

*APPLICATION of*  
**NEAR - OPTIMAL CONTROL METHODOLOGIES**

*to a*

**HVAC SYSTEM MODEL**

by

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A thesis submitted in partial fulfillment of the  
requirements for the degree of

**MASTER OF SCIENCE**

(Mechanical Engineering)

at the

**UNIVERSITY OF WISCONSIN - MADISON**

1991

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## *ABSTRACT*

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The commercial building sector accounts for approximately 15% of the total U.S. primary energy consumption. Heating, Ventilating, and Air-Conditioning (HVAC) systems use about 40% of the energy input for a typical commercial office-type building. The increasing real cost of energy supplies has fueled development of more efficient methods of HVAC system control offering great potential for energy savings in existing and new buildings. New software and hardware packages marketed as Building Energy Management Systems (BEMS) are available from many suppliers in response to the consumer's demand to take control of their energy bills.

Continuing efforts in advanced HVAC control development include the application of a variety of optimization techniques. Optimal control is based on finding the relationships between the controlled variables of the subject system and system operating costs, then analyzing that relationship (cost function) to predict the control point to achieve minimum (or maximum) cost.

Generally, more accurate data on the subject system and more computation time are required to produce the highest level of control performance. More simplified optimization methods tend to sacrifice

some control performance in return for lower implementation costs and better adaptability to a variety of systems. The International Energy Agency (IEA), recognizing energy conservation potential through improved building energy management technology, sponsored an evaluation of new Building Energy Management (BEM) Techniques. The basic objectives of IEA - ANNEX 17 were to review currently available BEMS technology and propose and evaluate improved BEM methodologies to be shared with manufacturers of these products. A number of research organizations were requested to participate in different subtasks. The University of Wisconsin was one of the participants in Subtask A: Prospective Assessment of BEMS Potential, to demonstrate improved HVAC control methods. The IEA established specifications for the study and all participants were provided the same HVAC system model on which the new supervisory control schemes would be tested. This was intended to "standardize" and facilitate comparison of study results among the participants. This study is the product of work in association with IEA - ANNEX 17.

A simplified methodology for deriving the optimized control functions has been applied to a simple building air-conditioning system model simulation at the University of Wisconsin [Pape 1988]. A single quadratic cost function was calculated from simulation runs, using TRNSYS simulation software, from which the control functions were derived analytically.

This study examines the application of a similar "system-based"

optimization procedure to the more detailed HVAC system model provided by the IEA. The optimization results were evaluated for robustness in control of the complex HVAC system simulation and energy savings potential compared to the "reference" supervisory control case.

Refining the system-based optimization techniques in the simulation environment is a practical step before an effective control algorithm can be recommended for validation testing in actual buildings.

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## *ACKNOWLEDGEMENTS*

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I am most grateful to my advisor, Professor John W. Mitchell, for the support and encouragement he has offered me in the process of this work. I surely appreciate the patience and understanding shown by Professor W.A. Beckman and Professor Sandy Klein in making a place for me in the Solar Energy Lab as a "part-time" student. The backing of my work associates at the Madison Johnson Controls Branch, particularly Mark Duszynski and Daryld Karloff, has been a valuable resource for me.

I'll remember the spirited and inspired atmosphere of the Lab and the friendly time spent here. From Doug and Jeff, both kind and capable whenever I asked for help, to Osama and Adel who shared their thoughts and views of the world outside of Madison, I have received much.

Rose and a dog named Cedar were there to help see me through the rough parts. And finally, I thank my Mother, my Sister and remember my Father, for always supporting me in their own special way.

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## NOMENCLATURE

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### Symbols

BEMS	-building energy management system
HVAC	- heating , ventilating and air-conditioning
C	- constraint function
F	- cost function
f	- vector of control variables
GAINS	- building internal heat gains from people, lights, and equipment
HR	- air humidity ratio
IEA	- International Energy Agency
J	- instantaneous total system power
M	- vector of discrete control variables
Ma	- air mass flow rate
Mw	- water mass flow rate
MIN O.A.	- economizer in minimum outside air operating mode
100% O.A.	- economizer in 100% outside air operating mode
OPT	- supervisory controller optimization
P	- system component instantaneous power
Q	- heat transfer rate

**Symbol**

$Q_c$	-	system total cooling coil heat transfer rate
$Q_h$	-	system total heating coil heat transfer rate
$R^2$	-	coefficient of determination
$s$	-	sample standard deviation
$T_{solair}$	-	combined outside air dry bulb and solar insolation equivalent temperature
$T$	-	temperature
$T_{asup}$	-	main supply air temperature setpoint
$T_{chw}$	-	chilled water supply temperature setpoint
$t$	-	tabulated t-value
$u$	-	vector of uncontrolled variables
$W$	-	energy
$X$	-	cost function regression coefficient
$x$	-	system variable

**Additional Subscripts and Superscripts**

$a$	-	air
$asup$	-	supply air
$act$	-	actual
$boil$	-	boiler
$c$	-	cooling
$chill$	-	chiller
$chw$	-	chilled water
$cond$	-	chiller condenser
$db$	-	dry bulb

elec	-	electricity
evap	-	chiller evaporator
opt	-	near-optimal value
pred	-	predicted value
rh	-	reheat
tow	-	cooling tower
wb	-	wet bulb



## *CHAPTER 1*

---

### *INTRODUCTION*

Major factors affecting heating, ventilating and air conditioning (HVAC) system operating costs are the initial mechanical and control equipment design, installation and continuing maintenance and operating schedules. New HVAC control methods present an opportunity for cost effective energy efficiency improvements. Recognizing this, the International Energy Agency (IEA) sponsored a study of improved Building Energy Management (BEM) methods. The IEA provided exercise specifications and a reference HVAC system model to be used by all participants to test new control methods.

A system-based, near-optimal control method developed at the Solar Energy Lab, University of Wisconsin-Madison was applied to a simplified HVAC system model (Pape,[1989]). The same control method has been applied here to the more detailed office building HVAC model from the IEA study.

Section 1.1 reviews "conventional" control methods in general use today in commercial buildings. Popular techniques for improving control performance are introduced in Section 1.2 with an emphasis on optimizing-type control schemes. Results of recent studies on this subject

will also be reviewed. The objectives of this study are then outlined in Section 1.3.

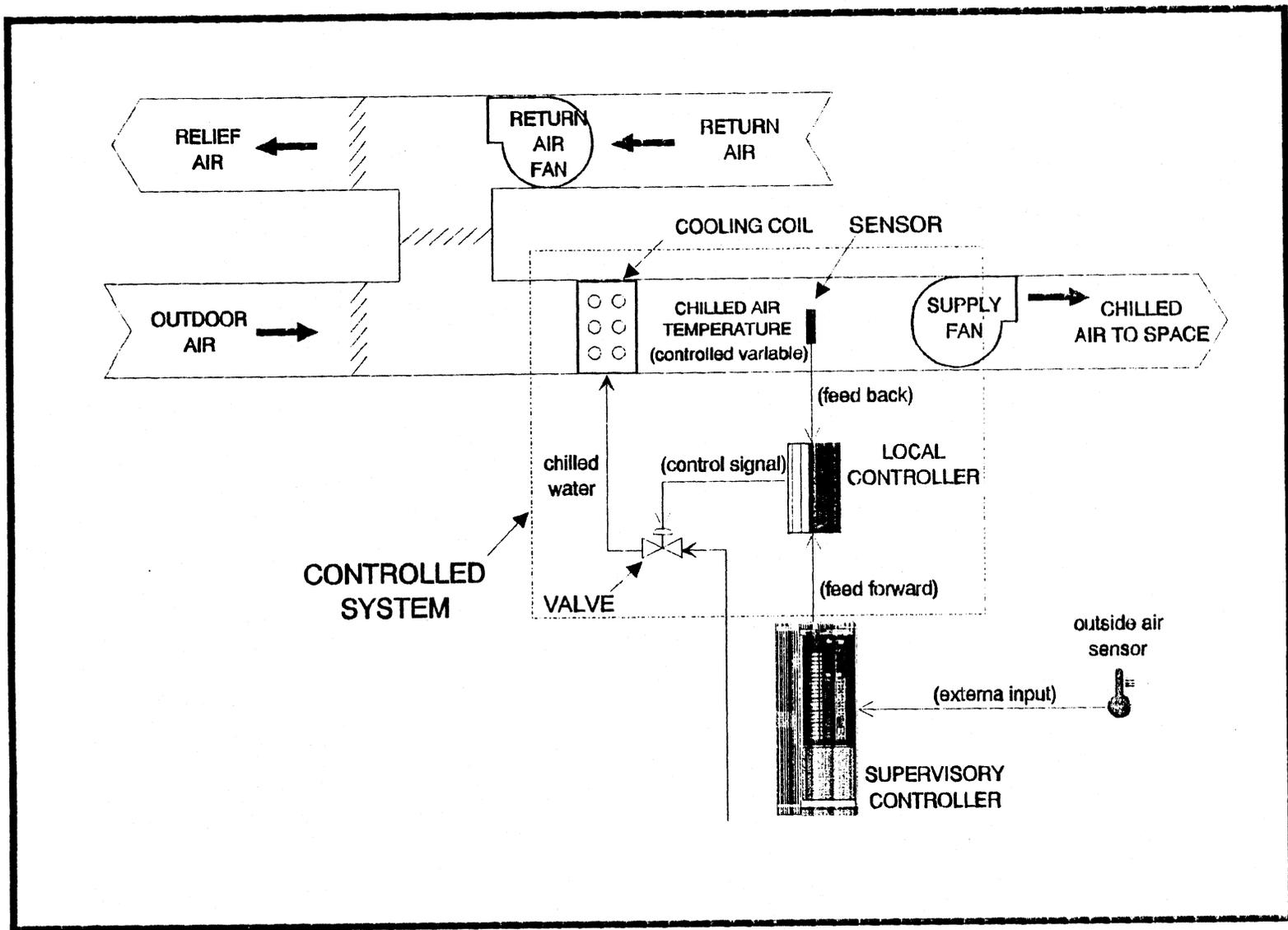
## 1.1 REVIEW of HVAC CONTROL

### 1.1.1 Principles of HVAC control

The coordinated operation of mechanical heating, cooling and ventilating equipment is necessary to maintain building interior space comfort conditions of temperature, humidity and air quality.

FIGURE 1.1 illustrates the typical components and terminology for a chilled air temperature control system. Automatic control of the chilled air temperature is accomplished by a *feedback* (or closed-loop) controller which measures the actual change in the *controlled variable* (chilled air temperature) and feeds back that information to the controller to generate a corrective control output signal. The control action continues until the controlled variable is brought to the *setpoint* value. No controller can maintain the controlled variable at the exact setpoint at all times. Some *error* (or offset) between the control setpoint and the actual value of the controlled variable (*control point*) is present in every control system.

In FIGURE 1.1 the *feedforward* (or open-loop) controller anticipates the effect of an external variable (outside air temperature) on the *controlled system*. A feedforward controller does not have a direct link between the



**FIGURE 1.1 - CHILLED AIR TEMPERATURE CONTROL SYSTEM**

value of the controlled variable and the controller. Feedforward control anticipates how an external variable will affect the system. The feedforward *control function* is the relationship between the chilled air temperature reset (output signal) and the changing outside air temperature (input signal) which is presumed to cause a change in building cooling load. In FIGURE 1.1, the feedforward controller output acts to change the control base of the feedback controller making this a feedback controller with feedforward compensation.

The chilled air temperature feedback controller is an example of a *local* HVAC control. A local control maintains the controlled variable at a setpoint and is usually located near the point of control. Major HVAC system components (chillers, boilers, air handlers, etc.) are often equipped with their own local controller which is then connected to the *supervisory* controller.

A supervisory controller receives sensor inputs from many points to monitor the operation of the HVAC system. This information can then be processed by the supervisory control function(s) to then output control signals to revise the setpoints of the local controllers. Digital computers are best suited for processing this information with the speed and accuracy needed to respond to the changing system operating conditions and most commercial supervisory controllers are computer based. Modern supervisory controllers come with different capabilities but most are programmable to use different control strategies.

The extensive monitoring and control flexibility of digital supervisory

controllers has led to the development of Building Energy Management Systems (BEMS) that can also take control of other building systems such as lighting and fire alarms. FIGURE 1.2 is a schematic of a modern BEM system with supervisory and local controllers. The potential energy cost savings offered by a well designed and operated BEMS has produced a market for this technology. The IEA has recognized this potential and encouraged the development of new BEM technology by sponsoring a review of new supervisory control strategies.

