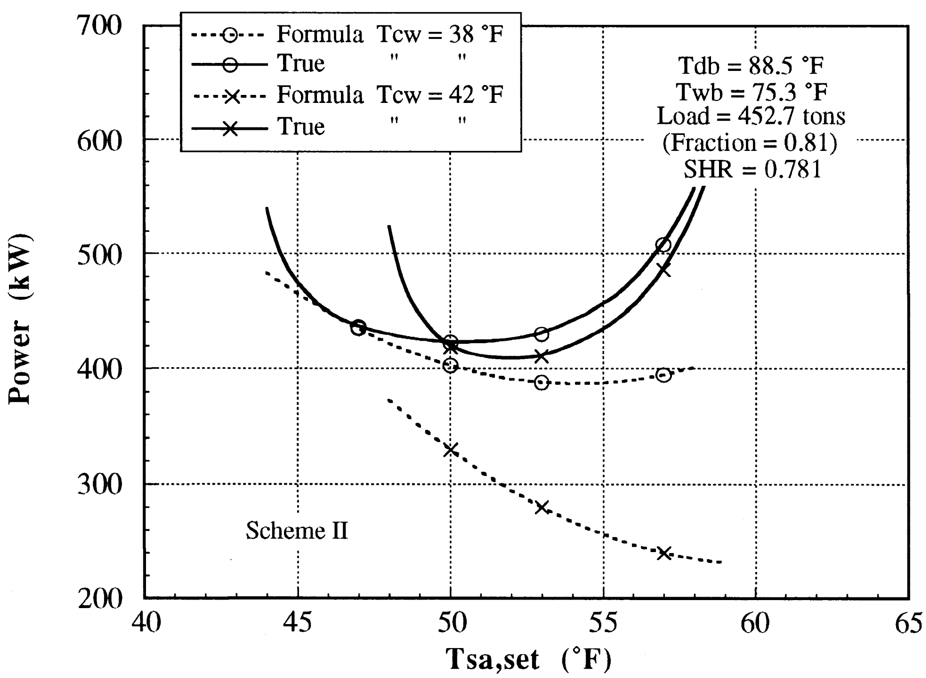


Figure 4.8 Formula and true power for a high cooling load, scheme II

temperatures. The same pattern is found in Figures 4.7 and 4.8, for scheme II. As a matter of fact, for a high load and at high chilled water temperatures, using the coefficients of scheme II, the predicted power was negative and was therefore not included in Figures 4.7 and 4.8. Thus it is concluded that in this case one can have the most confidence in the predicted power curves generated for medium loads and low chilled water and supply air temperatures.

An overall comparison of schemes I and II for both medium and high loads, shows that scheme I generally produces better curve fits than scheme II. This is verified by Figures 4.3 and 4.4, where it seen that the predicted high powers (which occur at high loads) are less accurate than the predicted medium powers (which occur at medium loads).

In the previous section it was demonstrated that the RMS is useful in determining the mathematical accuracy of the power formula versus the model formula. However, the RMS does not indicate the degree of confidence one can have in the formula at different loads. Actually, the formula performs much better at medium loads compared to high loads. Again, the reason why the formula fares better at medium loads is simply because there more data exists at these conditions.

4.3 ANALYSIS OF THE CONTROL SETTINGS

In this section the chilled water and supply air set point temperatures, or control settings, are first analyzed for a fixed load and then for a variable load. The focus of the analysis is on a medium load because the regression gave the most meaningful results for this situation. Thus only a brief discussion on a high load situation is included.

4.3.1 FIXED LOAD

To fully understand the behavior of the power and optimal control set point temperatures as a function of load the control settings need to be further analyzed. Figures 4.9 and 4.11 are expanded versions of Figures 4.5 and 4.7 and include additional information on the range of chilled water and supply air set point temperatures obtained during intuitive control. They also indicate both the true and formula predicted optimum control settings. Again, the true optimum is defined as the optimum found from simulations. Figures 4.10 and 4.12 are slightly different views of Figures 4.2 (a) and (b) and include the locations of the predicted and true optimum settings from Figures 4.9 and 4.11, respectively. The optimum settings for the high load, which can be found from Figures 4.6 and 4.8, are also included in Figures 4.10 and 4.12.

In Figures 4.9 to 4.12 it is seen that for scheme I both the formula and true optimal supply air control settings for a medium load are located within the upper and lower range of the supply air temperature used during intuitive control while for scheme II both fall outside the range. A similar comparison for the chilled water control setting shows, that for both schemes, the true optimum was located outside the upper and lower range of chilled water used during intuitive control while the predicted optimum was located inside the range. Another interesting point is that for scheme II neither the true chilled water nor

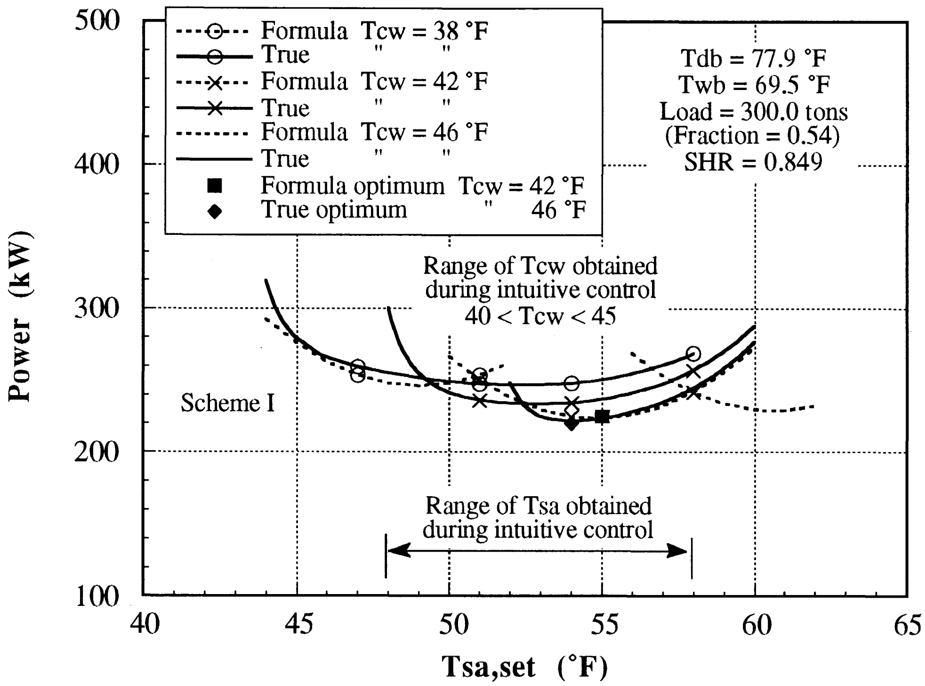


Figure 4.9 Formula and true optimum for a medium cooling load, scheme I

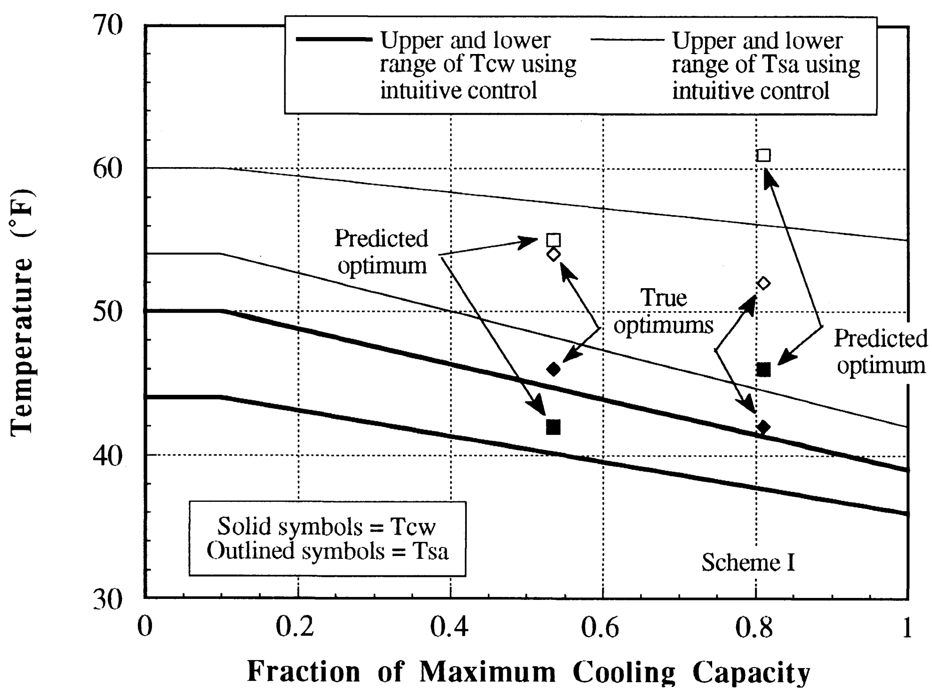


Figure 4.10 Comparison of control settings, scheme I

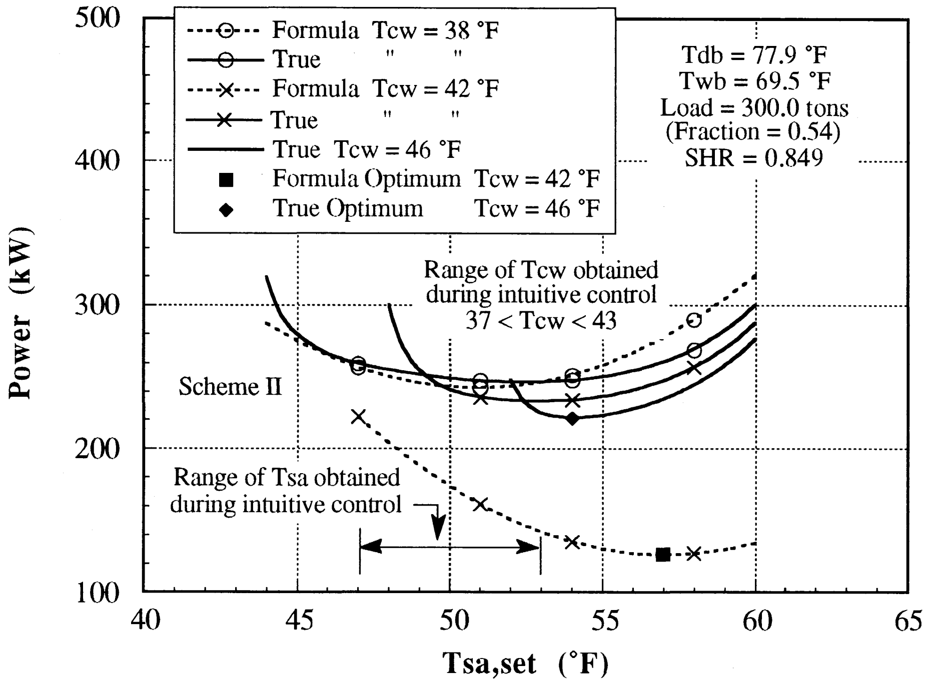


Figure 4.11 Formula and true optimum for a medium cooling load, scheme II

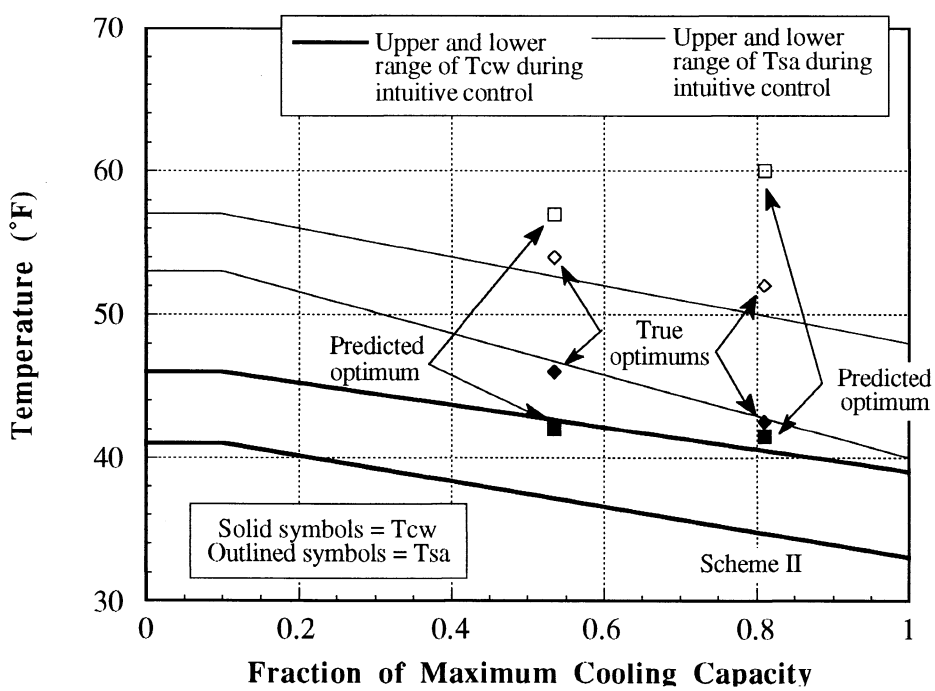


Figure 4.12 Comparison of control settings, scheme II

the supply air temperature optimum setting were included in the ranges used during intuitive control while opposite was true for scheme I.

An analysis for a high load yields results similar to that of a medium load. Figures 4.10 and 4.12 show that for both schemes both the formula and true optimum chilled water settings fall outside the upper and lower range of the chilled water temperature used during intuitive control. However, a similar comparison for the supply air setting shows that both the formula and true optimal supply air outside the upper and lower range used during intuitive control scheme II while only the predicted optimal supply air setting falls inside the range used during scheme I.

Several important conclusions can be drawn from this analysis. The first observation is that different intuitive control schemes yield different pairs of optimal chilled water and supply air control settings. Furthermore, comparing schemes I and II, the predicted supply air water setting varies more than is the case for the chilled water setting. Table 4.2 below summarizes the formula and true optimum settings found from the graphs.