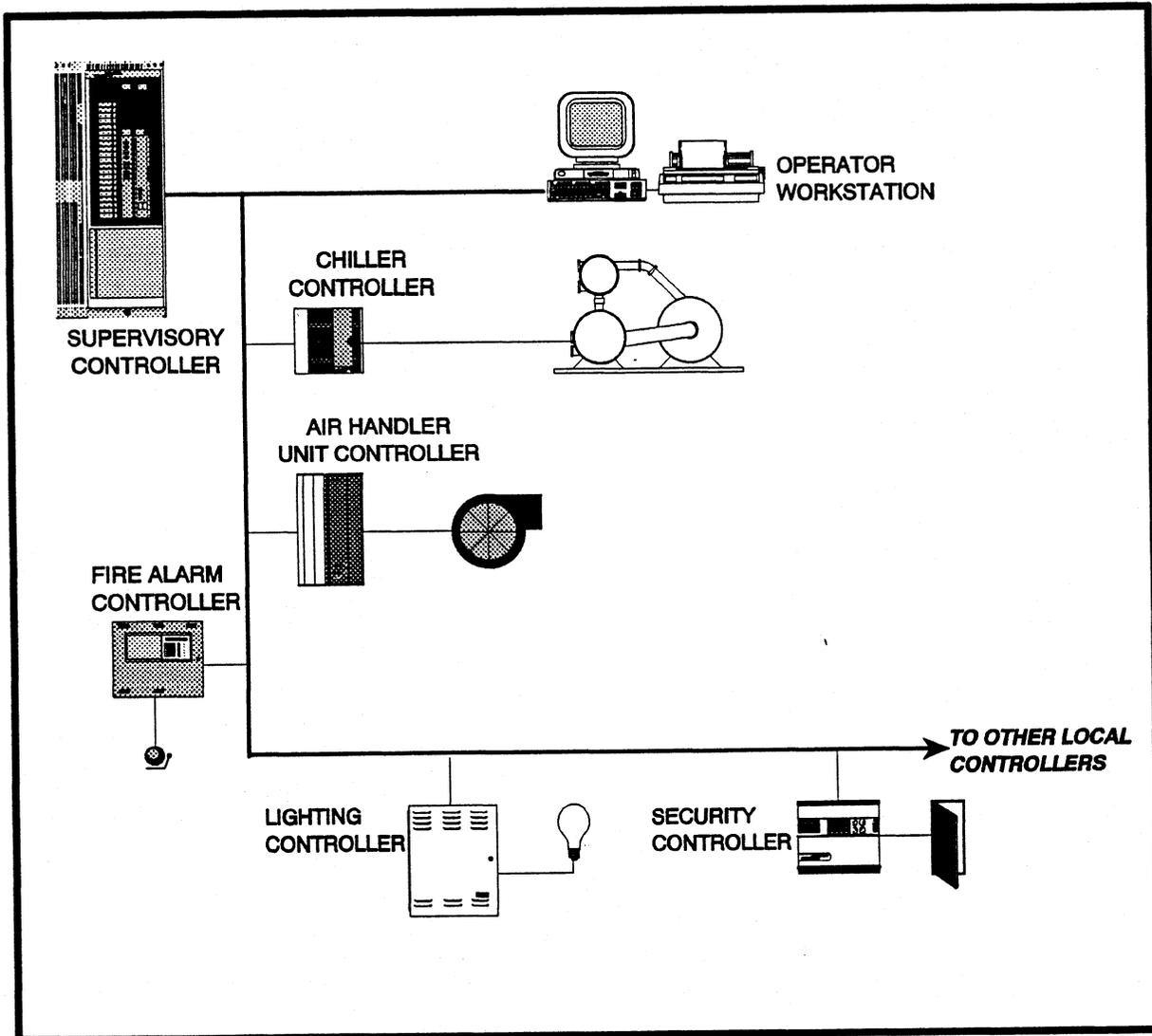
This study is an outcome of the IEA sponsored exercises and attempts to apply a particular control "optimizing" procedure to a sample HVAC system model with supervisory control.

## **1.2 REVIEW of OPTIMAL CONTROL**

### **1.2.1 Why optimal control ???**

Optimization is the process of finding the "optimal" solution to a problem. Human lives are made up of daily attempts to optimize decisions using the information that is available to make the best choices. The process of decision making has been developed into the mathematical science of optimization.

A mathematical optimization problem begins with the selection of the *subject system*. A set of independent variables that describe the state of



**FIGURE 1.2 - BUILDING ENERGY MANAGEMENT SYSTEM**

the system is then identified. There are often restrictions in the system that place *constraints* on the acceptable values of the variables. The objective (or desired outcome) of the optimization process is then translated into a *cost* (or object) *function* that relates the system variables to the objective. For example, the objective of a manufacturing production line optimization problem may be to maximize the output of finished products subject to limited raw material inputs (constraints). For HVAC systems, the objective may be to minimize the total power consumed by the system components while maintaining comfort conditions for the building occupants (constraints). The cost function is then a mathematical model of the selected cost of the system.

As stated by Gill (1981) "The solution of the optimization problem is the set of allowed values of the variables for which the cost function assumes an optimal value. In mathematical terms, optimization usually involves maximizing or minimizing the cost function." Expressed in mathematical form, the general optimization problem is to:

$$\begin{aligned} &\text{minimize } F(x) \\ &\text{subject to } C_i(x) = 0, i = 1, 2, \dots, m' \\ & \quad \quad \quad C_i(x) > 0, i = m'+1, \dots, m \end{aligned}$$

where  $F$  is the system cost function and the  $C_i$  are the set of constraint functions in terms of selected system variables ( $x$ ). The system cost needs to be minimized with respect to the system variables which are often subject to equality and inequality constraints. For example, an HVAC

system with multiple chillers would be subject to the equality constraint where the sum of the chiller outputs equal the system cooling load. The chilled water temperature limits required for proper operation of the chiller evaporator can be expressed as an inequality constraint. Many methods of solving optimization problems have been developed. The choice of a solution method most often depends on the particular properties of the cost and constraint functions. For example, a *multi-variable* cost function will require a solution method different than a cost function with one variable and a problem with no constraints will be approached differently than an optimization problem with nonlinear constraint functions.

### ***1.2.2 Optimization and HVAC control***

The principle of optimization has been applied to the control of HVAC systems. The objective of these optimization studies has often been to minimize the cost of operating the system while maintaining acceptable space temperature and/or humidity conditions. For this definition of the optimization problem, the cost could be the total power consumed by the system components as a function of selected independent system variables including control variables like chilled water and supply air set temperature and uncontrolled variables (forcing functions) like outside air temperature. The constraints on these variables might be set by the operating limits of the HVAC equipment and limits on space temperature and humidity that the occupants will tolerate.

This study introduces a simplified methodology for generating the set of near -optimal control functions for a specific chilled water air conditioning system.

### *1.2.3 Introduction to near-optimal control*

The optimal control of chilled water air conditioning systems was the subject of studies by Braun [1987, 1988] at the Solar Energy Lab, University of Wisconsin - Madison. A detailed optimization procedure was used to analyze cost functions developed for each component of a simulated air conditioning system from which important control and uncontrolled variable were identified. This "component-based" optimization routine solved the set of simultaneous cost and constraint functions using a nonlinear solution method to determine the optimal control.

To further simplify the optimizing process, a "system-based" control methodology was developed. This method is based on a single cost function which is derived empirically from the system being modeled. While the control calculated by this method is not exact, the near-optimal results compared well with the more detailed component-based solution. The simple quadratic form of the near-optimal control function was suggested for use in on-line control of air conditioning systems. The quadratic function represents the total system instantaneous power consumption ( $J$ ) in terms of the control and uncontrolled variables. The following formula may then be used to represent the total system power:

$$J(\mathbf{u}, \mathbf{f}, \mathbf{M}) = \mathbf{u}^T \hat{\mathbf{A}} \mathbf{u} + \hat{\mathbf{b}}^T \mathbf{u} + \mathbf{f}^T \hat{\mathbf{C}} \mathbf{f} + \mathbf{f}^T \hat{\mathbf{E}} \mathbf{u} + \hat{\mathbf{g}} \quad \{\text{Eq. 1.1}\}$$

where,

$\mathbf{u}$  = vector of uncontrolled variables

$\mathbf{f}$  = vector of control variables

$\mathbf{M}$  = vector of discrete control variables

$\hat{\mathbf{A}}, \hat{\mathbf{C}}, \hat{\mathbf{E}}$  = coefficient matrices

$\hat{\mathbf{b}}, \hat{\mathbf{d}}$  = coefficient vectors

and

$\hat{\mathbf{g}}$  is a scalar

The discrete control variables ( $\mathbf{M}$ ) are the noncontinuous system variables such as the number of chillers operating to meet the given system cooling load. The coefficients are empirically determined from system operating data using linear regression techniques. Once the coefficients are known, taking the derivatives of the power formula with respect to the control variables yields the control functions.

A study by Pape [1989] applied the near-optimal control methodology to a simple air-conditioning system simulation. A similar procedure has been applied here to a more complex HVAC system model simulation.

A detailed description of the "Reference" HVAC system model is provided

in Chapter 2 followed by a step-by-step presentation of the near-optimal control methodology and results in Chapter 3. A summary of the conclusions from this study will be offered in Chapter 4.

### *1.3 RESEARCH OBJECTIVES*

The BEMS exercises proposed by the IEA offered an opportunity to test the near-optimal control methodology on a detailed HVAC system model that was intended to be a more realistic simulation of actual buildings. The primary objectives of this study were:

1. To apply the system-based near-optimal control methodology to the IEA supplied HVAC system model
2. To evaluate the performance of the "optimized" control compared to the conventional HVAC system control

## CHAPTER 2

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### *REFERENCE HVAC SYSTEM*

A sample numerical model of an office building heating, ventilating and air-conditioning system with "conventional" supervisory controller will be introduced in Section 2.1. Procedures for performing a simulation of the system model are outlined using a simulation specification provided by the International Energy Agency (IEA) in Section 2.2 followed by a review of initial simulation results in Section 2.3. Revisions to the original system model are identified and a set of revised simulation results are documented in Section 2.4 to be used as the reference for comparison to a new control method introduced in CHAPTER 3.

#### *2.1 SYSTEM DESCRIPTION*

In 1979, the IEA had sponsored a study of the performance of new Building Energy Management (BEM) methods. In order to compare study results from a number of separate research participants, one HVAC system model was chosen as the reference case for all the participants to use. The system model is a numerical description of an existing commercial office (Collin Building) in Scotland and consists of 19 different FORTRAN code subroutines representing the system components (i.e., chiller, multi-zone building, supervisory controller, etc.). The complexity

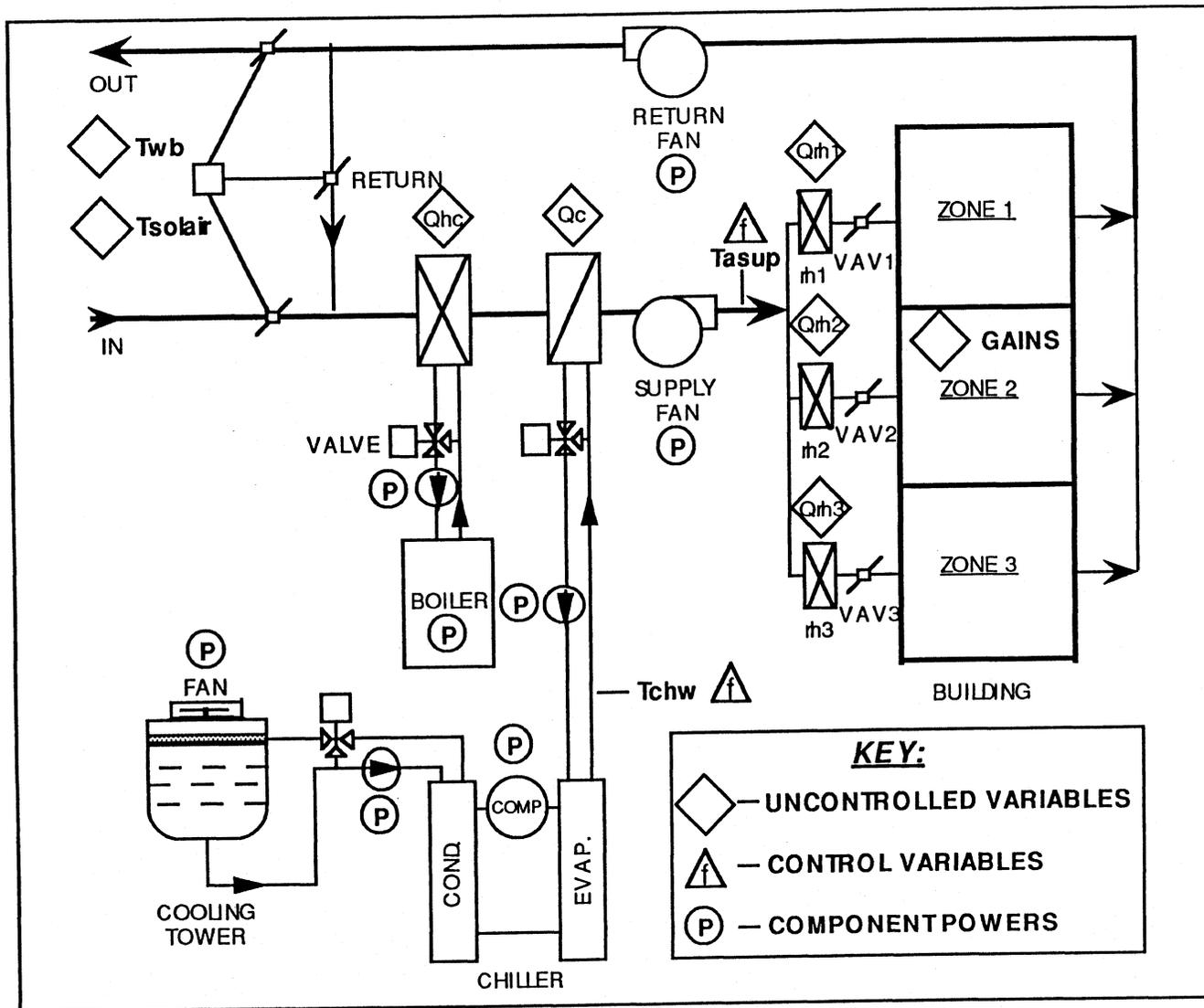
system was considered sufficient to provide a realistic environment to test new control methods with some expectation of having the results apply to real building situations.

### *2.1.1 System design*

A schematic of the HVAC system design is given in FIGURE 2.1. The system is a multi-zone, variable-air-volume design with zone hot water reheat and enthalpy economizer. The major mechanical equipment includes a single electric chiller with 370 KW design cooling capacity and one (1) hot water boiler with 351 KW input rating. The single VAV air handler has a design airflow capacity of 22.3 kg/sec.

### *2.1.2 System control description*

The control system for the HVAC model consists of a single supervisory controller component linked to the other system components. The supervisory controller reads input variables for temperature, air relative humidities and air pressures in the system. A Proportional-Integral-Derivative (PID) control algorithm calculates the controller output variables based on the input and setpoint values. A schematic of the information flow for the supervisory controller appears in FIGURE 2.2. The FORTRAN code for the supervisory controller is shown in Appendix B (No. 1).



**FIGURE 2.1: COLLIN BUILDING HVAC SYSTEM SCHEMATIC**

The controller logic executes the following control functions:

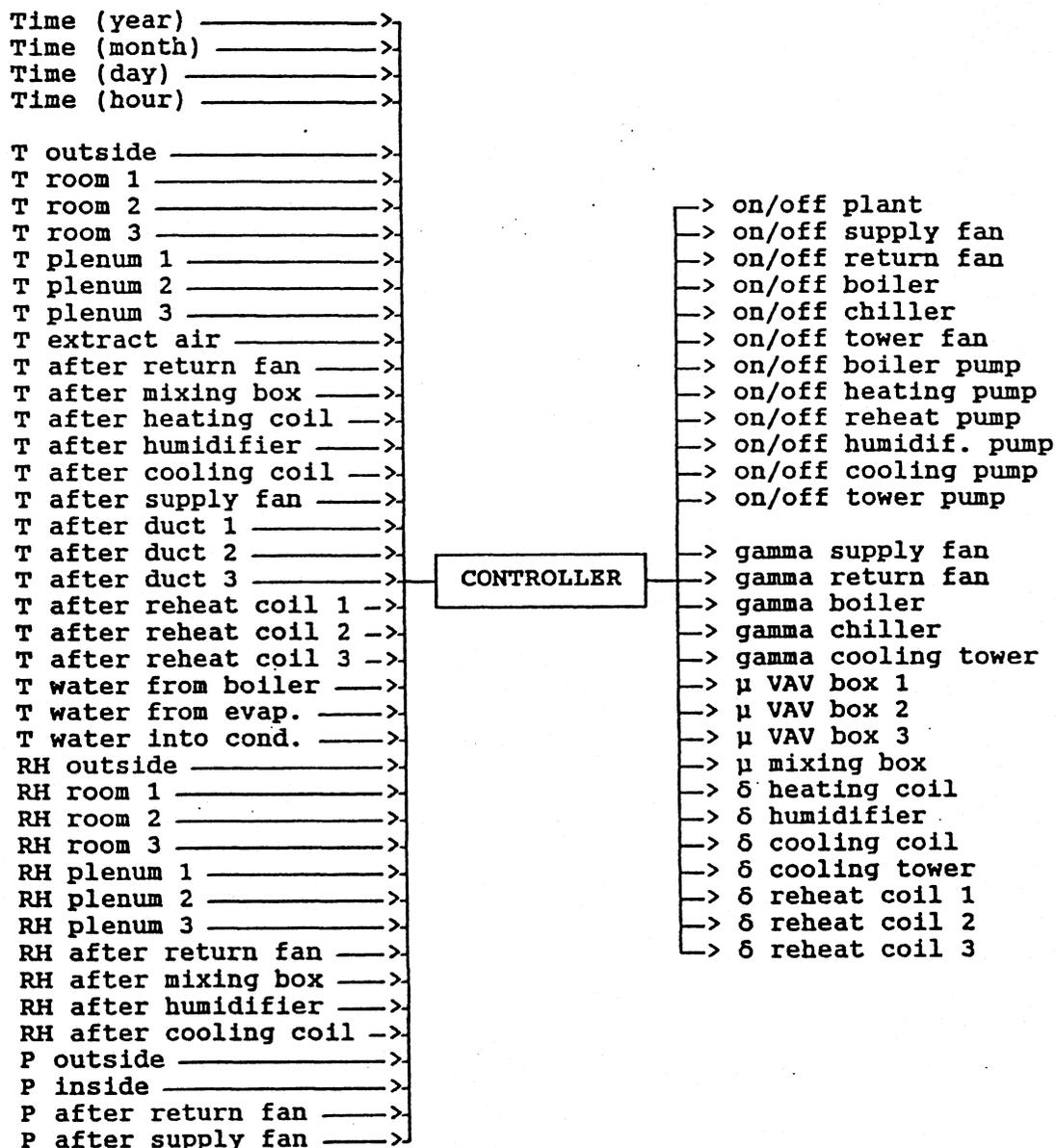
1. Seasonal switch over for winter, spring and summer operating modes.
2. Daily occupancy schedule on/off control of the heating/cooling plant.
3. Calculation of plant operating modes (heating, economizer free cooling, or mechanical cooling).
4. PID calculations for control of:
  - a) zone air temperature and humidity
  - b) main supply air temperature
  - c) chiller condenser supply water temperature
  - d) VAV duct static pressure

Most of the key HVAC system control variables are set by the controller to fixed values (setpoints) that can be reset from one operating season to the next. These control variables and their setpoint values for each season are given in TABLE 2.1.

**TABLE 2.1 - HVAC System Seasonal Control Variable Setpoints**

<b><u>VARIABLE DESCRIPTION</u></b>	<b><u>SETPOINT</u></b>
Zone air temperature, C	(Winter - 21, Spring - 23, Summer - 25)
Zone air relative humidity, %	50
Chilled water temperature, C	6
Condenser water temperature, C	21
Boiler hot water temperature, C	80
Main supply air temperature, C:	
	(heating mode) 26
	(cooling mode) 12

FIGURE 2.2  
SCHEME OF THE SUPERVISOR CONTROLLER



Acknowledgement

IEA ANNEX 17, Specification  
 for Exercise 2, Vincenzo  
 Corrado Polytechnic, Torino  
 1989

T = temperature  
 RH = air relative humidity  
 P = air pressure  
 gamma = control function  
 μ = control function to a damper  
 δ = control function to a three-way valve

There is no dehumidification control in the summer cooling mode, i.e., the zone relative humidities are allowed to float above 50 %.

## 2.2 SYSTEM SIMULATION

All IEA project participants were encouraged to use the same software to run the computer simulation of the HVAC system to facilitate comparison of results. The Transient Simulation Program TRNSYS (Klein, et.al, [1990]), developed at the University of Wisconsin - Madison, was selected as the simulation platform for this study.

### 2.2.1 Introduction to TRNSYS

Simulation of physical systems on computers has many benefits including the ease of changing the model parameters to run a different system test. Simulations can be an effective alternative when circumstances make it difficult or costly to conduct the same tests on real systems. The ability of the simulation program to accurately predict the real system behavior generally becomes more difficult as the system becomes more complex.

TRNSYS is a modular simulation program that was developed to model the operation of multi-component thermal systems over time. The individual component *TYPES* (chiller, controller, building, etc.) are individual FORTRAN subroutines linked together by input and output variable streams driven over time by forcing functions such as weather

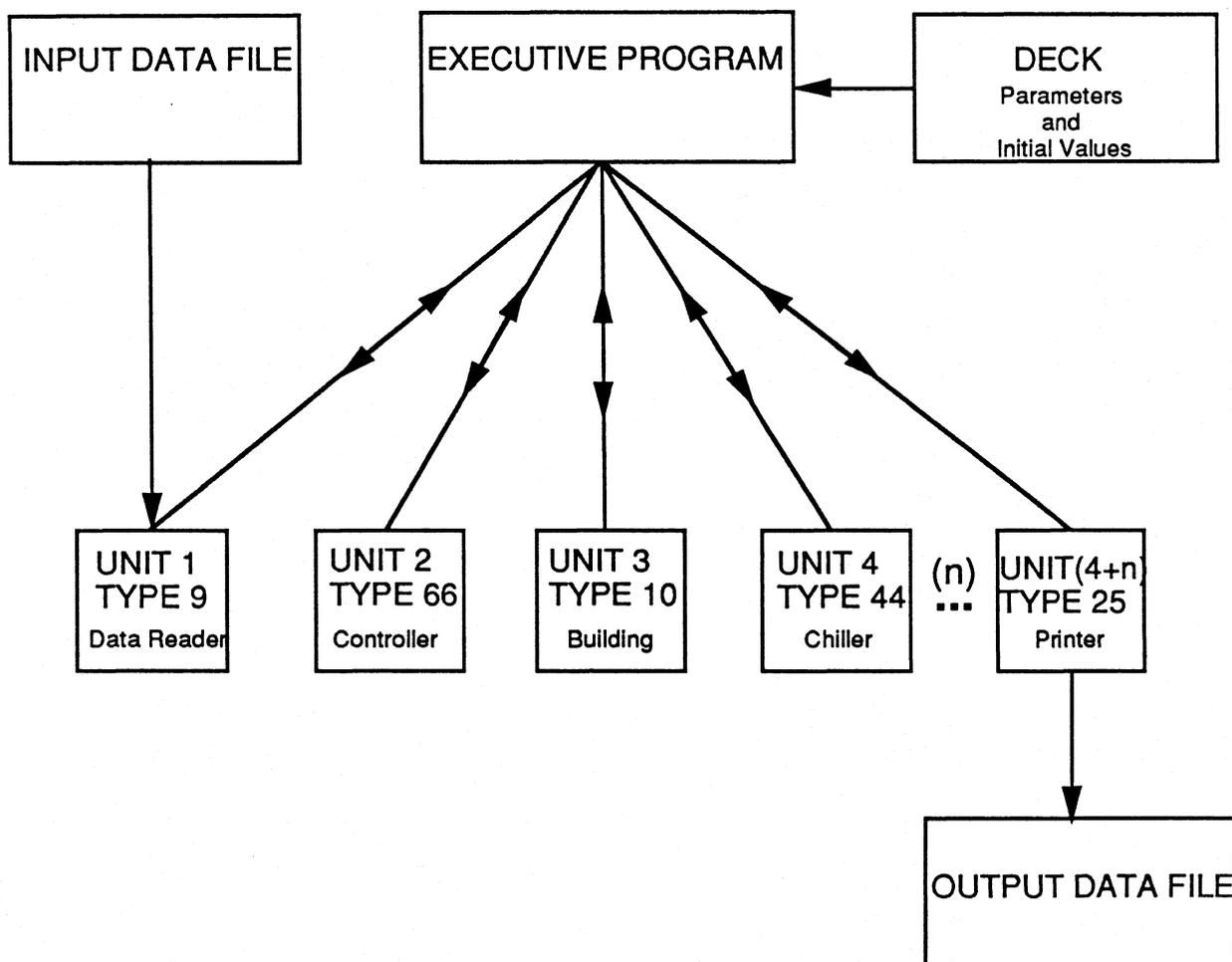
data from a given geographical location. The basic structure and component parts of a TRNSYS simulation run are illustrated in FIGURE 2.3. The system component *UNITS* are called by the TRNSYS *DECK* (main program) which contains all other necessary specifications for the simulation. There can be multiple Units of a given component Type. For example, in the case of the HVAC system in this study, the main heating and cooling coils Units and the three zone reheat coils Units all use the same heat exchange coil Type (subroutine). Only the parameter values differ between these coil Units. The TRNSYS deck for the HVAC System is provided in Appendix C (No. 1). Some standardized TRNSYS component Types, like the Weather Data Reader (Type 9) and Printer Output Device (Type 25), are used in the system, but the majority of the system Types were developed by the IEA and associates.