Table 4.2 Optimal control settings

		Formula		True	
Load	Scheme	Tcw	Tsa	Tcw	Tsa
Medium	I	42	55	46	54
Medium	II	42	57	46	54
High	I	46	61	42	52
High	II	42	60	42	52

Another important observation to be made from the plots above is that the predicted supply air optimum is only close to the true optimum if the true optimum had been included in the range of supply air during intuitive control. This is most clearly illustrated by comparing Figures 4.11 and 4.12, where both the predicted and true optimal supply air set point temperatures are located outside the intuitive range, to Figures 4.9 and 4.10, where the formula and true optimums are located inside the intuitive range.

All of the above shows that one can only have confidence in the optimal control settings if sufficient variation of the control variables is exercised during the initial operation. The variation of the control settings during the initial learning period must be broad enough so that the control settings that yield the true optimums are included for every set of forcing functions. Furthermore, this comparison emphasizes that the quadratic power formula is at best valid within the range of the operating data, and cannot be reliable when extended outside that range.

4.3.2 VARIABLE CONDITIONS

The difference between the control settings produced by the two different intuitive control schemes can also be demonstrated by fixing the wet bulb temperature and SHR and varying the load. Taking the derivatives of the power formula, equation (4.1), with respect to the chilled water and supply air temperatures, setting the results equal to zero, and rearranging yields the following two linear control laws for scheme I:

$$T_{sa,set,opt} = 45.1025 + 0.1946\ T_{wb} + 0.0040\ \text{Load} - 3.7298\ \text{SHR} \qquad (4.2)$$

$$T_{cw,set,opt} = 13.6569 + 0.0054\ T_{wb} - 0.0109\ Load + 3.1801\ SHR + 0.5613\ T_{sa,set,opt} \quad (4.3)$$

and for scheme II:

$$T_{sa,set,opt} = 63.0651 - 0.1085\ T_{wb} + 0.0112\ Load - 10.4894\ SHR \quad (4.4)$$

$$T_{cw,set,opt} = 71.8352 - 0.0419\ T_{wb} - 0.0141\ Load - 3.8217\ SHR - 0.4418\ T_{sa,set,opt} \quad (4.4)$$

Equations (4.2) to (4.5) show that there is a large difference in the magnitude of the coefficients, depending on the intuitive scheme used during the learning period. In addition, there are some differences in the signs. Both of the wet bulb coefficients, for example, go from being positive in scheme I to negative in scheme II.

Figure 4.13 shows that although the coefficients are different in magnitude, they do exhibit a similar dependence on the load. As the load increases the supply air temperature setting increases and the chilled water setting decreases. However, these results contradict the results in Figures 4.10 and 4.12, and Table 4.2, which show that the true optimum chilled water and supply air set point temperatures both decrease with increasing load. The results also contradict the results obtained by Pape [1989], who also discovered that the optimums decrease with an increasing load. However, in that study the forcing functions and control variables were allowed to be varied randomly over a wide range that ensured that the true optimum was included in the regression. In addition, the regression was based on about twice as many data points (approximately 4000) as was the case in this study.

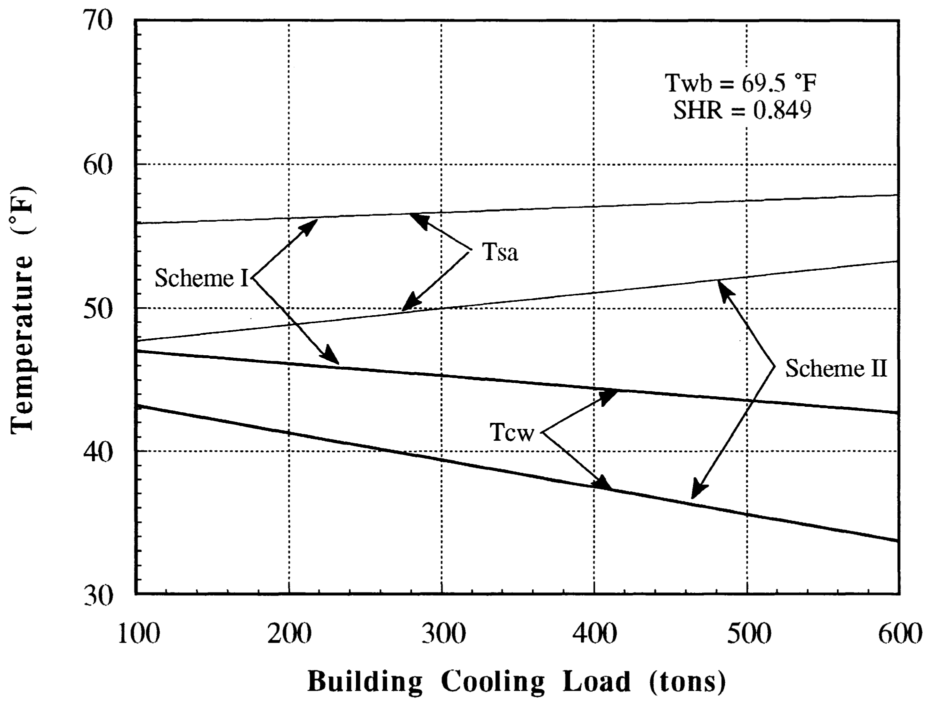


Figure 4.13 Comparison of predicted optimal control set points as a function of the load

4.4 COMPARISON OF THE TWO CONTROL APPROACHES

The idea of having a controller that learns how to optimally operate the system with the passage of time was the overall goal of this study. However, from the results above it is apparent that the method to achieve this must be further refined. Although the results presented in this section are not entirely positive, they do provide some additional insight to the problems at hand. The information on the performance of the BEMS controller presented here may or may not aid in solving the current problems.

One test that can be done on the controller is to see if it is able to predict the total system power consumption on what it has learned about the system in the past. Figure 4.14 demonstrates that the power formula, based on scheme I, actually predicts the total power from the simulation models very well. A similar result was obtained for scheme II. The root mean squares for these two cases were 3.559 kW and 6.655 kW, respectively.

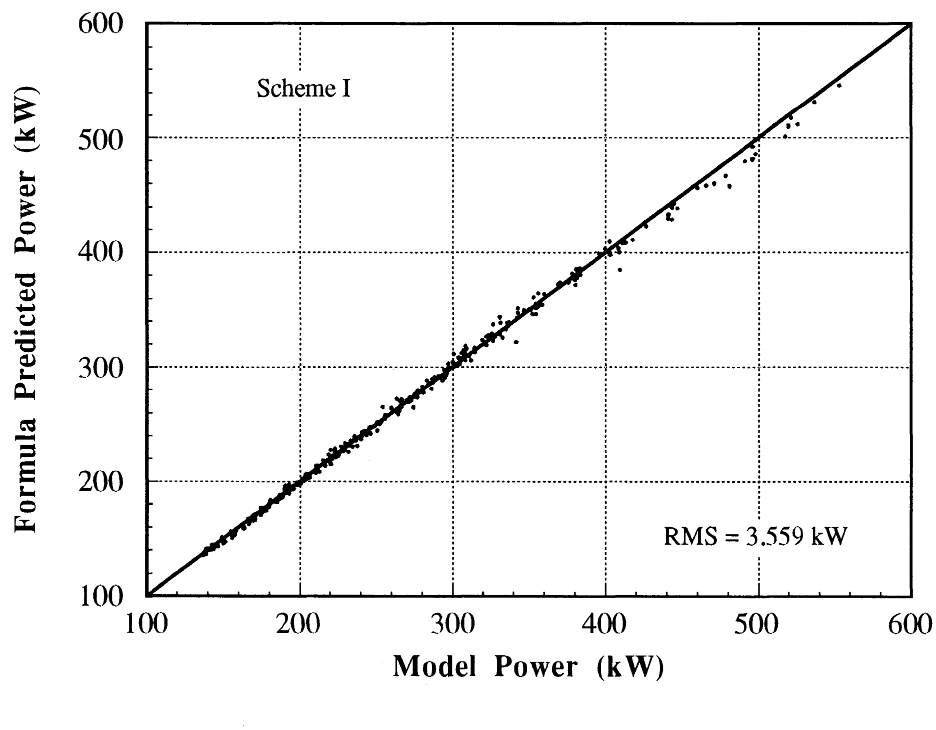


Figure 4.14 Formula predicted versus model power, scheme I

The chilled water and supply air set point temperatures calculated by the BEMS controller during the optimum control period also need to be analyzed. In Figures 4.15 and 4.16, scheme I and II, respectively, the optimum control settings from one simulation are compared to the ones obtained from another simulation using intuitive control. Note that only the first of the two weeks is plotted in these figures. One difference between the two schemes are the average magnitudes of the intuitive and predicted optimal control settings. These are higher for scheme I than for scheme II. However, the most interesting difference is the dissimilar patterns for the optimal control settings. In Figure 4.16, for example, the optimum chilled water set point temperature shows much more variation than in Figure 4.15. This is mainly because the optimal supply air control setting based on scheme I is more dependent on the load than the setting based on scheme II; Figure 4.13 verifies this.

Figure 4.17 shows the building cooling load profiles during intuitive optimal control for scheme I. Similar results were obtained using scheme II and were therefore not included. The differences in the load profiles, particularly at the peak loads, are due to the different sensible heat gains to the building. Since the supply air set point temperature is higher for the formula predicted control than the intuitive control, more air needs to be circulated though the zones and the supply air fans need to work harder. The motors that drive the supply air fans have inefficiencies, and the electrical energy that is not converted into driving the fans is dissipated as heat to the supply air stream. Hence, the total building load is increased, and the power is increased accordingly. An example of this is seen in Figure 4.15 on August 20 at 1600 hours, where the optimum supply air setting was much higher than during intuitive control. As a result, the difference between the optimum and intuitive loads at that particular time was about 25 tons.

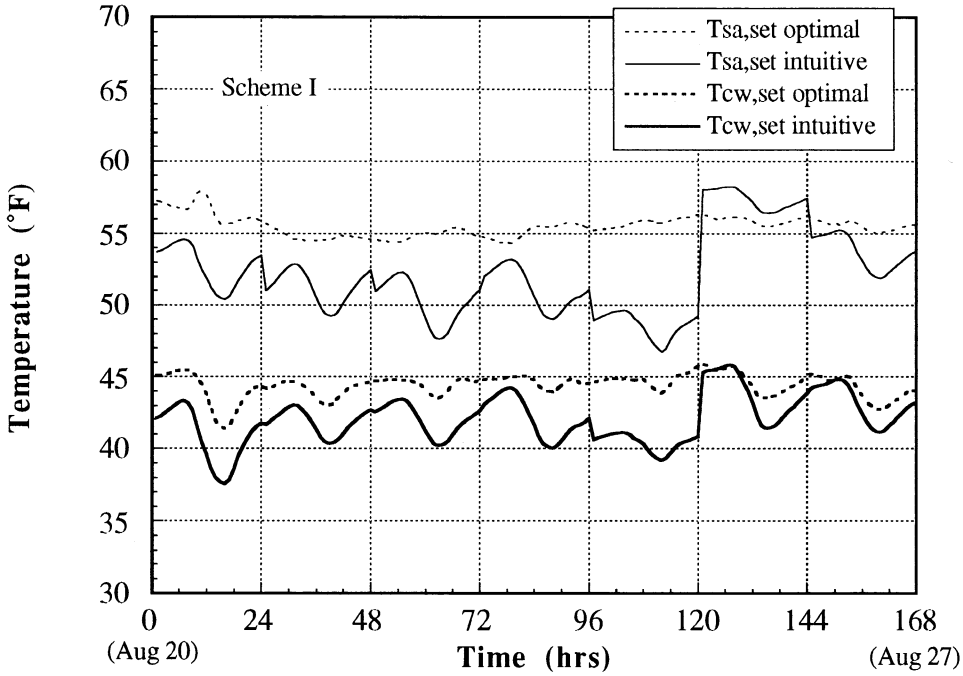


Figure 4.15 Comparison of control settings with the passage of time, scheme I

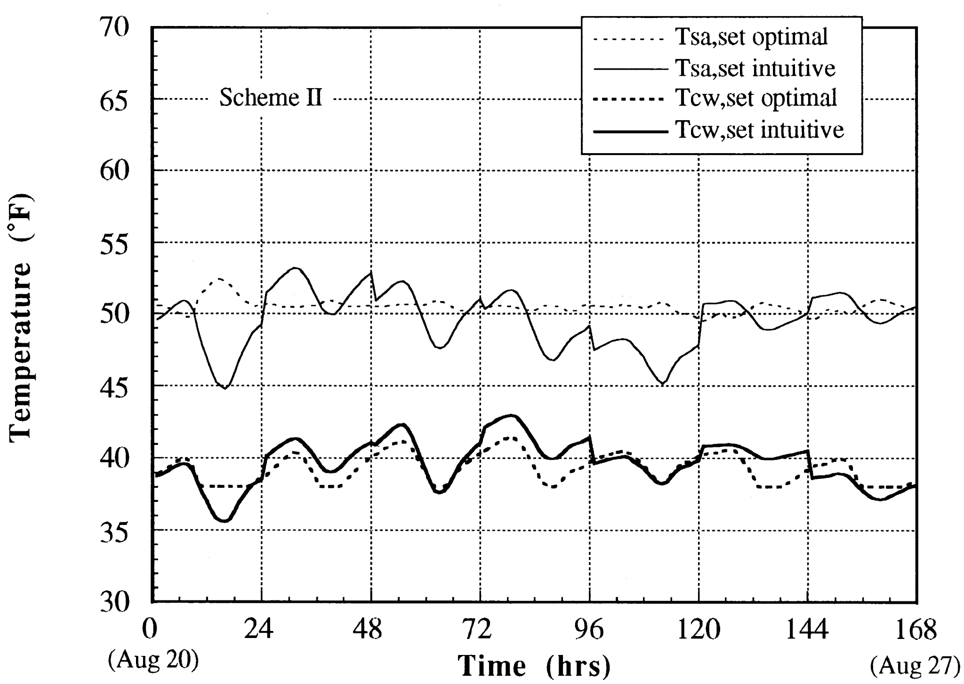


Figure 4.16 Comparison of control settings with the passage of time, scheme II

The remaining part of this section makes an attempt to quantify the energy differences using optimal control as opposed to intuitive control. Figure 4.18 shows the total power using intuitive and optimal control (for the first week) while Figure 4.19 shows the instantaneous and cumulative energy savings (for both weeks) for scheme I. It is seen that the total energy savings after two weeks were about 2000 kWh or about 2% of the total energy usage in that time frame. Figure 4.20 shows that the energy savings using scheme II were 1000 kWh, or about 1% . Note that these quantities of energy savings are not absolute, but are merely included so that a comparative study between scheme I and II can be performed.

The disadvantage of relying on the formula predicted control is that peak power is higher. Thus, even though energy savings might occur, demand would be increased, and consequently cost would be increased as well.

Figure 4.18 suggests that there might be some *real* instantaneous energy savings at low loads while Figures 4.19 and 4.20 suggest that the optimal control could do much better. For future studies, comparisons such as these should be made between the optimal control and an *actual* optimal control. However, this *actual* optimal control would have to be obtained by running numerous simulations, similar to the ones performed by Pape [1989]

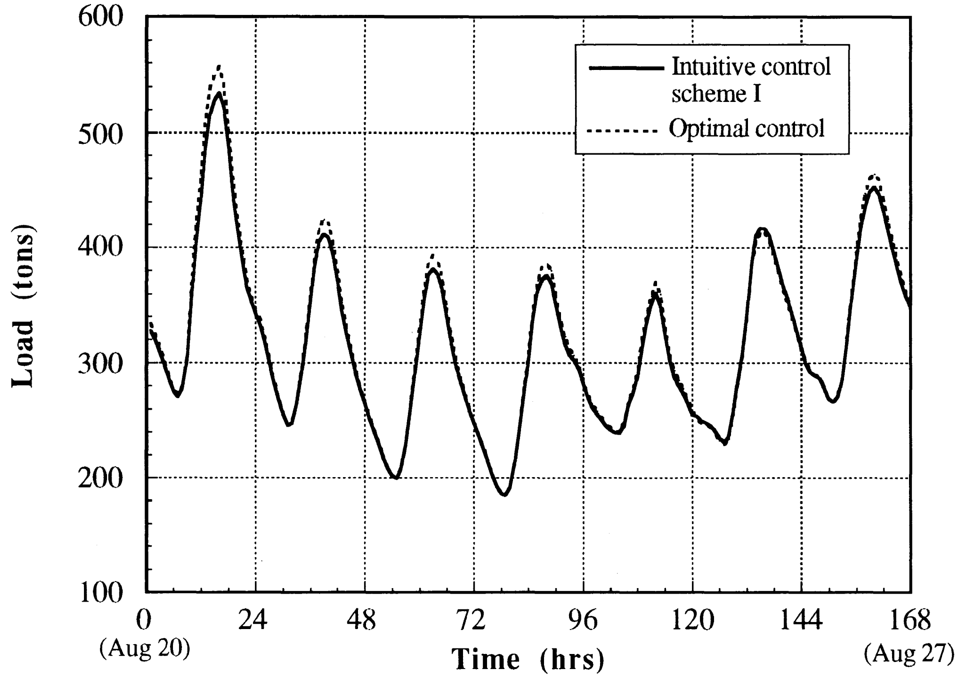


Figure 4.17 Loads during intuitive (scheme I) and optimal control operation

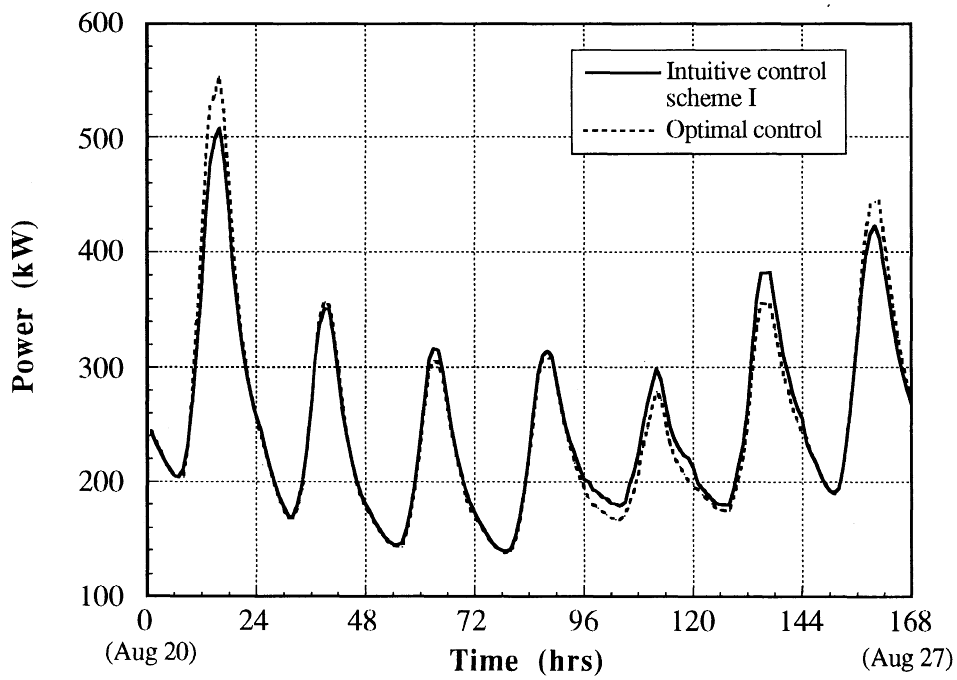


Figure 4.18 Powers during intuitive (scheme I) and optimal control operation

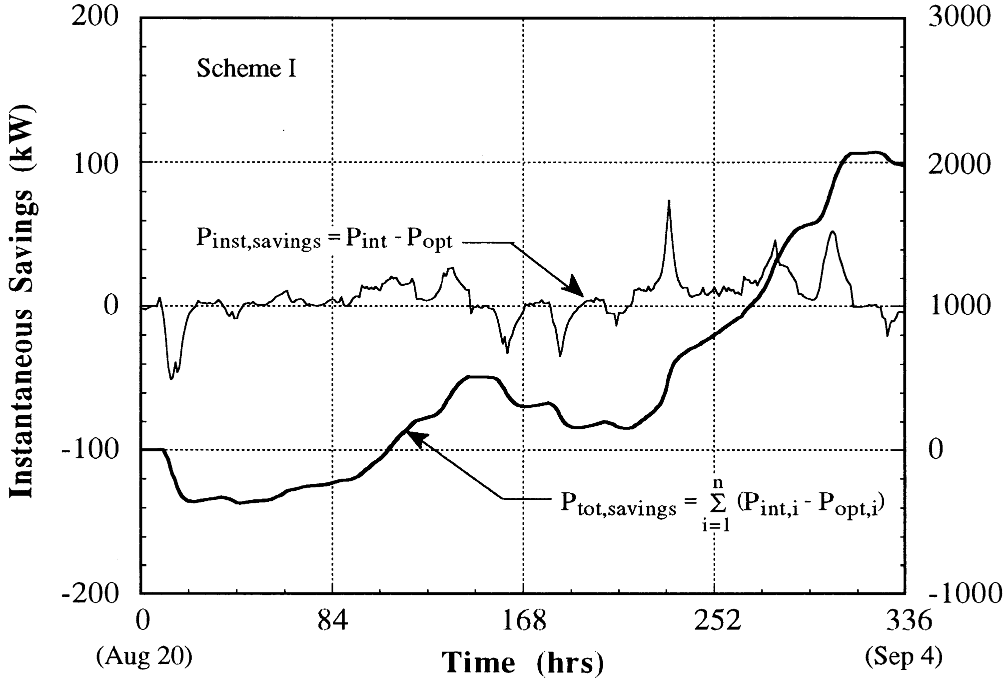


Figure 4.19 Instantaneous and cumulative energy savings, scheme I

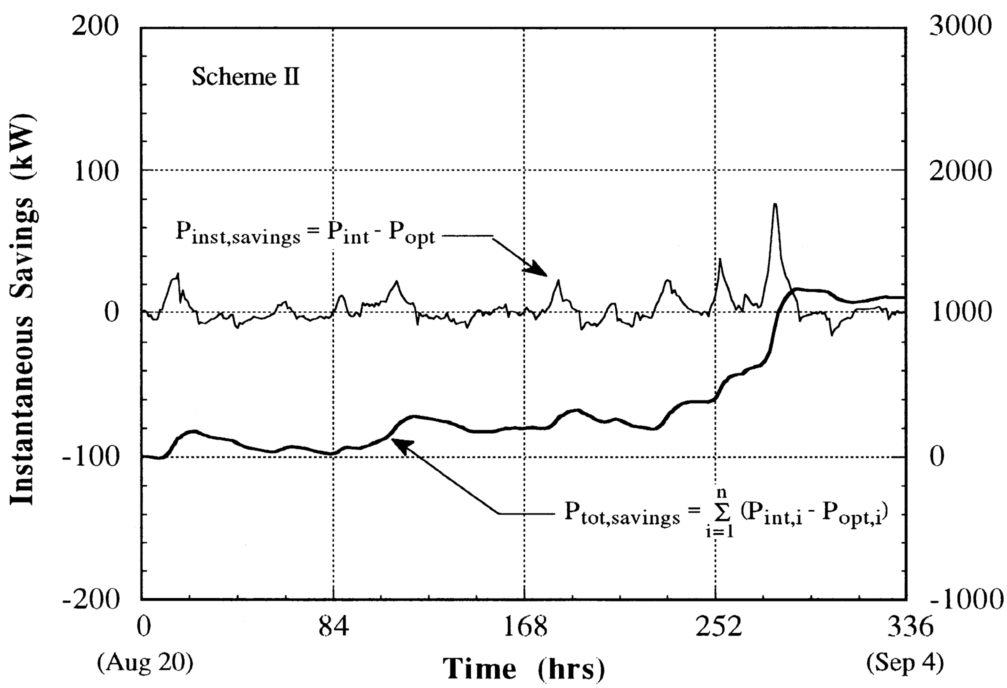


Figure 4.20 Instantaneous and cumulative energy savings, scheme II

4.5 CHAPTER SUMMARY

In this chapter the optimal control algorithms developed in Chapter 3 were tested on a simulated building and HVAC system. Several simulations had to be run before an analysis that accurately depicts the performance of the controller could be performed. Two different intuitive schemes for controlling the chilled water and supply air temperatures settings for the initial learning period were established, compared, and analyzed.

The main conclusion of this chapter is that the quadratic power formula accurately predicts the true power of the system, but not the optimal control. At high loads, where insufficient information has been obtained about the system, the power is less accurately predicted. However, the predicted optimal control settings depended strongly on the intuitive control strategy used during the initial learning period. An intuitive strategy without any variation produced unrealistic control settings. Two slightly different strategies, with day to day variation, yielded quite different optima.

For the optimal control methodology used in this research to succeed the control variables must be varies over regions that are close to the true optimal control settings. In other words, the short comings of the approach used in this research is not due to the lack of data points used in the regression, but rather due to the lack of quality of the data points, i.e., the data were not collected in the region near the true optimal values.

REFERENCES 4

Pape, F. L. F., "Optimal Control and Fault Detection in Heating, Ventilation and Air-Conditioning System", M. S. Thesis, University of Wisconsin-Madison, 1989.

CHAPTER
FIVE

CONCLUSIONS AND RECOMMENDATIONS

This chapter recapitulates the main conclusions of this thesis and provides a few recommendations for possible future work.

5.1 CONCLUSIONS

The overall objective of this thesis was to study emulation and control of heating, ventilation, and air conditioning systems. It was demonstrated that using emulators for air conditioning applications can be a very convenient and flexible way to develop, test, and tune HVAC equipment. The idea of using an emulator to develop and test a building energy management system controller was also explored. It was found that emulators can provide the *link* between testing control strategies in simulation and testing of the same strategies in actual test buildings. Therefore, the control algorithms developed in this study could eventually be tested on an emulator.

The advantage of using an emulator for testing a controller is that it can be tested on simulated and/or actual pieces of HVAC hardware. Although emulators have been demonstrated to provide very realistic situations for testing HVAC controllers and other equipment, pure simulation is still a viable tool in the development of control strategies.

One of the more specific goals of this study was to test a general control methodology, initially developed by Braun [1988], on a simulated building and HVAC system. This was done using simple but representative TRNSYS models. A BEMS controller that learns the behavior of the air conditioning system with the passage of time and attempts to control the system based on an optimal control strategy was developed.

The controller works as follows: Before anything is known about the behavior of the system an intuitive control scheme needs to be set up. As time goes by information about the uncontrolled variables, control variables, and total system power consumption is collected, stored, and arranged in a data base so that it can be used at a later time. At the end of a specified *learning period* a regression is performed automatically in the controller, producing the coefficients for the linear control laws As the simulation continues more data is collected, the data base is up-dated, new regressions are performed, and new control laws are continuously found.

Results from testing the controller demonstrate that the predicted optimal control settings did not always resemble that of the *true* optimal settings, even though the quadratic power formula that they were based on predicted the actual power quite well. One of the main reasons for this was that the control settings were not varied sufficiently during the initial learning period. The range of the intuitive control settings used during the initial learning period need to encompass the range of the true optimal control settings. Where this was not the case, the disagreement between the predicted and true optimal control settings was significant.

5.2 RECOMMENDATIONS

The short comings of the optimal control approach that was incorporated in the BEMS controller used in this study was not due to lack of data points used in the regression, but rather due to the lack of quality of the data points. If only true optimal control variables were used to determine the quadratic power formula, then the optimal control laws derived from this formula have been optimal. This knowledge should be incorporated in the controller. Thus the following recommendation are made:

1. A new and better method or scheme that provides more variation on the control settings during the initial learning period must be developed and implemented in the controller. The new scheme should be set up so that the control settings are varied in a range close to the predicted optimum. This would make more information available, and a better curve fit could be produced in the region close to the optimum.