Although the HVAC System model attempts to duplicate the complex interactions of a real system, TRNSYS component models assume steady-state operation and do not consider dynamic effects over time. Some IEA project participants chose to perform the simulation with another popular simulation program HVACSIM.

### **2.3 PRELIMINARY SIMULATION RESULTS**

The initial simulation of the HVAC system was run to establish baseline results to compare with later simulations using modified controllers. The IEA provided the specification defining all assumptions, procedures, and

FIGURE 2.3

**TRNSYS PROGRAM STRUCTURE SCHEMATIC**

parameters for running the initial reference simulation. The IEA published a number of revisions to the original specification issuing changes to many of the system component Types and the Deck. To avoid further delays caused by these revisions, the author selected one version of the specification (revised 07/90) to proceed with in this study. A copy of the specification for the Reference Exercise No. 2RR and New Control Strategy Exercise No. 3 is given in Appendix A (No. 1).

Since this study concentrates on new control procedures developed for chilled water cooling system operation, only summer cooling simulation results will be considered here. The simulation was run over two weeks of summer weather data from the actual location of the Collin Office Building in Scotland. The outside air temperatures ranged from a low of 9.5 C to a high of 30.7 C. The simulation timestep was specified at six minutes and relative tolerance for convergence was 0.005. Simulations were run on the MicroVax minicomputer using TRNSYS Version 13.1 at the Solar Energy Laboratory, University of Wisconsin - Madison.

### *2.3.1 Operational results*

The simulation output values for system temperatures, humidities, mass flows and component powers were saved to data files for later analysis. The power readings were integrated over time to calculate component energy consumption figures.

A sample of the initial simulation output of system component powers for the final simulation day are plotted in FIGURE 2.4. The chiller compressor power ( $P_{chill,init}$ ) reaches a maximum value (TIME = 345 hours) which is the chiller design compressor rating, indicating the chiller capacity is not adequate to meet the system cooling load at this point. Further observations of critical system temperatures in FIGURE 2.5 shows the undersized chiller allows the chilled water temperature ( $T_{chw}$ ) to exceeds the 6 C setpoint. Main supply air temperature ( $T_{asup,init}$ ) and zone 2 air temperatures ( $T_{z2}$ ) also drifted above their setpoints of 12 C and 25 C, respectively. Air temperature in sample Zone 2 exceeded the 25 C setpoint by as much as 2.7 C. In summary, the system was operating out of control for much of the second week of the simulation.

### 2.3.2 *Performance results*

The primary criteria for evaluating the performance of new control methods would be the energy consumed by the HVAC system model, to maintain the specified zone space conditions.

The daily energy consumed by the system is broken down by component groups in TABLE 2.2. The total of all energy consumed by the System over the two week simulation was 42,453 MJ. Chiller compressor energy ( $W_{chill}$ ) was the major energy consumer (41%) followed by fan energy (37%). The boiler and pump energy portions are 16% and 6%. A closer look at the energy consumption trends shows fan and chiller energies reached their highest values toward the last days of the simulation as

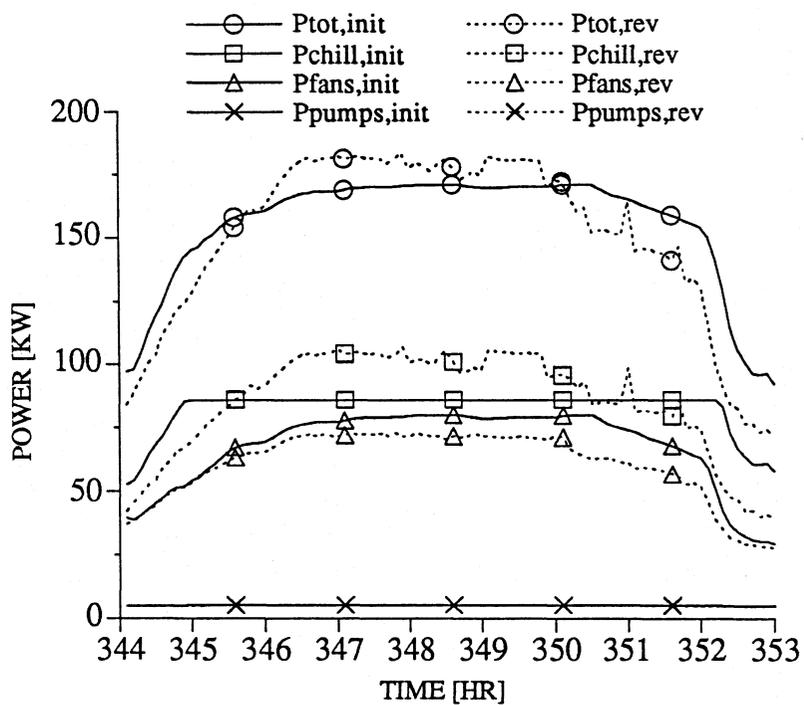


FIGURE 2.4: Initial and Revised System Powers (final day)

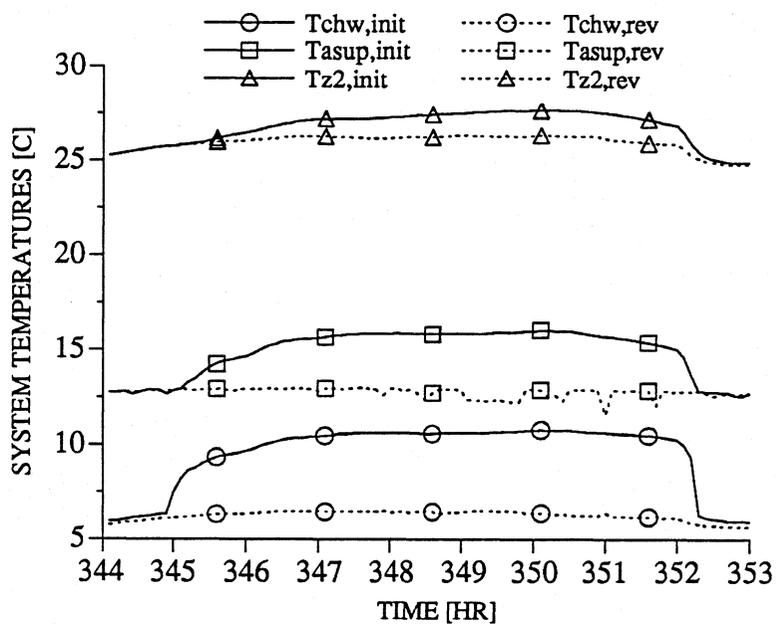


FIGURE 2.5: Initial and Revised System Temperatures (final day)

TABLE 2.2

INITIAL and REVISED HVAC SYSTEM COMPONENT ENERGY CONSUMPTION DATA

Time(HR)	<i>Wfans(MJ)</i>		<i>Wpumps(MJ)</i>		<i>Wchill(MJ)</i>	
	Initial	Revised	Initial	Revised	Initial	Revised
24.00	406.60	407.60	189.70	190.10	262.30	239.40
48.00	895.10	879.70	159.80	159.30	656.20	579.70
72.00	897.60	896.70	167.80	167.90	681.30	564.30
96.00	898.10	894.60	169.90	170.10	745.60	641.90
120.00	597.20	593.00	169.70	169.60	454.20	410.00
144.00	1006.00	1006.00	165.80	165.80	860.20	711.30
168.00	804.60	802.80	169.50	169.50	787.60	653.50
192.00	754.30	756.60	167.40	167.40	619.70	536.70
216.00	952.60	946.60	163.90	163.50	741.20	628.40
240.00	513.50	513.60	181.50	181.60	479.90	432.40
264.00	818.10	822.60	170.10	170.60	1094.00	910.20
288.00	1573.00	1558.00	165.80	164.80	2377.00	2031.00
312.00	1656.00	1589.00	167.70	166.10	2270.00	2001.00
336.00	1851.00	1766.00	167.20	164.60	2502.00	2165.00
360.00	2183.00	1961.00	168.40	166.20	2663.00	2754.00
TOTALS	15806.70	15393.80	2544.20	2537.10	17194.20	15258.80
CHANGE FROM INIT., %		-2.61		-0.28		-11.26

Time(HR)	<i>Welect(MJ)</i>		<i>Wboil(MJ)</i>		<i>Wtotal(MJ)</i>	
	Initial	Revised	Initial	Revised	Initial	Revised
24.00	858.50	837.00	2049.00	2059.00	2049.00	2059.00
48.00	1711.00	1619.00	176.40	176.80	176.40	176.80
72.00	1747.00	1629.00	607.10	608.40	607.10	608.40
96.00	1814.00	1707.00	583.30	590.50	583.30	590.50
120.00	1221.00	1173.00	645.90	648.80	645.90	648.80
144.00	2032.00	1883.00	253.30	252.30	253.30	252.30
168.00	1762.00	1626.00	549.50	543.40	549.50	543.40
192.00	1541.00	1461.00	518.80	517.50	518.80	517.50
216.00	1858.00	1739.00	171.70	171.30	171.70	171.30
240.00	1175.00	1128.00	896.60	892.20	896.60	892.20
264.00	2082.00	1903.00	337.20	346.10	337.20	346.10
288.00	4116.00	3754.00	39.65	40.54	39.65	40.54
312.00	4093.00	3757.00	79.53	79.60	79.53	79.60
336.00	4520.00	4096.00	0.00	0.00	0.00	0.00
360.00	5015.00	4881.00	0.00	0.00	0.00	0.00
TOTALS	35545.50	33193.00	6907.98	6926.44	42453.48	40119.44
CHANGE FROM INIT., %		-6.62		0.27		-5.50

warmer weather produced higher cooling loads. Cooling loads were greater than the chiller compressor capacity for most of the final four days, producing excessive fan consumption with the VAV system operating at maximum air flow rate.

Boiler energy was very high at the start of the simulation when the building pickup heating load was greatest. Daily boiler energy gradually decreased as the weather warms over the two weeks. Daily pump energy remained relatively constant throughout the simulation.

### *2.3.3 Revisions to HVAC system model*

Results from the initial system simulation indicated the supervisory controller could not control vital system setpoints with the undersized chiller. Some means of bringing the system back into control without changing the basic component designs was necessary before new control methods could be evaluated.

The author implemented a simple adjustment to the chiller operating parameters to increase the cooling capacity without changing the chiller design. The chiller model has a built in feature that allows the user to reset the design cooling capacity rating and have the chiller program iteratively calculate the "floating" compressor power. The chiller cooling capacity was increased from the original 370 KW to 450 KW. The new capacity was selected to meet the maximum anticipated cooling load. The

chiller (Unit 44) parameter revisions are noted in the TRNSYS deck, Appendix C (No. 1). The simulation was repeated with the chiller adjustments.

## **2.4 REVISED SIMULATION RESULTS**

The operational results from the revised simulation run (with re-sized chiller) are compared with the initial results in FIGURE 2.4 where chiller compressor power ( $P_{chill,rev}$ ) is seen to exceed the initial compressor power profile ( $P_{chill,init}$ ). In FIGURE 2.5, chilled water temperature ( $T_{chw,rev}$ ) is now under control with no unusual drift from the 6 C setpoint. Zone 2 air temperature ( $T_{z2,rev}$ ) still exceeds the setpoint by a maximum 1.3 C , a substantial reduction from the original 2.7 C deviation seen in the initial simulation.

The adjustments to the chiller significantly improved the control of the HVAC system. The remaining drift in supply air and zone air temperatures was due to insufficient cooling coil capacity. A redesign of the cooling coil component to restore full control of the system was not pursued in the interest of maintaining comparability of results with other IEA project participants.

### **2.4.1 Operational results**

Figures 2.6 and 2.7 are provided to help illustrate system operation for the

a simulation day with lower cooling load and higher zone reheat loads (day 4). The initial pickup reheat load causes boiler power ( $P_{\text{boil}}$ ) to peak when the building is first occupied and the plant turned on at 8 AM (TIME = 80 hours). The chiller turns on when any of the (3) zones temperatures exceeds 22 C. The reheat coil operates whenever the zone temperature falls below 24 C. Internal heat gains from people, lights and office equipment requires cooling to maintain zone temperatures over the mid-day period. People leave the building and other internal gains are shutoff at 4 PM (TIME = 88 hours) after which zone temperatures tend to drop and more reheat is required to hold temperatures above the 22 C lower cooling limit temperature. System temperature profiles for the fourth day are show in FIGURE 2.7, along with a plot of reheat coil power, to better illustrate the reheat operating characteristics. Chilled water, supply air and zone space temperatures are all controlled at or near their setpoints.

#### **2.4.2 Performance results**

The revised system energy consumption, after the chiller adjustments, are compared to the initial simulation results in TABLE 2.2. Total energy consumed for the revised simulation was 40,0119 MJ which is about 5% lower than the before the chiller adjustments. A general reduction in chiller energy ( $W_{\text{chill}}$ ) was responsible for most of the change. Fan consumption was somewhat lower (-2.6%) due to the lower supply air temperature maintained by the resized chiller. Other component energies for the pumps and boiler did not change significantly.

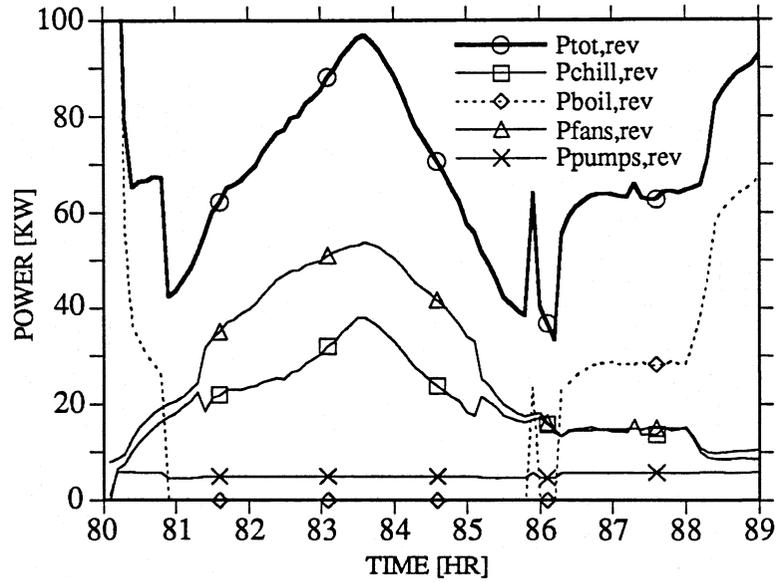


FIGURE 2.6: Revised Simulation Powers (day 4)

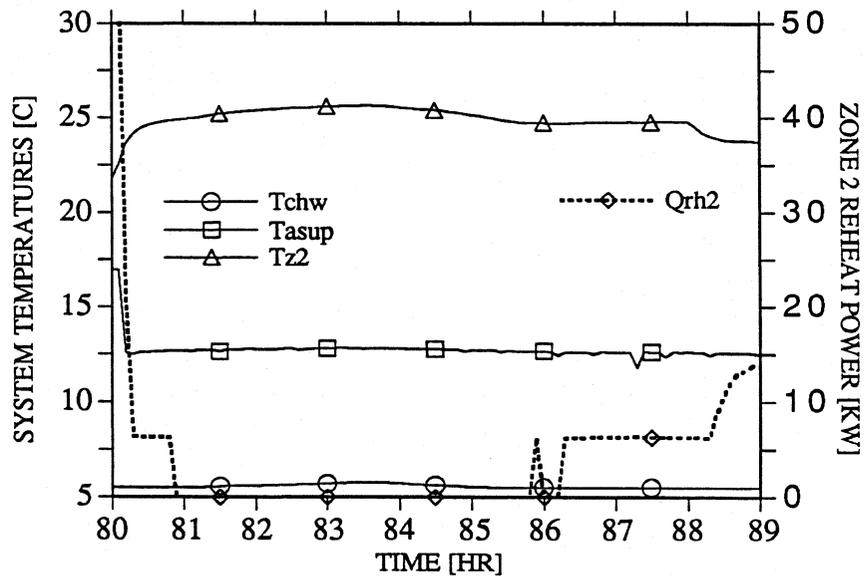


FIGURE 2.7: Revised System Temperatures (day 4)

### *2.4.3 Controller performance potential*

The setpoints of the reference controller were varied and the resulting simulation energy consumption was noted to establish some figure for the potential energy reduction available with optimized control. The best potential for energy savings appeared to be during low cooling load periods when the reheat system is operating. Simply resetting Tchw and Tasup to their maximum constraint values (8 C and 13 C) for the first half of the simulation reduced total system energy consumption by 4.5 % while still maintaining zone space temperatures. An effective control optimization procedure should then be expected to achieve and exceed this 4.5 % energy savings performance.

## **2.5 SUMMARY**

An HVAC System model was introduced for the purpose of testing new supervisory control methods. The TRNSYS simulation program was described and simulations of the HVAC System were run with the Reference supervisory control.

Results from the initial TRNSYS simulation identified a chiller undersizing problem that was partially corrected by resetting the chiller model operating parameters.

The operational and energy performance of the Revised HVAC system

simulation (with chiller adjustments) were documented and will be used as the "Reference" case for comparison with results in CHAPTER 3.

## CHAPTER 3

### *NEAR - OPTIMAL CONTROL of HVAC SYSTEM*

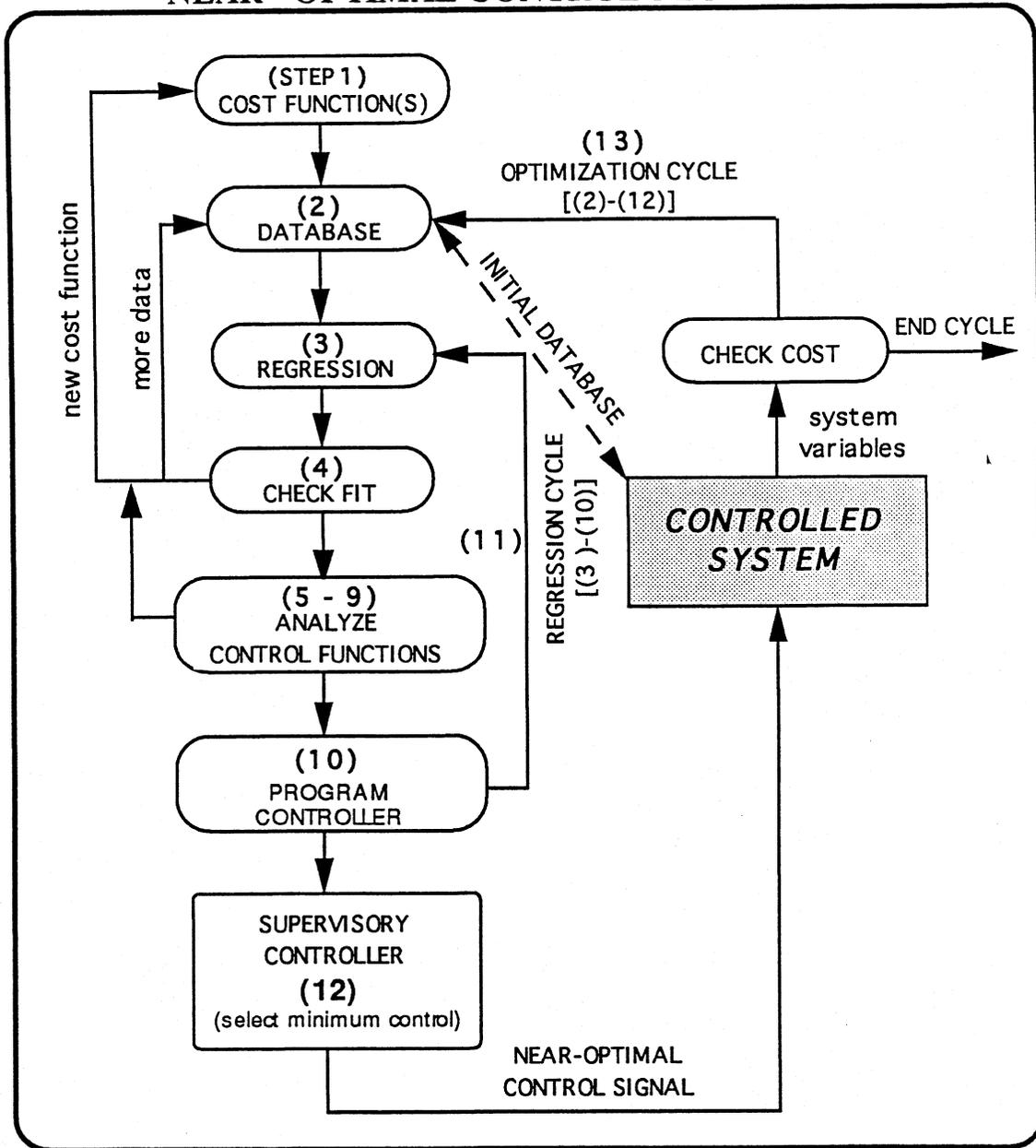
The IEA has provided guidelines for evaluating new Building Energy Management control methods on a reference HVAC system simulation model. The specifications allowed revisions to be made to most of the reference supervisory control functions with the exception that zone space temperatures would not be changed.

A system-based optimization procedure for deriving near-optimal control functions will be evaluated in application to the reference HVAC system introduced in CHAPTER 2. Section 3.1 will present the step-by-step optimizing procedure and will be followed by a detailed description of the first optimization run. Section 3.2 will present an analysis of the first optimization to be followed by discussion of results from a subsequent revised optimization run in Section 3.3.

#### *3.1 NEAR - OPTIMAL CONTROL METHODOLOGY*

Having introduced the concept of optimization as applied to HVAC system control in CHAPTER 1, the particular optimization procedure used in this study will be presented. The step-by-step optimization methodology that follows is illustrated in the flow-chart of FIGURE 3.1.

**FIGURE 3.1**  
**NEAR - OPTIMAL CONTROL FLOWCHART**



**STEP:**

- (1) Define the cost function for each discrete system control mode, assigning (1) cost variable, control variable(s), state variable(s) and constraints for each cost function.
- (2) Generate the data base for fitting the cost function(s) by simulating the system with control variables set over their expected operating range.
- (3) Perform multivariate least-squares regression to fit the cost function variable coefficients.
- (4) Check for cost function goodness of fit. If fit is not acceptable return to STEP (1) to redefine cost function.
- (5) Calculate the partial derivatives of the cost function with respect to control variable(s). Set the derivatives equal to zero and solve for control variable relations in terms of the forcing functions.
- (6) Calculate the second derivatives of the cost function with respect to control variable(s) and check for positive (local minima) or negative value (local maxima) for each control variable.

- (7) If all relations show local minima, solve all equations from STEP (5) simultaneously to obtain the set of control functions in terms of forcing functions.
- (8) If the controlled variable(s) show local maxima, set that variable to the constraint value which calculates the lowest cost when input into the cost function.
- (9) Check the control functions for agreement with the cost function predictions. If control function predictions of minimum cost point do not agree with the cost function, repeat STEPS (2) through (8). Recheck correlation. Return to STEP (1) and redefine the cost function if necessary.
- (10) Program the set of control functions into the Reference supervisory control component code.
- (11) Repeat the *regression cycle*, STEP (3) through (10), for each discrete *System control* and *operating* mode to complete the programming for the optimized supervisory controller.
- (12) Run the simulation with the optimized supervisory controller from STEP (11) and output cost and cost function variable values for each timestep as the database for the next *optimization cycle*.
- (13) Repeat the *optimization cycle*, Steps (2) through (12), until output cost values change less than the specified tolerance between

successive optimization cycles.

The assumptions and calculations for the first optimization run on the reference HVAC system will be presented to demonstrate the procedure.

### *3.1.1 Defining cost function (STEP 1)*

Braun (1988), in evaluating a system-based, near-optimal control method, has generally recommended the cost function for the total power consumption of a chilled water cooling system ( $P_{total}$ ) include the following set of independent control and uncontrolled variables:

#### CONTROL VARIABLES:

1. main supply air set temperature ( $T_{asup}$ )
2. chilled water supply set temperature ( $T_{chw}$ )
3. cooling tower air mass flow rate ( $M_{atow}$ )
4. condenser water mass flow rate ( $M_{wcond}$ )

#### UNCONTROLLED VARIABLES (forcing functions):

1. chilled water load at cooling coil ( $Q_c$ )
2. outside ambient wet-bulb temperature ( $T_{wb}$ )
3. sensible heat ratio (SHR)

and,

$$\begin{aligned}
 P_{\text{total}} = & \text{Fan Powers (supply + return + cooling tower)} \\
 & + \text{Pump Powers (condenser + evaporator + boiler)} \\
 & + \text{Chiller Compressor Power + Boiler Power}
 \end{aligned}$$

yielding the cost function:

$$P_{\text{total}} = f(T_{\text{asup}}, T_{\text{chw}}, M_{\text{atow}}, M_{\text{wcond}}, Q_{\text{c}}, T_{\text{wb}}, \text{SHR}) \quad \{\text{Eq. 3.1}\}$$

Using all the cost function variables in Equation 3.1 would have resulted in a very large number of coefficients (36) to be determined in the optimization analysis. To simplify the first optimization attempt the author used limited information on the operating characteristics of the system gained in CHAPTER 2 to eliminate less important variables.