2. If a predicted set of optimal control set point temperatures fall outside the range of the control settings used during the initial operation, then these control set points should not be used. Instead, the system should be controlled using an alternative control scheme.

3. Several changes could be made to make the simulated system more realistic. The model could, for instance, be made more complex by adding variable speed cooling tower fans and condenser pumps to the system.

4. Another interesting study would be to analyze the influences of system dynamics on the optimal control of the system.

5. The developed control strategies should eventually be tested on an emulator.

APPENDIX A

TRNSYS SIMULATION DECK

```
*********************************************************************
*** TRNSYS DECK (FINAL) ********************************************
*********************************************************************

NOLIST

SIMULATION 0 2400 1
*May 26 - Sep.
WIDTH 72
TOLERANCES .01 .01
LIMITS 100 10

EQUATIONS 26
TDESIGN=0
*Operate at design temps. of 45 F and 55 F
*0=off  and  1=on
SLIDER=0
*Regression slider
*0=off  and  1=on
REGSTART = 48.
*number of timesteps before data collection for regression begins
TSTEPS = 2016.
*number of timesteps (additional to REGSTART) before 1st regression
*is to occur
NEXTTSTEPS = 1.
*number of timesteps until next regression is to occur
STARTDAY=145
* May 26
* May i:n=120+i,Jun i:n=151+i,Jul i:n=181+i,Aug i:n=212+i
LATITUDE=36.1
* for Nashville
LOADMAX = 560.
FRACTION = 0.1
TZONE = [53,1]*1.8+32.
* from SI to English units
WZONE = [53,2]
FACTOR=550.
* scaling factor
QSENSBTU = [53,7]*0.94787*FACTOR
* from KJ/hr --> Btu/hr  ,plus an up-scaling factor
QLATBTU = [53,8]*0.94787*FACTOR
* from KJ/hr --> Btu/hr  ,plus an up-scaling factor
LOADBTU = [2,14]
LOADTONS = [2,14]/12000.
TVENT = ([2,11]-32.2)/1.8
* from English to SI units
MVENT = [7,3]/(2.2046)/FACTOR
* from lbm/hr to kg/hr ,plus a down-scaling factor
WVENT = [7,2]
```

```
QPEOPLE = [53,4]*0.94787*FACTOR
QINFILT = [53,5]*0.94787*FACTOR
QVENT = [53,6]*0.94787*FACTOR
WAMB = [1,6]
TWB = [60,2]
TAMBSI = ([1,5]-32.0)/1.8
* from english to SI units
PCCFANS = [13,1]*6


**********************************************************************
UNIT 1 TYPE 9 DATA READER (WEATHER-DATA IN ENGLISH UNITS) ******
**********************************************************************
PARAMETERS 28
*   Ndata  Tint  Month   m     aHour       m     a    DSR    m     a
*    (#)   (hr)   (A)   (X)   (+)  (B)    (X)   (+)   (C)   (X)   (+)
      8     1     - 1    1     0   -2      1     0    -3     1     0

*   GSR    m     a     TDB    m     a      HR      m      a   WIND1   m   a
*   (D)   (x)   (+)    (C)   (X)   (+) (0<HR<1) (X)    (+)   (E)   (X) (+)
    -4     1     0      5   0.18   32      6   0.0001   0     7     1   0

*  WIND2  m     a     LU   FRMT
*   (F)  (X)   (+)    (#)  (>0)
     8    1     0     22    -1


**********************************************************************
UNIT 60 TYPE 33 PSYCHROMETRICS (TDB + HR --> TWB)  ****************
**********************************************************************
PARAMETERS 5
*   MODE          UNITS       PATM   WETBULB_MODE    ERROR_MODE
*(TDB & HR) (SI=1,ENG=2)  (atm)      (0 OR 1)        (1 OR 2)
     4             2          1           1               1

INPUTS 2
*    TDB          HR
*    (F)        0<HR<1)
     1,5          1,6
     80          0.010


**********************************************************************
UNIT 52 TYPE 16 RADIATION PROCESSOR  ****************************
**********************************************************************
PARAMETERS 8
*   MODE         TRACKING          TILTED        DAY OF YEAR TO
*                  MODE           RAD. MODE     START SIMULATION
*  (Erbs=3)      (fixed=1)      (Isotropic=1)        (n=#)
```

3	1	1	STARTDAY
*LATITUDE	SOLAR CONST	SHIFT	SIM=SOLAR TIME
* (degrees)	(KJ/hr)	(degrees)	(if IE<0)
LATITUDE	4871.0	0.0	-1.0

INPUTS 4

* I	TIME OF LAST	TIME OF NEXT	GROUND REFL
* (KJ/m^2)	RAD. READING	RAD. READING	
1,4	1,19	1,20	0,0
0.0	0.0	0.0	0.2

INPUTS 4

* SLOPE S	AZIMUTH S	SLOPE E	AZIMUTH E
* (degrees)	(degrees)	(degrees)	(degrees)
0,0	0,0	0,0	0,0
90.0	0.0	90.0	-90.0

INPUTS 4

* SLOPE N	AZIMUTH N	SLOPE W	AZIMUTH W
* (degrees)	(degrees)	(degrees)	(degrees)
0,0	0,0	0,0	0,0
90.0	180.0	90.0	90.0

****
UNIT 53 TYPE 19 BUILDING (ZONE) MODEL ***************************
****
* ZONE
PARAMETERS 14

* MODE	UNITS	Va	K1	K2	K3	Cap
*(Energy rate)	(SI=1)	(m^3)	(med. construction)			
(KJ/C)						
1	1	150.0	0.1	0.017	0.049	500.0
* No. surfs	Tr init.	HR init.	Tmin	Tmax	HRmin	HRmax
* #	(C)	(kg/kg)	(C)	(C)	(kg/kg)	(kg/kg)
7	20.0	0.0075	18.0	25.0	0.0075	0.0075

INPUTS 7

* Tamb	HRamb	Tvent	mvent	HRvent	HR add	No. people
* (C)	(kg/kg)	(C)	(kg/hr)	(kg/kg)	(kg/hr)	#
TAMBSI	WAMB	TVENT	MVENT	WVENT	0,0	0,0
0.0	0.0	0.0	0.0	0.0	0.0	2

INPUTS 4

* Activity	Qir	Qint	Windspeed
* level	(KJ/hr)	(KJ/hr)	(m/s)

```
        0,0            0,0          0,0        1,7
        4              2000.        1000.      0.0

* WALLS
PARAMETERS 16
* Surface no.  Surface type    Area     Reflect.      Absorp.     Icoef
*      #       (exterior=1)   (m^2)                               std. ASHRAE
       1            1           9.0       0.70          0.80          2

*  Ntable      WALL 2     I      Area     WALL 3     I      Area    WALL 4   I     Area
* ASHRAE          #              (m^2)       #              (m^2)      #          (m^2)
   57.0           2      -1      30.0        3      -1      15.0       4    -1    30.0

* note:       I=indicates that PARAMETERS 4 through 7 is used for walls 2
*             through 4!

INPUTS 4
* Solar rad. S       Solar rad. E        Solar rad. N        Solar rad. W
*(KJ/hr(m^2)         (KJ/hrm^2)          (KJ/hr m^2)         (KJ/hrm^2)
     52,6               52,11               52,14               52,17
     0.0                0.0                 0.0                 0.0

*FLOOR & CEILING
PARAMETERS 14
* Surface no.  Surface type    Area     Reflect.      Absorp.     Icoef           Ntable

*      #       (interior=2)   (m^2)                               std. ASHRAE        #
       5            2          50.        0.70          0.80          3              16

* Surface no   Surface type    Area     Reflect.      Absorp.     Icoef           Ntable

*      #       (interior=2)   (m^2)                               std. ASHRAE        #
       6            2          50.0       0.70          0.80          3              19

* WINDOW
PARAMETERS 8
* Surface no.       Surface type           Area          Window mode    Transmitance.
*      #            (specify 5)            (m^2)         (trans. int=1)
       7                 5                  6.0              10.80

*hconv,inside      No.Ib    first No.Ib
*(KJ/hr m^2 C)       #          #
    30.0             1          5

INPUTS 5
*  Total. rad.       Beam rad.          Trans.             Loss coeff.        frac. Ib
*(KJ/hr m^2)         (KJ/hr m^2)       (KJ/hr m^2 C)         on floor
     52,6               52,7              0,0                 0,00,0
     0.0                0.0               0.80                12.3               1.0
```

*VIEW FACTORS
PARAMETERS 17

*Geometry mode	height	width	length	iw1	iw2	iw3	iw4	if
*(Rectangular)	(m)	(m)	(m)	#	# #	#	#	
1	3.0	5.0	10.0	1	4 3	2	5	

* ic	No. of windows	iwd	Lwd	Xwd	Ywd	hwd	Wwd
* #	#	#	#	#	# #	#	
6	1	7	1	1.0	0.5	2.0	3.0

****
UNIT 2 TYPE75 SYSTEM CONTROLLER ******************************
****
PARAMETERS 42

* UNITS	FOA	MAO,min	MACoil,max
* (2=ENG)	(0<#<1)	(lbm/hr)	(lbm/hr)
2	.1	8.00E3	1.60E5

*MwCoil,max	Cp,evap	NCoils	MACoil,min
* (lbm/hr)	(Btu/lbm F)	(#)	(lbm/hr)
1.05E5	1.00	6	1.60E4

* Reg.start	Collect start	Next reg. start
* (hours)	(hours)	(hours)
TSTEPS	REGSTART	NEXTTSTEPS

* Intuitive control operating set point temperatures (F):