The cooling tower loop of the Reference HVAC system has a fixed speed condenser pump and two-speed cooling tower fan. Anticipating only limited power reduction potential from this design, and to simplify the first system optimization run, the controlled variables  $M_{\text{atow}}$  and  $M_{\text{wcond}}$  were eliminated from the cost function. Since the system does not have humidity control in the cooling mode, the sensible heat ratio term was removed from the cost function. In an attempt to better model the reheat components of the system, a new variable for system LOAD was defined to be the sum of the total cooling load at the main cooling coil ( $Q_{\text{c}}$ ) plus the total heating load at the main heating coil and (3) reheat coils ( $Q_{\text{h}}$ ).

The resulting modified cost function is then:

$$P_{\text{total}} = f(T_{\text{asup}}, T_{\text{chw}}, T_{\text{wb}}, \text{LOAD}) \quad \{\text{Eq. 3.2}\}$$

where,

$$\text{LOAD} = (Q_c + Q_h)$$

with,

$Q_c$  = total net heat transfer at main cooling coil

and

$Q_h$  = total net heat transfer at all heating coils (main coil+[3] reheat coils)

Previous optimization studies [Braun, (1988), Pape (1989)] have produced good results using the bi-quadratic form of Equation 3.2, which is:

$$\begin{aligned} P_{\text{total}} = & X_0 + X_1 (T_{\text{asup}}) + X_2 (T_{\text{chw}}) + X_3 (\text{LOAD}) + X_4 (T_{\text{wb}}) \quad \{\text{Eq. 3.3}\} \\ & + X_5 (T_{\text{asup}}^2) + X_6 (T_{\text{chw}}^2) + X_7 (\text{LOAD}^2) + X_8 (T_{\text{wb}}^2) \\ & + X_9 (T_{\text{asup}} T_{\text{chw}}) + X_{10} (T_{\text{asup}} \text{LOAD}) + X_{11} (T_{\text{asup}} T_{\text{wb}}) \\ & + X_{12} (T_{\text{chw}} \text{LOAD}) + X_{13} (T_{\text{chw}} T_{\text{wb}}) + X_{15} (\text{LOAD} T_{\text{wb}}) \end{aligned}$$

The bi-quadratic cost function consists of fifteen predictor variables ( $T_{\text{asup}}$ ,  $T_{\text{chw}}$ ,... [LOAD  $T_{\text{wb}}$ ]), their coefficients [ $X_1, X_2, \dots, X_{15}$ ], and one constant,  $X_0$ .

### 3.1.2 *Generating cost function regression database (STEP 2)*

An initial set of predictor variable values is needed to calculate the coefficients of the bi-quadratic cost function {Eq. 3.3}. A separate data file was input to the reference system simulation to force the control variables (Tasup, Tchw) across their expected operating ranges. This method of obtaining the cost function database is similar to the procedure expected for a real building where the cooling plant controls would be cycled through their operating ranges and system variables recorded and used for commissioning the optimized control program. The program code for generating the input data file and a sample of the input file appear in Appendix E (No. 1). The simulation output values for Ptotal and other cost function variables were saved to data files yielding 3600 data sets over the two week simulation period (one for each six minute timestep). A sample portion of the cost function database output from the simulation is given in Appendix E (No. 2) starting at 80 hours into the simulation (8 AM on day four), when the cooling plant first turns on in the morning.

### 3.1.3 *Regression of cost function (STEP 3)*

Using the MINITAB statistical software package, a multi-variate, least-squares regression was run to fit the bi-quadratic cost function {Eq. 3.3} to the database from STEP 2.

The MINITAB regression package has standard functions that measure the influence that predictors have on the predicted cost. It is desirable that the

interaction predictor, which is the product of the two control variables (Tasup x Tchw), be kept in the regressed cost so that the derivatives of the cost function with respect to the control variables will produce two coupled control functions. Special MINITAB commands can be used to force selected predictors to be retained in the regressed cost function.

### *3.1.4 Check of cost function fit (STEP 4)*

The quality of the cost function fit can be judged by the standard deviation "s" and coefficient of determination "R<sup>2</sup>". These values are calculated by MINITAB. The coefficient of determination is the percentage of a variation in the actual system total power that can be explained by the regressed cost function. MINITAB also outputs the "t-ratio" indicator of the relative influence of the individual predictors on the predicted value. Unusual observations are another part of the MINITAB output that identifies predictor data sets that produce a large residual. This information can be used to eliminate data sets with large residuals.

The MINITAB output of the initial cost function regression is given in Appendix D (No. 1). It was observed that the first day of the simulation produced a large number of high-residual observations in the regression output. This is due to the high initial pickup heating loads when first starting the simulation. The building zones were coldest at the start of the simulation and it took about 24 hours for the building temperatures to

establish a stabilized occupied/unoccupied profile. Similar behavior can be expected in a real building. To improve the fit of the cost function, the first 24 hours of the database were removed and the regression repeated. This same procedure should be considered when applying optimization methods to real buildings. The goodness of fit ( $R^2$ ) value was 87.5% of the variation in the actual system power being predicted by the regressed cost function. The standard deviation was 14.5 KW. To better examine the fit, the cost function predicted system power ( $P_{tot,pred}$ ) is compared to the actual reference system power value ( $P_{tot,ref}$ ) for day 4 of the simulation in FIGURE 3.2. The plot shows a poor fit in the initial and final (reheat) operation periods of the day and a much closer prediction over the middle (cooling only) portion of the day.

In an attempt to improve the fit for the system heating operation, the original LOAD predictor variable was split into separate cooling load ( $Q_c$ ) and heating load ( $Q_h$ ) predictors to give the revised cost function:

$$P_{total} = f(T_{asup}, T_{chw}, T_{wb}, Q_c, Q_h) \quad \text{\{Eq. 3.5\}}$$

The MINITAB command file and output for the regression run (OPT 1) on revised cost function {Eq. 3.5} is show in Appendix D (No. 2). There was a significant improvement from the initial regression with  $s = 0.7673$  and a near perfect fit of  $R^2 = 99.9\%$ . The fitted cost function was:

$$\begin{aligned}
 P_{\text{total}} = & 48.1 + 2.13 (T_{\text{asup}}) - 0.066 (T_{\text{chw}}) + 0.495 (Q_{\text{c}}) + 1.34 (Q_{\text{h}}) \quad \{\text{Eq.3.6}\} \\
 & - 7.78 (T_{\text{wb}}) + 0.987 (T_{\text{asup}}^2) + 0.0021 (T_{\text{chw}}^2) + 0.00073 (Q_{\text{c}}^2) \\
 & - 0.000165 (Q_{\text{h}}^2) + 1.04 (T_{\text{wb}}^2) + 0.0115 (T_{\text{asup}} T_{\text{chw}}) \\
 & + 0.0487 (T_{\text{asup}} Q_{\text{c}}) + 0.0213 (T_{\text{asup}} Q_{\text{h}}) - 1.79 (T_{\text{asup}} T_{\text{wb}}) \\
 & - 0.00946 (T_{\text{chw}} Q_{\text{c}}) - 0.0137 (T_{\text{chw}} Q_{\text{h}}) - 0.0122 (T_{\text{chw}} T_{\text{wb}}) \\
 & + 0.00231 (Q_{\text{c}} Q_{\text{h}}) - 0.0527 (Q_{\text{c}} T_{\text{wb}}) - 0.0296 (Q_{\text{h}} T_{\text{wb}})
 \end{aligned}$$

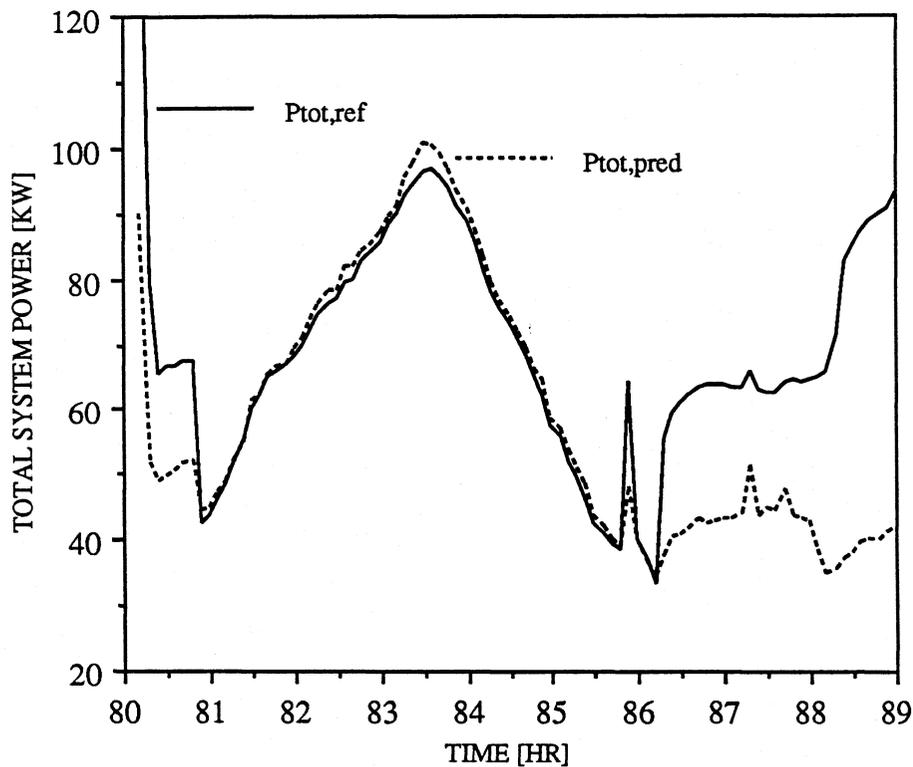


FIGURE 3.2: Initial Cost Function Fit (day 4)

### 3.1.5 Deriving control functions (STEPS 5-9)

The control functions were analytically derived from the first-order

derivatives of the fitted cost function (Equation 3.6). The partial derivatives in terms of the control variables were set equal to zero and solved for the set of control functions. Checking the sign of the second order partial derivatives of the control variables identifies whether that control function defines a local maximum or minimum control point. The procedure for deriving the control functions from cost function Equation 3.6 is demonstrated here .

**STEP:**

(5) find first-order controlled variable derivatives

$$\frac{\partial P_{total}}{\partial T_{chw}} = -.066 + .0042 T_{chw} + .0115 T_{asup} - .00946 Q_c - .0137 Q_h - .0122 T_{wb}$$

$$\frac{\partial P_{total}}{\partial T_{asup}} = 2.13 + 1.974 T_{asup} + .0115 T_{chw} + .00487 Q_c + .0213 Q_h - 1.79 T_{wb}$$

(6) check second order derivatives

$$\frac{\partial^2 P_{total}}{\partial T_{chw}^2} = + 0.0042 \text{ (minima)}$$

$$\frac{\partial^2 P_{total}}{\partial T_{asup}^2} = + 1.974 \text{ (minima)}$$

(7) solve for control functions

$$T_{chw,opt} = 18.6398 + 2.3231 Q_c + 3.2909 Q_h + 0.3978 T_{wb} \quad \{\text{Eq.3.7}\}$$

$$T_{\text{asup,opt}} = -1.19154 - 0.03813 Q_c - 0.03053 Q_h + 0.90581 T_{\text{wb}} \quad \{\text{Eq. 3.8}\}$$

- (8) Since both control variables show local minima in STEP 6, skip  
STEP 8

### 3.1.6 *Check of control functions (STEP 9)*

The set of control functions obtained in STEP 7 were examined to predict the potential performance of the "optimized" control before actually running the simulation. The cost function, Equation 3.6, is plotted in FIGURE 3.3 showing the relationship between the control variables ( $T_{\text{chw}}$ ,  $T_{\text{asup}}$ ) and the total predicted system power ( $P_{\text{tot,pred}}$ ) as the other cost function variables were held constant at average values for sample day 4. These plots predict that system power will drop as  $T_{\text{chw}}$  increases and the minimum power point will occur at  $T_{\text{asup}}$  between 9 C and 10 C.

The linear control functions {Equations 3.7 and 3.8} are plotted over the anticipated range of cooling loads ( $Q_c$ ) in FIGURE 3.4. The plots show predicted optimal chilled water temperatures ( $T_{\text{chw,opt}}$ ) that are clearly over the chiller's design operating range. The unexpectedly high prediction of the optimal  $T_{\text{chw}}$  could be the result of many factors including the particular cost function, the regression database or regression procedure used.