*TCWHIGH	TCWLOW	TSAHIGH	TSALOW	TCWH	TCWL	TSAH	TSAL
* day 1:				* day 2:			
*I 50.	38.	60.	55.	49.	39.	59.	50.
*II							
42.	39.	53.	47.	41.	36.	54.	48.
* day 3:				* day 4:			
*I 48.	37.	58.	50.	46.	38.	57.	46.
*II							
43.	35.	56.	44.	44.	37.	57.	47.
* day 5:				* day 6:			
*I 46.	37.	56.	43.	47.	36.	56.	45.
*II							
46.	33.	56.	43.	45.	37.	55.	42.
* day 7:							
*I 44.	36.	54.	42.				

```
*II
    43.           35.          53.        40.

* Slider Mode     Frac of max. cap    Design set points
   SLIDER          FRACTION            TDESIGN


INPUTS 22
*    TWB              TDB               HR amb.        Tzone        HR zone

*     (F)             (F)              (lbm/lbm)        (F)         (lbm/lbm)
     TWB              1,5                WAMB          TZONE         WZONE


*   Qsenstot         Qlattot            Sensible       TAOCoil      MAOCoil

* w/vent load       w/vent load       ventilation load
*   (Btu/hr)         (Btu/hr)           (Btu/hr)         (F)         (lbm/hr)
  QSENSBTU          QLATBTU              QVENT           7,1           7,3

*   WOCoil           TWOCoil            QCoilFan     QMWLPump      MWEvap

*  (lbm/lbm)          (F)               (Btu/hr)       (btu/hr)     (lbm/hr)
      7,2             7,4                 8,3             6,3          6,2

*Qcoil,total    MWCoil       PCH      PPUMP    PCCFAN   PTFAN  PTPUMP
* (btu/hr)      (lbm/hr)
    7,6          7,5          5,6       12,1      13,1      10,1     4,3

*INITIAL VALUES FOR SIMULATION
    70.          90.          0.011      75.       0.01
    0.0          0.0          0.0        75.       0.0
    0.0085       50.          0.0        0.0       0.0
    0.0          0.0          0.0        0.0       0.0       0.0      0.0


***************************************************************************
UNIT 3 TYPE 51 COOLING TOWE***********************************************
***************************************************************************
PARAMETERS 11
* NOTE: Enter 12 parameters for mode 2, 11 parameters for mode 1.
*    Units       Mode       Geom          Ncell       Va,cell,max Pcell,max
*  (2=Eng)   (2=Data)  (2=XFlow)        (#)          (ft3/hr)      (KW)
      2           1           2            2            3.726E6       11.19
```

```
*   Va,off      Vs        Ti,sump      LU/c        Ndata/n    Print
*   (ft3/hr)    (ft3)     (F)          (#)         (#)        (1=Print)
    5.589E5     0.0       85.0         3.767       -1.210     1

INPUTS          7
*     Twi       Mw,i      Ta,i         Tewb        Tmain      g1          g2
*     (F)       (lbm/hr)  (F)          (F)         (F)        (-1;0,1)    (-1;0,1)
      5,3       5,4       1,5          TWB         0,0        2,4         2,5
      95.0      7.57E5    100.0        77.0        60.0       1.0         1.0

**********************************************************************
UNIT 4 TYPE 3 PUMP (TOWER TO CHILLER; includes motor efficiency=.91) ****
**********************************************************************
PARAMETERS 2
*  Mmax         Pmax
* (lbm/hr)      (KW)
  7.57E5        23.4

INPUTS 3
*    Ti         Mi          g
*    (F)        (lbm/hr)    (0,1)
     0,0        3,2         2,1
     85.0       7.57E5      1.0

* NOTE:   The control signal issued from the controller must be unity
*         for this pump since the efficiency characteristic of the
*         drive is not included is this simulation (i.e, this is a
*         constant speed pump which cannot be throttled).


**********************************************************************
UNIT 6 TYPE 3 PUMP (AIR HANDLER TO CHILLER)  *********************
**********************************************************************
PARAMETERS 6
*  Mmax         Pmax        C0         C1      C2      C3
* (lbm/hr)      (KW)        (const)    (x)     (x2)    (x3)
  6.31E5        16.9        0.0        0.0     0.0     1.0

INPUTS 3
*    Ti         Mi
*    (F)        (lbm/hr)    (0,1)
     0,0        14,1        2,2
     60.0       6.31E5      1.0
```

```
*******************************************************************
UNIT 5 TYPE 53 PARALLEL CHILLERS **********************************
*******************************************************************
PARAMETERS 12
*    Units      Nmot      Qmax        Qmin          LU        Ndata
*  (2=Eng)     (0,1)    (Btu/hr)    (Btu/hr)        (#)        (#)
      2         .95      8.80E6       0.0           23         50

*    Qdes      DTdes      Pdes        Cp,cw        Cp,ew       Print
*  (Btu/hr)     (F)       (KW)     (Btu/lbmF)   (Btu/lbmF)  (1=Print)
    6.72E6      50.0      353         .998         1.00         2

INPUTS 6
*  Tchw,set    Tev,in     Mev         Tc,in         Mc          Nch
*    (F)        (F)     (lbm/hr)       (F)       (lbm/hr)       (#)
     2,6        2,10      6,2          3,1          4,2         2,7
     40.0       40.0     6.31E5        85.0        7.57E5       1.0

* NOTE:  The constants for the empirical equation used in this model
*        must be input into the fortran source code.


*******************************************************************
UNIT 15  TYPE 65   FLOW CONVERTER II (Mode: Chiller==>AHU) ***********
*******************************************************************
PARAMETERS 2
*   MODE      NAHUS
*   (1,2)      (#)
      1         6

INPUTS 1
*     MI
*  (lbm/hr)
     5,2
    6.31E5


*******************************************************************
UNIT 8 TYPE 3 FAN (AIR HANDLING UNIT) ****************************
*******************************************************************
PARAMETERS 6
*   Mmax      Pstar       C0          C1            C2          C3
*  (lbm/hr)   (KW)      (const)       (x)          (x2)        (x3)
    1.60E5     21.3      .0826         0.0          0.0        1.051

INPUTS 3
*     Ti        Mi          g
*    (F)     (lbm/hr)     (0,1)
     0,0       7,3         2,3
```

```
     75.0      1.60E5      1.0

***************************************************************************
UNIT 7 TYPE 52 COOLING COIL (AIR HANDLING UNIT)  *****************
***************************************************************************
PARAMETERS 20
*    Mode          Units        Nrows      Ntubes        Ltube     Hduct
*  (2=Detail)    (2=Eng)         (#)         (#)          (ft)       (ft)
       2             2             4          52          10.5       6.15

*     Do            Di          Ktube       Fthick       Fspace     Nfin
*     (ft)          (ft)     (Btu/hrftF)     (ft)          (ft)   (#/tube/pass)
     .0521        .04625       231.7       .00109       .00595     1764

*    Kfin         FinMode        Dfin       Wcl,rows    MWC_max  DTdes
* (Btu/hrftF)  (2=Annular)       (ft)         (ft)       (lbm/hr)     (F)
     136.9           2           .104         .139        1.05E5      10

* Re,laminar  F_full_circuit
*      (#)       (.25,.5,1.0)
    1000.0          1.0

INPUTS 6
*    Tidbc          Wic            Ma          Tw,i          Mw     TAOC_set
*     (F)     (lbm,w/lbm,a)   (lbm/hr)        (F)        (lbm/hr)      (F)
      2,8           2,9           8,2          5,1          15,1        2,11
     80.0         .01003       1.60E5        40.0        1.05E5       50.

***************************************************************************
UNIT 14  TYPE 65   FLOW CONVERTER (AIR HANDLING UNIT==>CHILLER)
***************************************************************************
PARAMETERS 2
*    MODE      NAHUS
*    (1,2)        (#)
       2            6

INPUTS 1
*      MI
*   (lbm/hr)
      7,5
    1.05E5

***************************************************************************
UNIT 10  TYPE 60   ELECTRIC MOTOR (TOWER FAN; VSD)  ****************
***************************************************************************
PARAMETERS 6
```

```
*   MODE             PShaft,rated        ServiceFactor       C1
*(2=3Constants)         (kW)               (0<#<1)         (const)
       2                22.4                 1.15            70.0

*      C2                C3
*     (x^2)            (const)
      180.0              1.38

INPUTS 1
*   PShaft
*    (kW)
       3,3
       0.0

***********************************************************************
UNIT 12  TYPE 60   ELECTRIC MOTOR (MAIN WATER LOOP PUMP; VSD) ****
***********************************************************************
PARAMETERS 6
*   MODE             PShaft,rated        ServiceFactor       C1
*(2=3Constants)         (kW)               (0<#<1)         (const)
       2                18.7                 1.15            70.0

*      C2                C3
*     (x^2)            (const)
      180.0              1.38

INPUTS 1
*   PShaft
*    (kW)
       6,3
       0.0

***********************************************************************
UNIT 13  TYPE 60   ELECTRIC MOTOR (COIL FAN; CSD) ******************
***********************************************************************
PARAMETERS 6
*   MODE             PShaft,rated        ServiceFactor       C1
*(2=3Constants)         (kW)               (0<#<1)         (const)
       2                22.4                 1.15            20.0

*      C2                C3
*     (x^2)            (const)
      300.0              1.125

INPUTS 1
*   PShaft
*    (kW)
```

```
        8,3
        0.0

*********************************************************************
UNIT 43 TYPE 25 PRINTER (INPUT AND SUMPOWER) ********************
*********************************************************************
PARAMETERS 4
*   Interval   Time,start  Time.stop   Output_Unit
*     (hr)        (hr)        (hr)         (#)
        1          0.0       10000.0        15

INPUTS 6
      TWB    LOADBTU    2,13       2,6        2,11     2,12
    TWETB     LOAD       SHR     TCHWSET    TAOCSET  SUMPOW

END
```

APPENDIX B

BEMS CONTROLLER

```
C**********************************************************************
C                                                                     *
C BEMS CONTROLLER:                                                    *
C                                                                     *
C This subroutine models a BEMS controller. The model is responsible for both   *
C local and supervisory control. The local control involves adjusting the variable   *
C speeds of the main water loop pumps and supply air fans in the air handling unit   *
C (VAV system). The controller is used together with a local loop controller for the   *
C cooling coil routine, which provides the right coil mass flow rate to meet the coil   *
C air outlet temperature. This temperature is used to determine the status of the   *
C power devices.                                                      *
C                                                                     *
C The supervisory part of the controller consists of an intuitive and optimal control   *
C scheme.                                                             *
C                                                                     *
C In the intuitive control scheme a set of control variables are calculated. These   *
C calculations are based on a set of upper and ower limits of the two control   *
C variables (the chilled water set- point temperature and supply air set-point   *
C temperature), the total building cooling load, the maximum chiller capacity, and a   *
C specified fraction of the total chiller capacity.                   *
C                                                                     *
C Information on the two uncontrolled variables and on the three uncontrolled   *
C variables (the total building load, Sensible heat ratio (SHR), and wet-bulb   *
C temperature) are continously and stored in an array. When a pre-determined time   *
C set-point is reached the controller regresses the the available data and and a set of   *
C coefficients are determined.                                        *
C                                                                     *
C In the optimal control the coefficients are rearranged so that a new set of control   *
C variables can be determined. Temperature constraints across the cooling coil and   *
C minimum and maximum temperature limits on the control variables are also   *
C included in the optimal controller. New regressions continuously upgrade the   *
C optimal set point temperatures, every hour, or every time period as specified by   *
C the user.                                                           *
C                                                                     *
C                              Øystein Ulleberg    May 1993           *
C                                                                     *
C**********************************************************************

      SUBROUTINE TYPE75(TIME,XIN,OUT,T,DTDT,PAR,INFO)

      DIMENSION XIN(22),OUT(33),PAR(42),INFO(10)
      CHARACTER*4 MODE
      INTEGER W,ROWS,COLUMNS
      INTEGER ROUND,UNITS,COUNT1,COUNT2,WEEK,PTS,C,R,I,NUM
      INTEGER FLAG,NDATA,K,J,SLIDER,TDESIGN,YTIME
      PARAMETER (ROWS=4000,COLUMNS=7,W=7,TOL=.0001)
C        Note: If ROWS is changed here it also must
C          be changed in the subroutines below!
```

```
      REAL DSTEPS, MAXLOAD, MINLOAD, MAXTWB, MINTWB, MAXSHR
      REAL MINSHR, FAO, MAOMIN, MACMAX, MWCMAX, CPW, NCOILS
      REAL MACMIN, TSTEPS, REGSTART, TSTEPSNEXT, TCWHIGH(W)
      REAL TCWLOW(W), TSAHIGH(W), TSALOW(W), YTSA(ROWS)
      REAL YTCW(ROWS), YNUM(ROWS), TWB, TDB, WAMB, TZONE, WZONE
      REAL QSENSTOT, QLATTOT, QVENTSENS, TAOC, MAC, WOC, TWOC
      REAL QCCFAN, QMWLPUMP, MWEVAP, QCOIL, MWC
      REAL PCHILLER, PMWPUMP, PCCFAN, PTFAN, PTPUMP
      REAL SUMPOW, QSENS, QVENTLAT, QLAT, LOAD, SHR, b(21), QFANS
      REAL DELTATCW, DELTATSA, FRACTION, TCWSET, TSASET, SLOPE1
      REAL  SLOPE2, Y1, Y2, REGTIME, REALPTS, SUMSQ, POWFIRST(ROWS)
      REAL DATA(ROWS, COLUMNS)
      DOUBLE PRECISION q(21)
      REAL POWACT(ROWS), DUMMY, RMS, L, POWEST, DTFOR, DTAPPROX
      REAL LOADTONS, TSASETHIGH, REALI, TAIC, WIC, TWIEV, QCHILLER, F
      COMMON /SIM/ TIME0,TFINAL,DELT
      COMMON /ARRAY/ DATA,q

C*** NOMENCLATURE ********************************************** *
C                                                                  *
C          CPA  =  Specific heat of air                            *
C          CPW  =  Specific heat of water                          *
C      COLUMNS  =  Number of colums in DATA array                  *
C         DATA  =  Array including data to be regressed            *
C     DELTATSA  =  Supply-air temperature difference               *
C       DSTEPS  =  Counter                                         *
C        DUMMY  =  Dummy variable                                  *
C          FAO  =  Fraction of outdoor air used in return air      *
C     FRACTION  =  Fraction of Building load                       *
C          HFG  =  Heat of vaporization for water                  *
C            L  =  Total system cooling load in tons               *
C         LOAD  =  Total system cooling load in Btu/hr             *
C          MAC  =  Air mass flow rate through the cooling coil     *
C       MACMAX  =  Maximum air mass flow rate provided by fan      *
C       MACMIN  =  Minimum air mass flow rate through cooling coil *
C                  (for air quality)                               *
C       MAOMIN  =  Minimum outside air ventilation flow rate       *
C                  (for air quality)                               *
C      MAXLOAD  =  Maximum building cooling load encountered       *
C       MAXTWB  =  Maximum wet-bulb temperature encountered        *
C       MAXSHR  =  Maximum SHR encountered                         *
C      MINLOAD  =  Minimum building cooling load encountered       *
C       MINTWB  =  Minimum wet-bulb temperature encountered        *
C       MINSHR  =  Minimum SHR encountered                         *
C          MWC  =  Water mass flow rate through every coil         *
C       MWCMAX  =  Maximum mass flow rate through each coil provided *
C                  by pump                                         *
C       MWEVAP  =  Total water mass flow rate through chiller evaporator *
C          NCH  =  Number of parallel chillers                     *
```

```
C        NCOILS  =  Number of cooling coils                                *
C         NDATA  =  No. of timesteps to be regressed                       *
C      PCHILLER  =  Chiller power                                          *
C        PCCFAN  =  Supply air fan power                                   *
C       PMWPUMP  =  Main water loop pump power                             *
C        POWACT  =  Actual power consumption (for checking purposes)       *
C        POWEST  =  Estimated power consumption                            *
C      POWFIRST  =  Estimated power consumption (for checking purposes)    *
C         PTFAN  =  Cooling tower fan power                                *
C        PTPUMP  =  Cooling tower pump power                               *
C           PTS  =  Number of points to be regressed                       *
C             q  =  Array of estimated coefficients from regression        *
C        QCCFAN  =  Load introduced by fan (=power)                        *
C      QCHILLER  =  Load meet by the chiller                               *
C     QCHILLMAX  =  Maximum load which can be meet by the chiller          *
C         QCOIL  =  Load on cooling coil                                   *
C      QCOILSEN  =  Sensible cooling coil load                             *
C          QLAT  =  Latent building load (w/out ventilation load)          *
C       QLATTOT  =  Total latent building load (w/ ventilation load)       *
C      QMWLPUMP  =  Load introduced by main water loop pump (=power)       *
C         QSENS  =  Sensible building load (w/out ventilation load)        *
C      QSENSTOT  =  Total sensible building load (w/ ventilation load)     *
C      QVENTLAT  =  Latent ventilation load                                *
C     QVENTSENS  =  Sensible ventilation load                              *
C      REGSTART  =  Starting point of regression period                    *
C       REGTIME  =  No. of timesteps before optimal control is to occur    *
C          ROWS  =  Number of rows in DATA array                           *
C           RMS  =  Root Mean Square                                       *
C           SHR  =  Building Sensible Heat Ratio                           *
C        SLOPE1  =  Slope between TCWHIGH and TCWLOW                       *
C        SLOPE2  =  Slope between TASHIGH and TSALOW                       *
C        SUMPOW  =  Total system power consumption                         *
C         SUMSQ  =  Sums of squares                                        *
C          TABS  =  Absolute temperature                                   *
C          TAIC  =  Cooling coil air inlet temperature                     *
C          TAOC  =  Cooling coil air outlet temperature                    *
C           TCW  =  Chilled water temperature variable                     *
C       TCWHIGH  =  Initial and max. chilled water set-point temperature   *
C       TCWLOW\  =  Final and min. chilled water set-point temperature     *
C        TCWSET  =  Chilled water set point temperature                    *
C          TENG  =  Temperature in English units                           *
C           TDB  =  Outdoor dry-bulb temperature                           *
C           TSA  =  Supply-air temperature variable                        *
C       TSAHIGH  =  Initial and max. supply-air set-point temperature      *
C        TSALOW  =  Final and min. supply-air set-point temperature        *
C        TSASET  =  Supply air set point temperature                       *
C           TSI  =  Temperature in SI-units                                *
C        TSTEPS  =  No. of timesteps before first regression is to occur   *
C    TSTEPSNEXT  =  No. of timesteps before next regression is to occur    *
```

```
C              TWB  =  Outdoor wet-bulb temperature                         *
C             TWOC  =  ater coil outlet temperature                         *
C            TZONE  =  Zone temperature                                     *
C             WAMB  =  Ambient humidity ratio                               *
C              WIC  =  Humidity of air in front of coil                     *
C              WOC  =  Humidity of air behind the coil                      *
C            WZONE  =  Zone humidity                                        *
C               Y1  =  Relative y-intercept.  Actual = TCWHIGH + Y1         *
C               Y2  =  Relative y-intercept.  Actual = TSAHIGH + Y2         *
C                                                                           *
C        C,I,J,K,R  =  Counters                                             *
C           COUNT1  =  Counter                                              *
C           COUNT2  =  Counter                                              *
C                                                                           *
C*************************************************************************** *


C*****STATEMENT FUNCTIONS ****************************************
      ROUND(RNUM)=NINT(RNUM)
      TSI(TEMP,UNITS)=(TEMP-32)/1.8*(UNITS-1)+TEMP*(2-UNITS)
      TENG(TEMP,UNITS)=(1.8*TEMP+32)*(2-UNITS)+TEMP*(UNITS-1)
      TABS(UNITS)=459.67*(UNITS-1)+273.15*(2-UNITS)
      HFG(UNITS)=1050.*((UNITS-1)+(2-UNITS)/.42995)
      CPA(UNITS)=.244*((UNITS-1)+(2-UNITS)/.23886)
      QCHILLMAX(UNITS)=560.0*((UNITS-1)*12000.+(2-UNITS)
     .*12000./.94787)

      If (info(7).eq.0.) then
       write(*,*) time
c        write(*,*)'tsaset,tcwset=',tsaset,tcwset
      endif


C*****FIRST CALL OF THE SIMULATION ********************************
      IF(INFO(7).EQ.-1)THEN
       COUNT1=0
       COUNT2=1
       DSTEPS=24.0
       WEEK=0
       MAXLOAD=0.
       MINLOAD=560.*12000.
       MAXTWB=0.
       MINTWB=150.
       MAXSHR=0.
       MINSHR=1.0
       NI=22
       NP=42
       ND=0
       INFO(6)=33
```

```
     INFO(9)=1
     CALL TYPECK(1,INFO,NI,NP,ND)
       MODE='OFF'
    ENDIF


C*****SET PARAMETER (ONLY ON FIRST CALL)*************************
    IF(INFO(1).NE.IUNIT) THEN
      IUNIT          =  INFO(1)
      UNITS          =  ROUND(PAR(1))
      FAO            =  PAR(2)
      MAOMIN         =  PAR(3)
      MACMAX         =  PAR(4)
      MWCMAX         =  PAR(5)
      CPW            =  PAR(6)
      NCOILS         =  ROUND(PAR(7))
      MACMIN         =  PAR(8)
      TSTEPS         =  PAR(9)
      REGSTART       =  PAR(10)
      TSTEPSNEXT     =  PAR(11)
      TCWHIGH(1)     =  PAR(12)
      TCWLOW(1)      =  PAR(13)
      TSAHIGH(1)     =  PAR(14)
      TSALOW(1)      =  PAR(15)
      TCWHIGH(2      =  PAR(16)
      TCWLOW(2)      =  PAR(17)
      TSAHIGH(2)     =  PAR(18)
      TSALOW(2)      =  PAR(19)
      TCWHIGH(3)     =  PAR(20)
      TCWLOW(3)      =  PAR(21)
      TSAHIGH(3)     =  PAR(22)
      TSALOW(3)      =  PAR(23)
      TCWHIGH(4)     =  PAR(24)
      TCWLOW(4)      =  PAR(25)
      TSAHIGH(4)     =  PAR(26)
      TSALOW(4)      =  PAR(27)
      TCWHIGH(5)     =  PAR(28)
      TCWLOW(5)      =  PAR(29)
      TSAHIGH(5)     =  PAR(30)
      TSALOW(5)      =  PAR(31)
      TCWHIGH(6)     =  PAR(32)
      TCWLOW(6)      =  PAR(33)
      TSAHIGH(6)     =  PAR(34)
      TSALOW(6)      =  PAR(35)
      TCWHIGH(7)     =  PAR(36)
      TCWLOW(7)      =  PAR(37)
      TSAHIGH(7)     =  PAR(38)
      TSALOW(7)      =  PAR(39)
      SLIDER         =  ROUND(PAR(40))
```

```
      FRACTION          =  PAR(41)
      TDESIGN           =  ROUND(PAR(42))
      write (*,*)'slider=', slider
      write (*,*)'tdesign=', tdesign
     ENDIF


C*****EFFECT CALCULATIONS ****************************************
      k
      TWB          =  XIN(1)
      TDB          =  XIN(2)
      WAMB         =  XIN(3)
      TZONE        =  XIN(4)
      WZONE        =  XIN(5)
      QSENSTOT     =  XIN(6)
      QLATTOT      =  XIN(7)
      QVENTSENS    =  XIN(8)
      TAOC         =  XIN(9)
      MAC          =  XIN(10)
      WOC          =  XIN(11)
      TWOC         =  XIN(12)
      QCCFAN       =  XIN(13)*3413.0    !from SI to English units
      QMWLPUMP     =  XIN(14)*3413.0    !from SI to English units
      MWEVAP       =  XIN(15)
      QCOIL        =  XIN(16)
      MWC          =  XIN(17)
      PCHILLER     =  XIN(18)
      PMWPUMP      =  XIN(19)
      PCCFAN       =  XIN(20)
      PTFAN        =  XIN(21)
      PTPUMP       =  XIN(22)


C*****BUILDING LOAD CALCULATIONS *******************************
     QVENTSENS1=MAC*CPA(UNITS)*(TSASET-TZONE)
     QSENS=QSENSTOT-QVENTSENS+QCCFAN*NCOILS
     QFANS=QCCFAN*NCOILS
     QVENTLAT=HFG(UNITS)*MAC*(WOC-WZONE)
     QLAT=QLATTOT-QVENTLAT
     LOAD=QSENS+QLAT

     IF(LOAD.GT.0.)THEN
      SHR=QSENS/LOAD
     ENDIF


C*****TOTAL POWER CONSUMPTION CALCULATION ******************

     SUMPOW=PCHILLER+PMWPUMP+PTFAN+PTPUMP+NCOILS*PCCFAN
```

```
C*****INTUITIVE CONTROL OF TCWSET AND TSASET******************

   IF(TIME.LE.(TSTEPS+REGSTART)) THEN  !@LOOP1

    IF(TDESIGN.EQ.1) THEN  !Operating at design set points (optional):
     TSASET=55.
     TCWSET=45.
     GOTO 500
    ENDIF


C***Setting up the intuitive control scheme:

    IF(TIME.GT.(COUNT2*DSTEPS+WEEK*168)) THEN
      COUNT2=COUNT2+1
      IF (COUNT2.EQ.8) THEN
        WEEK=WEEK+1
         write (*,*) 'week=',week
       COUNT2=1
      ENDIF
    ENDIF


    IF(LOAD.GT.QCHILLMAX(UNITS)) THEN
      IF (INFO(7).EQ.0.) THEN
       WRITE (*,*)'*******CONTROLLER WARNING*******'
       WRITE(*,*)'MAXIMUM LOAD OF ',QCHILLMAX(UNITS),
   @              ' TONS HAS BEEN'
       WRITE(*,*)'EXCEEDED.  TIME=',TIME,'  LOAD=',LOAD
     ENDIF
    ENDIF

    DELTATCW=TCWLOW(COUNT2)-TCWHIGH(COUNT2)
    DELTATSA=TSALOW(COUNT2)-TSAHIGH(COUNT2)

    IF((LOAD/QCHILLMAX(UNITS)).LE.FRACTION)THEN
     TCWSET=TCWHIGH(COUNT2)
     TSASET=TSAHIGH(COUNT2)
    ELSE
     SLOPE1=(DELTATCW)/((1-FRACTION)*QCHILLMAX(UNITS))
     SLOPE2=(DELTATSA)/((1-FRACTION)*QCHILLMAX(UNITS))
     Y1=-SLOPE1*FRACTION*QCHILLMAX(UNITS)
     Y2=-SLOPE2*FRACTION*QCHILLMAX(UNITS)
     TCWSET=TCWHIGH(COUNT2)+Y1+SLOPE1*LOAD
     TSASET=TSAHIGH(COUNT2)+Y2+SLOPE2*LOAD
    ENDIF

   ELSE  !@LOOP1
```

```
C***END OF INTUITIVE CONTROL SCHEME


C*****OPTIMAL CONTROL OF TCWSET AND TSASET *******************

C***Finding power formula coefficients using regression subroutine:

      REGTIME=TSTEPS+REGSTART+COUNT1*TSTEPSNEXT
      IF((TIME.GT.REGTIME).AND.(INFO(7).EQ.0))THEN  !@LOOP2
       IF(SLIDER.EQ.0) REALPTS=(TIME-1-REGSTART)
       IF(SLIDER.EQ.1) REALPTS=(TIME-1-REGSTART-COUNT1)
       PTS=INT(REALPTS+SIGN(0.5,REALPTS))  !PTS --> made an integer
       CALL REGRESS(PTS)
       COUNT1=COUNT1+1
       SUMSQ=0.
       DO 20 R=1,PTS
        POWFIRST(R)=q(1)+q(2)*DATA(R,2)+q(3)*DATA(R,3)
     @    +q(4)*DATA(R,4)+q(5)*DATA(R,5)+q(6)*DATA(R,6)
     @    +q(7)*DATA(R,2)*DATA(R,2)+q(8)*DATA(R,3)*DATA(R,3)
     @    +q(9)*DATA(R,4)*DATA(R,4)+q(10)*DATA(R,5)*DATA(R,5)
     @    +q(11)*DATA(R,6)*DATA(R,6)+q(12)*DATA(R,2)*DATA(R,3)
     @    +q(13)*DATA(R,2)*DATA(R,4)+q(14)*DATA(R,2)*DATA(R,5)
     @    +q(15)*DATA(R,2)*DATA(R,6)+q(16)*DATA(R,3)*DATA(R,4)
     @    +q(17)*DATA(R,3)*DATA(R,5)+q(18)*DATA(R,3)*DATA(R,6)