A closer look at the control functions shows the predicted optimal chilled water supply temperature ( $T_{\text{chw,opt}}$ ) increases when either the  $Q_c$  or  $T_{\text{wb}}$

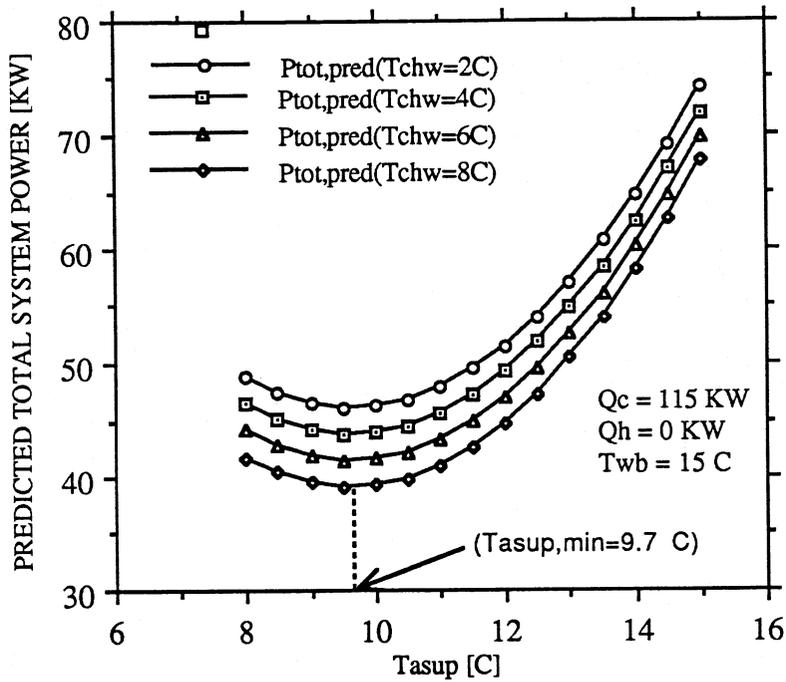


FIGURE 3.3: OPT 1 Cost Function (100% O.A.)

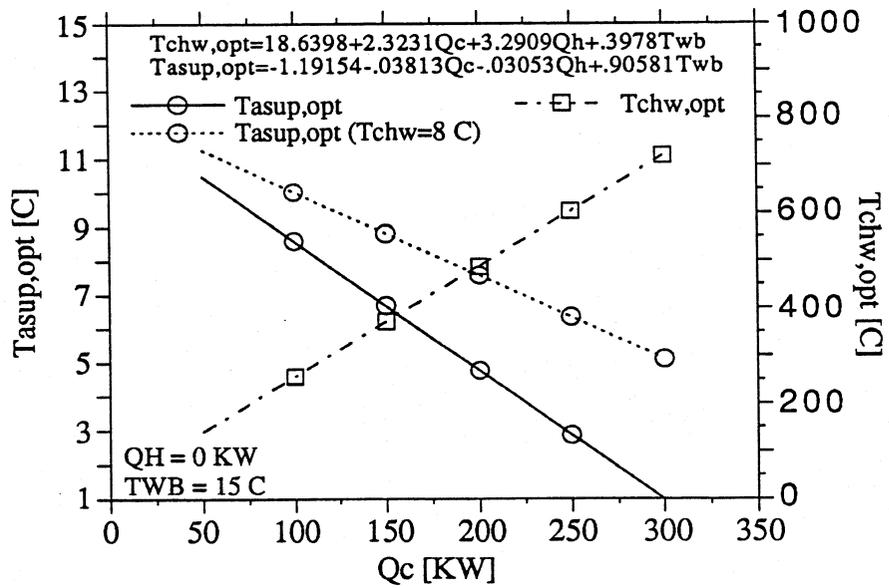


FIGURE 3.4: OPT 1 Control Functions (100% O.A.)

increase. This behavior is unexpected when considering previous studies [Braun (1988), Pape (1989)] which produced opposite results (optimal  $T_{chw}$  decreasing with increasing  $Q_c$  or  $T_{wb}$ ). Since  $T_{chw,opt}$  predicted by the control function is above the the chiller's operating range,  $T_{chw,opt}$  was set to the upper constraint value (8 C) for implementing the optimized controller. The control function for  $T_{asup,opt}$  is replotted for  $T_{chw,opt}$  set equal to the 8 C constrained value. This plot correctly predicts the minimum power point ( $T_{asup,opt} = 9.7$  C) on the  $P_{tot,pred}$  ( $T_{chw}=8$  C) curve in FIGURE 3.3. The control functions also predict the optimal supply air temperature ( $T_{asup,opt}$ ) should be lowered as cooling load or  $T_{wb}$  increases. This agrees with previous studies. The control functions predict that lowering  $T_{asup}$  as the heating load  $Q_h$  increases will reduce power. This is an unexpected result, since lowering the supply air temperature should lead to greater reheat load and actually increase the total power for this particular system.

Values for  $T_{chw,opt}$  and  $T_{asup,opt}$ , calculated from the control functions, were input into the cost function {Eq. 3.6} to calculate the total system power predicted when using the optimized controller ( $P_{tot,opt-pred}$ ). The other cost function variables values were taken from day 4 of the reference simulation. Example plots of  $P_{tot,opt-pred}$  and the actual reference system power ( $P_{tot,ref}$ ) are compared in FIGURE 3.5. The predicted, optimized system power ( $P_{tot,opt-pred}$ ) plot show a significant reduction in system power over the middle portion of the sample simulation day. The system power predicted with the optimized control averaged 19 % less than the reference case over the sample day.

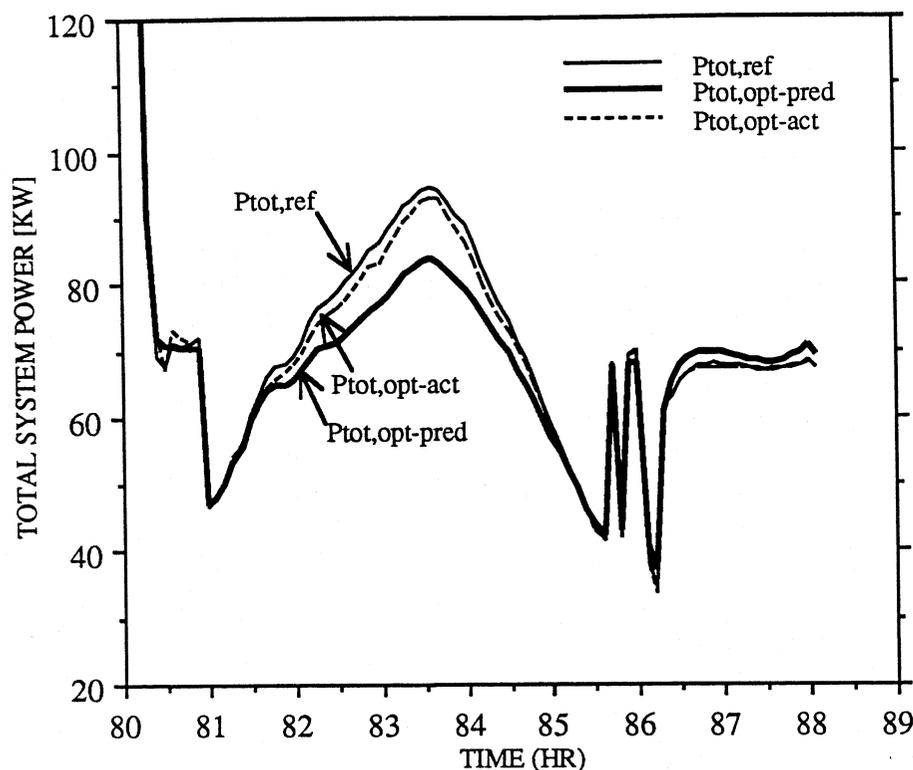


FIGURE 3.5: OPT 1 Predicted and Actual Optimized System Power (100% O.A.day 4)

### 3.1.7 Implementing control functions (STEP 10)

The next step was to program the control functions into the supervisory control component to run the HVAC system simulation under optimized control. The supervisory control code was also modified to feedback the predictor variables  $Q_c$ ,  $Q_h$ , and  $T_{wb}$  for input to the control functions. The linear control functions were added to the cooling control section of the supervisory control code. A check that the control variables are kept within the constraint values, was also programmed into the OPT 1

supervisory controller.

### 3.1.8 *System operating modes (STEP 11)*

In an attempt to improve system control using a single cost function, the single control mode was subdivided into two operating modes to provide better prediction of the System power under changing operating conditions.

The reference HVAC system economizer has two cooling modes. In the first mode, the economizer is set at 100% outside air when the return air enthalpy is greater than outside air enthalpy. In the second mode, the economizer is switched to 10% minimum outside air. For the purpose of clarity, the first mode will in future be referred to as the "100% O.A." mode and the second mode of cooling operation as the "MIN O.A." mode. Experience from the reference simulations (Chapter 2) showed that the 100% O.A. mode tended to correspond to lower cooling and higher heating load conditions, while the MIN O.A. mode related to higher cooling load operating conditions. Separate control functions were derived for each economizer operating mode using the same cost function which was fit to separate sets of regression data collected in the two different economizer operating modes.

Up to this point, only the control functions for the 100% O.A. mode have been derived. STEPS 2 through STEP 10 of this Section were then repeated

to derive the MIN O.A control functions. The MINITAB command and output file for this mode regression are given in Appendix D (No. 3). Checking the regressed cost function again shows near perfect agreement with the actual system power ( $s = 1.365 \text{ KW}$ ,  $R^2 = 99.9\%$ ). FIGURE 3.6 plots the fitted cost function showing the predicted effect of the control variables on System power. The cost function predicts that lowering  $T_{\text{asup}}$  will decrease system power.

In deriving the control functions, the second-order partial derivative for  $T_{\text{asup}}$  was negative indicating a local maximum point. This condition and the cost function plots indicate that the control function  $T_{\text{asup,opt}}$  be set to the lower constraint value (10 C). The set of control functions for the MIN O.A. mode were then:

$$T_{\text{asup,opt}} = 10 \text{ C (lower constraint value)} \quad \{\text{Eq. 3.9}\}$$

$$T_{\text{chw,opt}} = 2.12 + 0.294 T_{\text{asup}} - 0.00898 Q_{\text{c}} + 0.0388 Q_{\text{h}} + 0.334 T_{\text{wb}} \quad \{\text{Eq. 3.10}\}$$

The control function for  $T_{\text{chw,opt}}$  is plotted over the anticipated range of cooling loads ( $Q_{\text{c}}$ ) in FIGURE 3.7. The control function predicts that  $T_{\text{chw,opt}}$  should decrease with increasing cooling load and increases with heating load or  $T_{\text{wb}}$  to minimize System power.

A sample prediction of the HVAC system performance using control functions Equations 3.9 and 3.10 is shown in FIGURE 3.8. The predicted total system power ( $P_{\text{tot, opt-pred}}$ ) averaged 40 % less than the reference

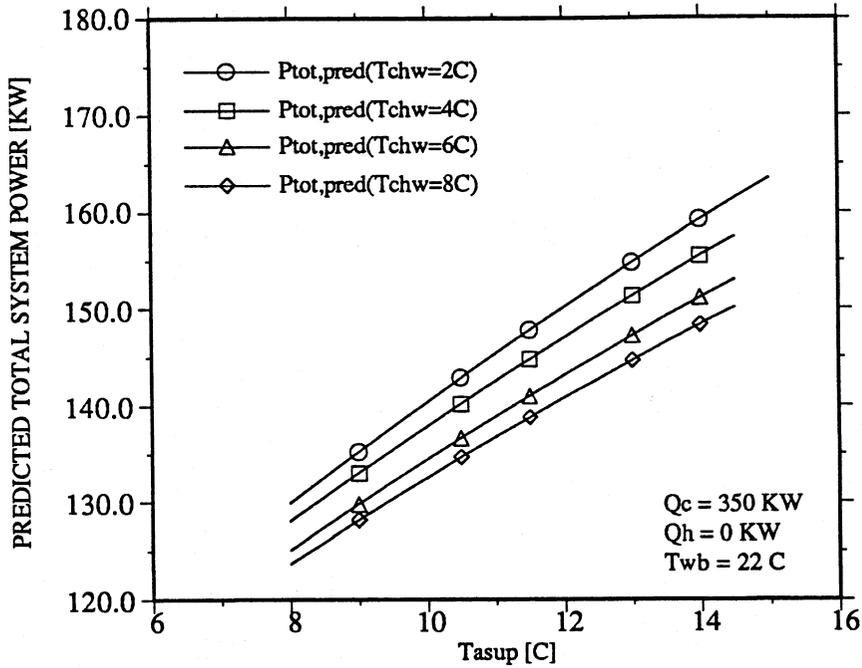


FIGURE 3.6: OPT 1 Cost Function (MIN O.A.)