     @    +q(19)*DATA(R,4)*DATA(R,5)+q(20)*DATA(R,4)*DATA(R,6)
     @    +q(21)*DATA(R,5)*DATA(R,6)
        POWACT(R)=DATA(R,7)
        SUMSQ=(POWACT(R)-POWFIRST(R))**2.0+SUMSQ

C***Searching for the min & max loads,Twb's and SHR'S:

        DUMMY=DATA(R,3)*12000.      !load in Btu's
        IF(DUMMY.GT.MAXLOAD) MAXLOAD=DUMMY
        IF(DUMMY.LT.MINLOAD) MINLOAD=DUMMY
        IF(DATA(R,2).GT.MAXTWB) MAXTWB=DATA(R,2)
        IF(DATA(R,2).LT.MINTWB) MINTWB=DATA(R,2)
        IF(DATA(R,4).GT.MAXSHR) MAXSHR=DATA(R,4)
        IF(DATA(R,4).LT.MINSHR) MINSHR=DATA(R,4)

20      CONTINUE
       RMS=SQRT(SUMSQ/(PTS-1))

      ENDIF  !@LOOP2


C***For loads, Twb, and SHR's that never have been encountered before and
C***intuitive control is therfore used:

      IF(((LOAD.GT.MAXLOAD).OR.(LOAD.LT.MINLOAD).OR.
```

```
@    (TWB.GT.MAXTWB).OR.(TWB.LT.MINTWB).OR.
@    (SHR.GT.MAXSHR).OR.(SHR.LT.MINSHR)).AND.(INFO(7).EQ.0))
@    THEN

       WRITE (*,*)'*******CONTROLLER WARNING*******'
       WRITE (*,*)'TIME = ',TIME
       WRITE (*,*)'NEW AMBIENT CONDITIONS HAVE BEEN ENCOUNTERED:'
       WRITE (*,*)'   MINTWB,MAXTWB,TWB=',MINTWB,MAXTWB,TWB
       WRITE (*,*)'
MINLOAD,MAXLOAD,LOAD=',MINLOAD,MAXLOAD,LOAD
        WRITE (*,*)'   MINSHR,MAXSHR,SHR=',MINSHR,MAXSHR,SHR

       DELTATCW=TCWLOW(COUNT2)-TCWHIGH(COUNT2)
       DELTATSA=TSALOW(COUNT2)-TSAHIGH(COUNT2)

       IF((LOAD/QCHILLMAX(UNITS)).LE.FRACTION)THEN
        TCWSET=TCWHIGH(COUNT2)
        TSASET=TSAHIGH(COUNT2)
       ELSE
        SLOPE1=(DELTATCW)/((1-FRACTION)*QCHILLMAX(UNITS))
        SLOPE2=(DELTATSA)/((1-FRACTION)*QCHILLMAX(UNITS))
        Y1=-SLOPE1*FRACTION*QCHILLMAX(UNITS)
        Y2=-SLOPE2*FRACTION*QCHILLMAX(UNITS)
        TCWSET=TCWHIGH(COUNT2)+Y1+SLOPE1*LOAD
        TSASET=TSAHIGH(COUNT2)+Y2+SLOPE2*LOAD
       ENDIF

       GOTO 100

      ENDIF


C***Optimum set point temperatures calculated based on coefficients:

      L=LOAD/12000.0    ! Load in tons

       TSASET=1.0/(q(21)*q(21)/(2.*q(10))-2.*q(11))
     @      *(q(6)+q(15)*TWB+q(18)*L+q(20)*SHR
     @      +q(21)*(-1./(2.*q(10)))*(q(5)+q(14)*TWB
     @      +q(17)*L+q(19)*SHR))

       TCWSET=(-1./(2.*q(10)))*(q(5)+q(14)*TWB+q(17)*L
     @      +q(19)*SHR+q(21)*TSASET)

       IF (INFO(7).EQ.0) THEN
        WRITE (*,*)'Predicted TCWSET,TSASET=',TCWSET,TSASET
        WRITE (*,*)' '
       ENDIF
```

```
C***Estimated power using power formula:

100    POWEST=q(1)+q(2)*TWB+q(3)*L+q(4)*SHR
   @      +q(5)*TCWSET+q(6)*TSASET+q(7)*TWB*TWB
   @      +q(8)*L*L+q(9)*SHR*SHR+q(10)*TCWSET*TCWSET
   @      +q(11)*TSASET*TSASET+q(12)*TWB*L
   @      +q(13)*TWB*SHR+q(14)*TWB*TCWSET
   @      +q(15)*TWB*TSASET+q(16)*L*SHR
   @      +q(17)*L*TCWSET+q(18)*L*TSASET+q(19)*SHR*TCWSET
   @      +q(20)*SHR*TSASET+q(21)*TCWSET*TSASET


C***Minimum chilled water temperature constraint:

      FLAG=0  !Resetting Flag

      IF (TCWSET.LE.38.0) THEN
       IF (INFO(7).EQ.0) THEN
        WRITE (*,*)'*******CONTROLLER WARNING*******'
        WRITE (*,*)'TCWSET,TSASET=',TCWSET,TSASET
        WRITE (*,*)'A NEW TCWSET IS SET TO 38 F'
        WRITE (*,*)' '
       ENDIF
       TCWSET=38.0
       FLAG=1
      ENDIF

      IF (TCWSET.GE.55.0) THEN
       IF (INFO(7).EQ.0) THEN
        WRITE (*,*)'*******CONTROLLER WARNING*******'
        WRITE (*,*)'TCWSET,TSASET=',TCWSET,TSASET
        WRITE (*,*)'A NEW TCWSET IS SET TO 55 F'
        WRITE (*,*)' '
       ENDIF
       TCWSET=55.
       FLAG=2
      ENDIF


C***Minimum Supply air-Chilled water temperature difference constraint:

      DTAPPROX=-0.41909+0.01278*L+0.12118*SHR


C***Logical constraint (Tsa must be greater that Tcw and less
C***than Tsa,design):

      TSASETHIGH=55.
      IF (TSASET.GE.TSASETHIGH) THEN
```

```
        IF (INFO(7).EQ.0) THEN
         WRITE (*,*)'*******CONTROLLER WARNING*******'
         WRITE (*,*)'TCWSET,TSASET=',TCWSET,TSASET
        ENDIF

        IF (FLAG.EQ.1) THEN
         TSASET=55.   !Tsa,design
         FLAG=3
        ELSE IF(FLAG.EQ.2) THEN
         TSASET=TCWSET+10.
         FLAG=3
        ENDIF

       ENDIF


C***Logical Tsaset limit (Tsa must be greater than Tcw):

       IF(TSASET.LE.TCWSET) THEN
        IF (INFO(7).EQ.0) THEN
         WRITE (*,*)'*******CONTROLLER WARNING*******'
         WRITE (*,*)'TCWSET,TSASET=',TCWSET,TSASET
        ENDIF

        TSASET=TCWSET+DTAPPROX+0.001

       ENDIF


C***Minimum temperature Difference constraint:

       IF(FLAG.EQ.3) GOTO 200

       DTFOR=TSASET-TCWSET

       IF (DTFOR.LT.DTAPPROX) THEN
        IF (INFO(7).EQ.0) THEN
         WRITE (*,*)'*******CONTROLLER WARNING*******'
         WRITE (*,*)'MINIMUM TEMP. DIFFERENCE CONSTRAINT VIOLATED'
        ENDIF

        TCWSET=TSASET-DTAPPROX

       ENDIF

200    CONTINUE


      ENDIF !@LOOP1
```

```
C*****END OF TCWSET AND TSASET OPTIMAL CONTROL****************

C*****READING IN DATA TO BE REGRESSED ***************************

C***Using data only with less significant digits:

      TIME=SIGDIGITS(TIME)
      TWB=SIGDIGITS(TWB)
      LOADTONS=LOAD/12000.
      LOADTONS=SIGDIGITS(LOADTONS)
       SHR=SIGDIGITS(SHR)
      TCWSET=SIGDIGITS(TCWSET)
      TSASET=SIGDIGITS(TSASET)
      SUMPOW=SIGDIGITS(SUMPOW)

      IF((SLIDER.EQ.0).AND.(TIME.GT.REGSTART)) THEN
       REALI=TIME-REGSTART
       I=INT(REALI+SIGN(0.5,REALI))
       DATA(I,1)=TIME
       DATA(I,2)=TWB
       DATA(I,3)=LOADTONS    !in tons
       DATA(I,4)=SHR
       DATA(I,5)=TCWSET
       DATA(I,6)=TSASET
       DATA(I,7)=SUMPOW
       GOTO 500
      ENDIF


      IF((TIME.GT.REGSTART).AND.(TIME.LT.(REGSTART+TSTEPS+1))) THEN
       REALI=TIME-REGSTART
       I=INT(REALI+SIGN(0.5,REALI))
       DATA(I,1)=TIME
       DATA(I,2)=TWB
       DATA(I,3)=LOADTONS    !in tons
       DATA(I,4)=SHR
       DATA(I,5)=TCWSET
       DATA(I,6)=TSASET
       DATA(I,7)=SUMPOW
      ENDIF

      NDATA=INT(TSTEPS+SIGN(0.5,TSTEPS))
      IF((TIME.GT.(REGSTART+TSTEPS)).AND.(INFO(7).EQ.0.))THEN
       DO 30 K=1,7
        DO 40 J=1,NDATA-1
         DATA(J,K)=DATA(J+1,K)
40       CONTINUE
30      CONTINUE
```

```
      ENDIF

      IF(TIME.GT.(REGSTART+TSTEPS))THEN
       DATA(NDATA,1)=TIME
       DATA(NDATA,2)=TWB
       DATA(NDATA,3)=LOADTONS    !in tons
       DATA(NDATA,4)=SHR
       DATA(NDATA,5)=TCWSET
       DATA(NDATA,6)=TSASET
       DATA(NDATA,7)=SUMPOW
      ENDIF

500   CONTINUE

C*****END OF DATA READING  ***************************************


C*****CONTROL OF PUMPS AND FANS (LOAD DEPENDENT)**************

C***No load:

      IF(LOAD.EQ.0) THEN
        MODE='OFF'


C***Starting devices for a load not equal to zero:

      ELSE IF ((LOAD.GT.0).AND.(MAC.LT. .1 .OR. MWC.LT. .1
     +         .OR. MWEVAP.LT. .1)) THEN

        MODE='ON'
        P2G  =.1
          F1G  =.1
        P1G  =1.0
        F2G  =1.0
        F3G  =1.0
        NCH  =1
        TAIC =TZONE
        WIC  =WZONE
        TWIEV =TWOC


C***Running mode:

      ELSE IF ((LOAD.GT.0).AND.(MAC.GE. .1 .OR. MWC.GE. .1)) THEN


C*****Tower pumps and fans are running with constant speed:
```

```
      MODE='ON'
      P1G =1.0
      P2G =MWC/MWCMAX
      F2G =1.0
      F3G =1.0
      NCH =1

C*****Evaluation of supply air fan speed for variable speed operation:

       MAC=MAX(QSENS/NCOILS/(CPA(UNITS)*(TZONE-TAOC)),MACMIN)
       F1G=MAC/MACMAX
       TWIEV=TWOC+QMWLPUMP/(MWEVAP*CPW)

       QCHILLER=QCOIL*NCOILS+QMWLPUMP
       IF(QCHILLER.GT.QCHILLMAX(UNITS))THEN
         WRITE (*,*)'******* CONTROLLER WARNING *******'
         WRITE (*,*)'MAXIMUM CHILLER LOAD IS SURPASSED!'
         WRITE (*,*)'TERMINATE SIMULATION'
       ENDIF

       IF(FAO*MAC.GT.MAOMIN)THEN
         F=FAO
       ELSE
         F=MAOMIN/MAC
       ENDIF
       TAIC=F*TDB+(1-F)*TZONE
       WIC=F*WAMB+(1-F)*WZONE
     ENDIF

C***Shut off mode:

     IF(MODE.EQ.'OFF')THEN
       P1G=0.0
       P2G=0.0
       F1G=0.0
       F2G=0.0
       F3G=0.0
       NCH=0
      TAIC=TZONE
      WIC=WOC
      TWIEV=TCWSET
     ENDIF

C*****SETTING THE OUTPUTS***************************************

     OUT(1)        =    P1G
     OUT(2)        =    P2G
```

```
      OUT(3)      =   F1G
      OUT(4)      =   F2G
      OUT(5)      =   F3G
      OUT(6)      =   TCWSET
      OUT(7)      =   NCH
      OUT(8)      =   TAIC
      OUT(9)      =   WIC
      OUT(10)     =   TWIEV
      OUT(11)     =   TSASET
      OUT(12)     =   SUMPOW
      OUT(13)     =   SHR
      OUT(14)     =   LOAD
      OUT(15)     =   POWEST
      OUT(16)     =   RMS
      OUT(17)     =   q(5)
      OUT(18)     =   q(6)
      OUT(19)     =   q(10)
      OUT(20)     =   q(11)
      OUT(21)     =   q(14)
      OUT(22)     =   q(15)
      OUT(23)     =   q(17)
      OUT(24)     =   q(18)
      OUT(25)     =   q(19)
      OUT(26)     =   q(20)
      OUT(27)     =   q(21)
      OUT(28)     =   QSENS
      OUT(29)     =   QVENTSENS
      OUT(30)     =   QVENTSENS1
      OUT(31)     =   QLAT
      OUT(32)     =   QVENTLAT
      OUT(33)     =   QFANS
      RETURN
      END

C********************************************************************* *
C                                                                      *
C  This function cuts of the number of significant digits of a real number down to a  *
C  desired number n.                                                   *
C                                                                      *
C********************************************************************* *

      FUNCTION SIGDIGITS(X)
        X=10000.0*X
         XI=INT(X+SIGN(0.5,X))
        X=XI/10000.0
        SIGDIGITS=X
      RETURN
      END
```

```
C******************************************************************** *
C                                                                     *
C  REGRESSION SUBROUTINE:                                             *
C                                                                     *
C  This subroutine performs a 2nd order least square linear regresionion.  Data on   *
C  theTWB,LOAD,SHR,TCWSET,TSASET, and SUMPOW is made available from  *
C  the simulation.  The 21 coefficients in the quadratic power formula are then     *
C  calculated.                                                        *
C                                                                     *
C******************************************************************** *

      SUBROUTINE REGRESS(PTS)

      INTEGER PTS,NDATA,NCOEFF,R
      INTEGER I,J,K
      PARAMETER (R=4000, NCOEFF=21, NDATA=7)
      REAL DATA(R,NDATA)
      DOUBLE PRECISION A(R),B(R),C(R),D(R),E(R)
      DOUBLE PRECISION X(R,NCOEFF),Y(R,1),XT(NCOEFF,R)
      DOUBLE PRECISION C1(NCOEFF,NCOEFF),C2(NCOEFF,1)
      DOUBLE PRECISION COEFFS(NCOEFF,1),SUM
      DOUBLE PRECISION q(NCOEFF)
      DOUBLE PRECISION TSASET(R),TCWSET(R)
      DOUBLE PRECISION TWB(R),L(R),SHR(R),TCW(R),TSA(R)
      DOUBLE PRECISION POWEST(R), POWREAL(R)
      COMMON /ARRAY/ DATA,q


C*****NOMENCLATURE ***************************************************
C                                                                     *
C          PTS  =  Number of rows of data points from simulation      *
C        NDATA  =  Number of columns of data from simulation          *
C       NCOEFF  =  Number of coefficients to be determined            *
C        I,J,K  =  Counters                                           *
C         DATA  =  Data from simulation to be regressesd              *
C    A,B,C,D,E  =  Input variables:                                   *
C            A  =  Twb                                                *
C            B  =  Load                                               *
C            C  =  SHR                                                *
C            D  =  Tcw                                                *
C            E  =  Tsa                                                *
C            X  =  "X"  matrix                                        *
C            Y  =  "Y"  matrix                                        *
C           XT  =  Transpose of "X" matrix                            *
C           C1  =  Matrix product: "XT" x "X" = "C1"                  *
C           C2  =  Matrix product: "XT" x "Y" = "C2"                  *
C       COEFFS  =  Calculated coefficients (output)                   *
C          SUM  =  Running total                                      *
C            q  =  Calculated coefficients                            *
```

```
C         TSASET  =  Optimal supply air temperature                       *
C        TCWSET   =  Optimal chilled water temperature                    *
C                                                                         *
C                            Øystein Ulleberg  March ,1993                *
C                                                                         *
C*************************************************************** *

C***Organizing the data into the desired matrix forms:

    DO 30 I=1,PTS
      A(I)=DATA(I,2)
      B(I)=DATA(I,3)     !in tons
      C(I)=DATA(I,4)
      D(I)=DATA(I,5)
      E(I)=DATA(I,6)
      X(I,1)=1
      X(I,2)=A(I)
      X(I,3)=B(I)
      X(I,4)=C(I)
      X(I,5)=D(I)
      X(I,6)=E(I)
      X(I,7)=A(I)*A(I)
      X(I,8)=B(I)*B(I)
      X(I,9)=C(I)*C(I)
      X(I,10)=D(I)*D(I)
      X(I,11)=E(I)*E(I)
      X(I,12)=A(I)*B(I)
      X(I,13)=A(I)*C(I)
      X(I,14)=A(I)*D(I)
      X(I,15)=A(I)*E(I)
      X(I,16)=B(I)*C(I)
      X(I,17)=B(I)*D(I)
      X(I,18)=B(I)*E(I)
      X(I,19)=C(I)*D(I)
      X(I,20)=C(I)*E(I)
      X(I,21)=D(I)*E(I)

      Y(I,1)=DATA(I,7)

30  CONTINUE


C***Transpose of "x" matrix:

    DO 40 I=1,PTS
     DO 40 J=1,NCOEFF
      XT(J,I)=X(I,J)
40  CONTINUE
```

```
C***Multiplying transpose of "X" by "X":

      SUM=0.0
      DO 70 J=1,NCOEFF
        DO 70 I=1,NCOEFF
          DO 75 K=1,PTS
            SUM = SUM + XT(I,K) * X(K,J)
75        CONTINUE
      C1(I,J) = SUM
      SUM = 0.0
70    CONTINUE


C***Multiplying transpose of "X" by "Y":

      SUM=0.0
      J=1
      DO 90 I=1,NCOEFF
        DO 95 K=1,PTS
          SUM = SUM + XT(I,K) * Y(K,J)
95      CONTINUE
      C2(I,J) = SUM
      SUM = 0.0
90    CONTINUE


C***Solving the linear equations (C1 is "XT" x "X", and C2 is "X" x "Y"):

      CALL SOLVE(NCOEFF,1,C1,NCOEFF,C2,NCOEFF,COEFFS)

      DO 110 I=1,NCOEFF
        q(I)=COEFFS(I,1)
110   CONTINUE

      END

C******************************************************************* *
C                                                                     *
C  LINEAR SYSTEMS SOLVER SUBROUTINE:                                  *
C                                                                     *
C  This routine performs a gaussian elimination with scaled and partial pivoting to  *
C  solve a linear system of equations. Inputs are the coefficient matrix, a(i,j) and  *
C  the rhs  vector, b(i). The dimensions of a and b are as defined in the calling  *
C  program. The routine replaces the lower triangular elements in the forward  *
C  elimination step with the scaling factors and returns the solution in the "x" vector.  *
C  The routine is set-up to compute multiple solutions given n right hand sides the b  *
C  and x vectors should be dimensioned to accomodate from 1 to nrhs i.e., dimension  *
```

```
C  x(idimb, nrhs) and dimension b(idimb,nrhs)                              *
C                                                                          *
C                    Developed by Doug Reind and modified by Øystein Ulleberg   *
C                                                                          *
C*********************************************************************** *

      SUBROUTINE SOLVE(n, nrhs, a, idima, b, idimb, x)

      integer n, p, i, j, k, l, idima, idimb, nrhs
      integer piv(4000), irow
      double precision a(idima, n), b(idima, nrhs)
      double precision x(idimb, nrhs), mult, sum, scalmax
      double precision scale(4000), maxratio, ratio


C***Set up pivot array and compute the scale factors:

      do 20 i=1, n
       piv(i) = i
       scalmax = 0.
       do 15 j=1, n
        scalmax = max(scalmax, abs(a(i,j)) )
 15     continue
       scale(i) = scalmax
       if (scale(i) .eq. 0.) then
         WRITE(*,*) '*******CONTROLLER WARNING*******'
         WRITE(*,*) 'NO SOLUTION EXISTS IN THE REGREESION'
       endif
 20    continue


C***Loop for forward elimination:

      do 105 l=1, n-1

       maxratio = 0.0

       do 80 p=l, n
        irow = piv(p)
        ratio = abs(a(irow,l)) / scale(irow)
        if (ratio.gt.maxratio) then
          maxratio = ratio
          k = p
        endif
 80     continue


C***Pivot row interchanges:
```

```
      irow   = piv(k)
      piv(k) = piv(l)
      piv(l) = irow


C***Elimination:

      do 100 i=l+1, n
       mult = a(piv(i),l) / a(irow,l)
        do 90 j = l+1, n
         a(piv(i),j) = a(piv(i),j) - mult * a(irow,j)
 90      continue
       a(piv(i),l) = mult
 100    continue          ! end of elimination
 105   continue           ! end of forward loop


C***b vector:

      do 110 k=1, nrhs
       do 110 l=1, n-1
        do 110 i=l+1, n
         b(piv(i),k) = b(piv(i),k) - a(piv(i),l)*b(piv(l),k)
 110   continue


C***Backward substitution:

C***Calculating first, the bottom x entry:

      do 200 k=1, nrhs
        x(n,k) = b(piv(n),k) / a(piv(n), n)
        sum = 0.

       do 150 i=n-1, 1, -1
        sum = b(piv(i),k)
         do 140 j=i+1, n
          sum = sum - a(piv(i),j) * x(j,k)
 140       continue
        x(i,k) = sum / a(piv(i),i)
 150    continue

 200   continue

      return
      end
```

APPENDIX C

PLOTS OF COEFFICIENTS

In this appendix, plots of coefficients are shown. Figures C.1 to C.4 demonstrate the stabilization of the coefficients used in the optimal control laws, where the coefficients were initially obtained using intuitive control schemes I and II. The time period shown, two weeks, is the same as for the period of comparison in Section 4.4 of Chapter 4. The main conclusion that can be drawn from the plots is that both the magnitude and signs of the coefficients are different for the two different schemes. Furthermore, the coefficients are also seen to stabilize as the simulation progresses.

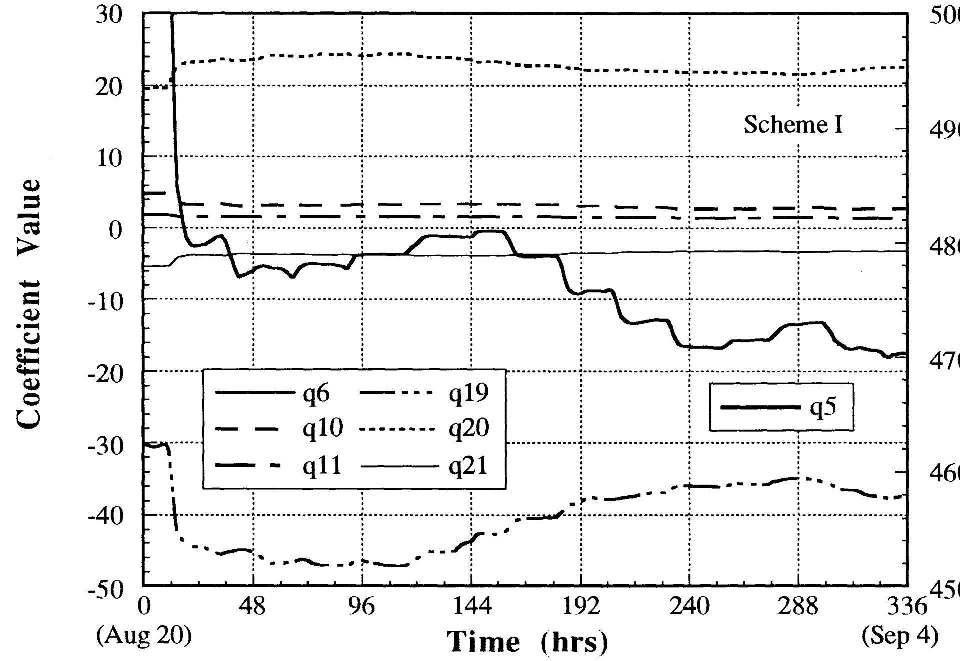


Figure C.1 First set of coefficients as a function of time, scheme I

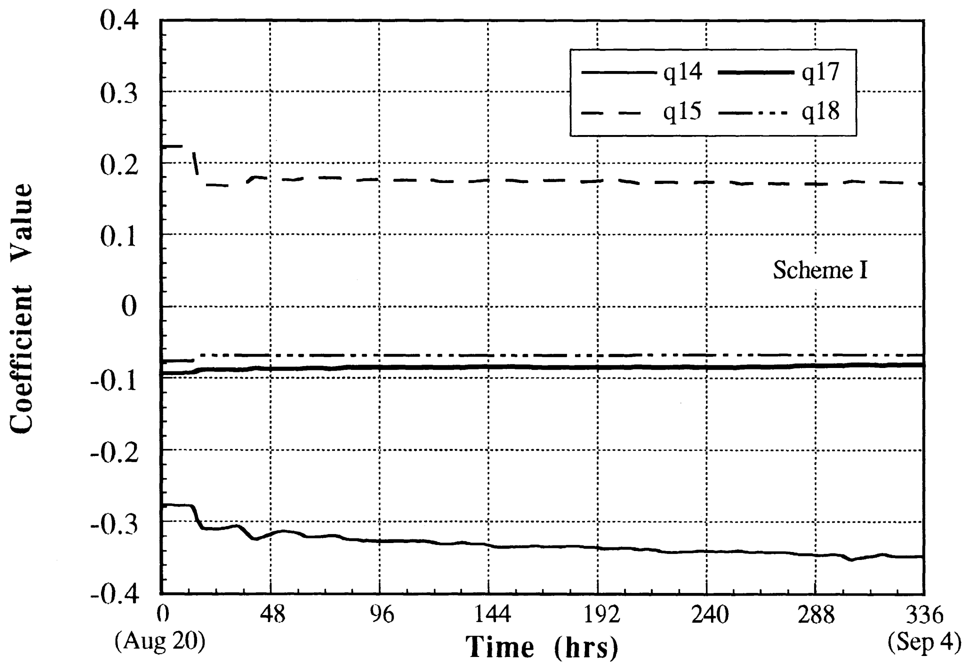


Figure C.2 Second set of coefficients as a function of time, scheme I

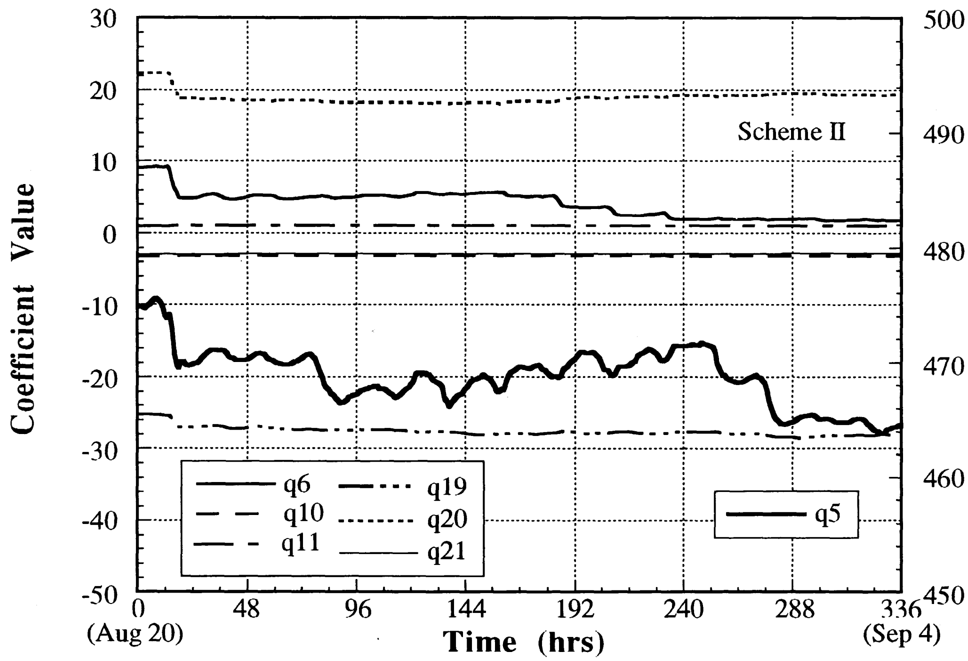


Figure C.3 First set of coefficients as a function of time, scheme II

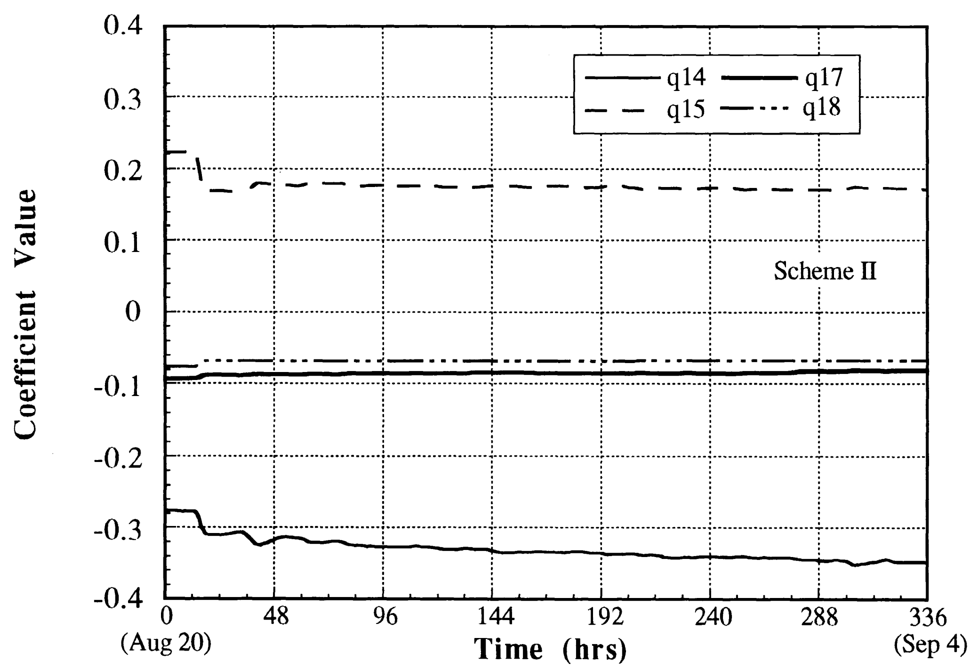


Figure C.4 Second set of coefficients as a function of time, scheme II