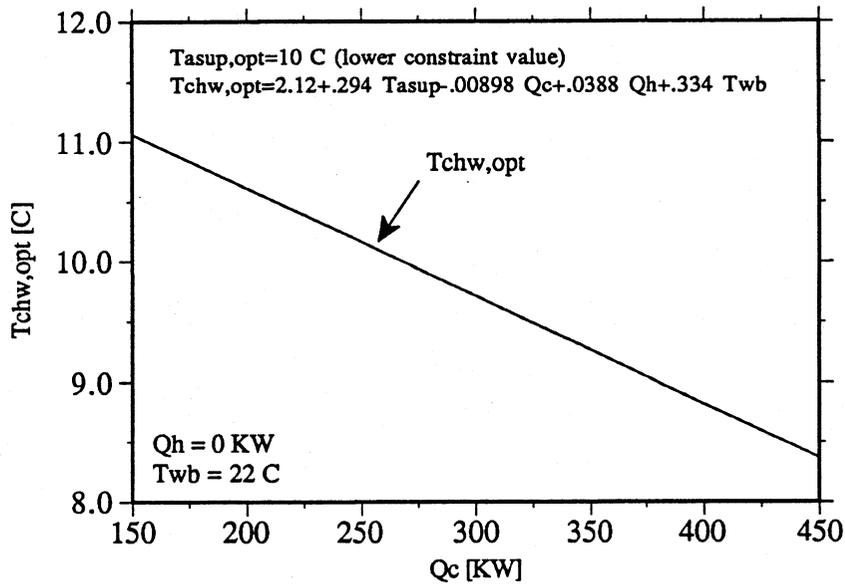


FIGURE 3.7: OPT 1 Control Functions (MIN O.A.)

system power for the final day. Assuming the reference controller is working properly, this is a larger power reduction than would be expected.

The control functions for the MIN O.A. mode {Eq 3.9, 3.10} were also programmed into the optimized supervisory control. The complete fortran code for the first optimized supervisory controller (OPT 1) with control functions for both cooling operating modes appears in Appendix B (No. 2).

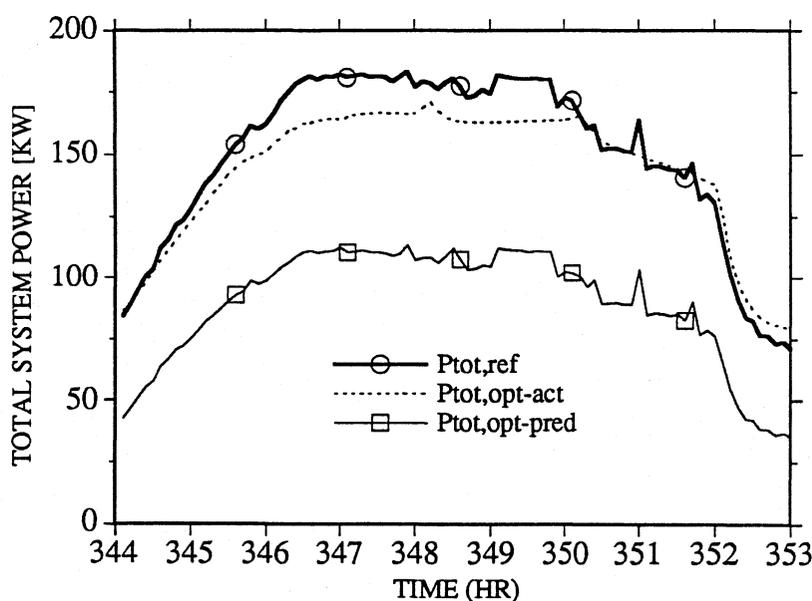


FIGURE 3.8: OPT 1 Optimized System Power (MIN O.A., final day)

### 3.1.9 Running optimized simulation (STEP 12)

Having programmed the optimized supervisory controller, the HVAC

system simulation was run with the (OPT 1) control. system powers, energy consumption and all cost function predictor variables were output and saved for evaluation and to conduct subsequent regression cycles to "fine-tune" the control (STEP 13).

Plots of the actual system power from the simulation with optimized controller, are seen in FIGURES 3.5 and 3.8. In FIGURE 3.5 (day 4, 100% O.A. mode) the system power with optimized control ( $P_{tot,opt-act}$ ) averaged 4.4% higher than the reference case. The optimized system power for the last day of the simulation (MIN. O.A. mode) averaged 4.5% less than the reference case. In both cases the predicted power performance with the optimized controller did not agree with the actual performance.

Integrated energy consumption totals for the entire two week simulation for both the reference and optimized simulation (OPT 1) appear in TABLE 3.1. The total system energy consumed with optimized control (OPT 1) is slightly more (+0.6%) than the reference case. The fan ( $W_{fans}$ ) and chiller ( $W_{chill}$ ) components showed overall energy reductions of 3.1% and 1.8%. The generally lower  $T_{asup}$  in the optimized simulation, required less total air flow to meet the same cooling load and, therefore, less fan energy than reference. Higher  $T_{chw, opt}$  in the later days of the optimized simulation required less chiller energy use. Reheat and cooling coil pump energy were higher to compensate for the lower  $T_{asup}$  and higher average  $T_{chw}$  settings. The 13.5% increased boiler energy cancelled the other energy savings as the zone reheat coils ran more to compensate for the lower supply air temperatures.

TABLE 3.1

REFERENCE and OPTIMIZED (OPT 1) SYSTEM COMPONENT ENERGY CONSUMPTION DATA

Time(HR)	<i>Wfans</i> (MJ)		<i>Wpumps</i> (MJ)		<i>Wchill</i> (MJ)	
	Reference	OPT. (1)	Reference	OPT. (1)	Reference	OPT. (1)
24.00	407.60	392.50	190.10	186.70	239.40	321.10
48.00	879.70	875.20	159.30	168.20	579.70	610.50
72.00	896.70	831.80	167.90	172.10	564.30	639.20
96.00	894.60	838.90	170.10	175.30	641.90	694.80
120.00	593.00	549.90	169.60	171.40	410.00	487.90
144.00	1006.00	920.20	165.80	172.00	711.30	777.50
168.00	802.80	736.00	169.50	174.30	653.50	709.10
192.00	756.60	709.70	167.40	173.00	536.70	598.00
216.00	946.60	880.70	163.50	170.60	628.40	692.60
240.00	513.60	477.90	181.60	184.80	432.40	500.00
264.00	822.60	746.30	170.60	174.00	910.20	850.50
288.00	1558.00	1518.00	164.80	170.20	2031.00	1824.00
312.00	1589.00	1598.00	166.10	171.10	2001.00	1829.00
336.00	1766.00	1802.00	164.60	169.40	2165.00	2008.00
360.00	1961.00	2043.00	166.20	169.60	2754.00	2447.00
TOTALS	15393.80	14920.10	2537.10	2602.70	15258.80	14989.20
CHANGE FROM REF., %		-3.08		2.59		-1.77

Time(HR)	<i>Welect</i> (MJ)		<i>Wboil</i> (MJ)		<i>Wtotal</i> (MJ)	
	Reference	OPT. (1)	Reference	OPT. (1)	Reference	OPT. (1)
24.00	837.00	900.20	2059.00	2202.00	2896.00	3102.20
48.00	1619.00	1654.00	176.80	208.40	1795.80	1862.40
72.00	1629.00	1643.00	608.40	663.00	2237.40	2306.00
96.00	1707.00	1709.00	590.50	689.40	2297.50	2398.40
120.00	1173.00	1209.00	648.80	740.40	1821.80	1949.40
144.00	1883.00	1870.00	252.30	296.70	2135.30	2166.70
168.00	1626.00	1619.00	543.40	610.30	2169.40	2229.30
192.00	1461.00	1481.00	517.50	621.10	1978.50	2102.10
216.00	1739.00	1744.00	171.30	230.10	1910.30	1974.10
240.00	1128.00	1163.00	892.20	1075.00	2020.20	2238.00
264.00	1903.00	1771.00	346.10	383.30	2249.10	2154.30
288.00	3754.00	3512.00	40.54	45.96	3794.54	3557.96
312.00	3757.00	3599.00	79.60	92.17	3836.60	3691.17
336.00	4096.00	3980.00	0.00	0.00	4096.00	3980.00
360.00	4881.00	4660.00	0.00	0.00	4881.00	4660.00
TOTALS	33193.00	32514.20	6926.44	7857.83	40119.44	40372.03
CHANGE FROM REF., %		-2.05		13.45		0.63

In summary, the performance of the first optimized controller (OPT 1) showed no net improvement over the original fixed set-point control. The earlier observation, that the predicted and actual optimized control performance did not agree (see FIGURES 3.5 and 3.8), was reason to suspect that the optimization results were not valid. And considering the unusual characteristics of the control functions, a further review of the optimization procedure and results was conducted.

### **3.2 REVIEW OF FIRST OPTIMIZATION**

The observation that the power performance of the HVAC system, with optimized control, was not predictable suggested a problem with the initial definition of the system cost function {Eq. 3.5}. A cost function with the near perfect fit demonstrated in this case would be expected to accurately estimate a future value for the system power provided that the input predictor variable values are within constraints and the predictor variables themselves are independent of each other. It is this question of independence that was further examined.

#### **3.2.1 *Test for cost function variable independence***

To confirm the independence of the OPT 1 cost function {Eq. 3.5} variables a series of reference simulation runs was conducted. The set-points for  $T_{asup}$  and  $T_{chw}$  were changed for each simulation run and output values

for  $Q_c$ , and  $Q_h$  were recorded. A summary of the simulations is presented in TABLE 3.2 for a portion of day four. Looking at sample TIME = 80.2 hours, the values for heating load ( $Q_h$ ) shows a definite increase, from 117.4 KW to 130.7 KW (+11.3%), when supply air temperature was reset from 12 C to 10 C and all other predictor variables were unchanged. At the same time, the cooling load ( $Q_c$ ) increased from 36.5 KW to 56.0 KW , a 53% rise. A similar 2 C change in the water temperature setpoint showed no clearly identifiable influence on  $Q_c$  or  $Q_h$ . These results indicate a definite influence between the controlled variable  $T_{sup}$  and two other predictor variables  $Q_c$  and  $Q_h$ , violating the condition of independence required of the cost function predictor variables. A redefinition of the cost function was necessary.

The cause of the influence between the supply air set temperature and the coil loads might originate anywhere in the system's supervisory control, local controls or components. Two likely causes are the local zone temperature control and condensation at the cooling coil. The (3) zones operate with a fixed 25 C space temperature set-point and local PID control of the VAV box and reheat coil. The control dead-band allows drift around the set-point, i.e., the control is not perfect. It is therefore understandable that variations in critical zone inputs such as supply air temperature will produce variations in room temperature and humidity which in turn affects the system loads  $Q_c$  and  $Q_h$ . This behavior is illustrated by the plots in FIGURES 3.9 and 3.10, which show a definite variation in zone air temperature and humidity as supply air temperature is changed from one simulation run to the next. In this case, lower supply

TABLE 3.2

SAMPLE HVAC SYSTEM - CONTROL VARIABLE and STATE VARIABLE RELATIONSHIP SUMMARY DATA

Time(HR)	Ptotal (KW)			Qc (KW)			Qh (KW)		
	Reference	CASE 1	CASE 2	Reference	CASE 1	CASE 2	Reference	CASE 1	CASE 2
80.20	158.32	161.75	159.73	36.54	56.05	36.08	117.45	130.68	119.40
80.30	79.25	81.75	78.21	41.63	60.33	40.74	47.54	53.49	46.23
80.40	65.30	67.44	64.57	55.56	79.90	55.40	30.30	33.19	30.22
80.50	66.47	66.27	62.04	66.23	95.13	67.06	25.56	27.92	25.62
80.60	66.66	65.39	65.30	74.25	104.99	73.96	22.16	24.43	22.17
80.70	67.49	66.91	65.58	81.09	109.79	80.06	21.18	23.33	21.08
80.80	67.24	66.25	65.25	87.41	117.56	86.56	18.65	20.58	18.59
80.90	42.32	43.79	40.26	92.71	125.01	91.84	0.00	19.43	0.00
81.00	43.54	45.09	41.44	96.82	132.32	96.01	0.00	0.00	0.00
81.10	45.99	47.60	43.06	103.98	133.19	101.08	0.00	0.00	0.00
81.20	48.32	50.05	47.53	109.59	142.52	116.63	0.00	0.00	0.00
81.30	51.74	53.36	48.83	117.87	149.84	116.23	0.00	0.00	0.00
81.40	55.42	56.51	52.56	125.83	160.78	124.39	0.00	0.00	0.00
81.50	60.07	61.25	56.22	138.25	169.57	133.68	0.00	0.00	0.00
81.60	62.14	63.28	59.88	140.96	178.46	142.28	0.00	0.00	0.00
AVERAGE	65.35	66.45	63.36	91.25	121.03	90.80	18.86	22.20	18.89
CHANGE FROM REF., %		1.67	-3.04		32.64	-0.49		17.75	0.17

Time(HR)	Tchw (C)			Tasup (C)		
	Reference	CASE 1	CASE 2	Reference	CASE 1	CASE 2
80.20	5.50	5.50	7.50	12.53	10.62	12.58
80.30	5.50	5.50	7.50	12.52	10.63	12.59
80.40	5.50	5.50	7.50	12.60	10.68	12.65
80.50	5.50	5.50	7.50	12.63	10.56	12.68
80.60	5.50	5.50	7.50	12.64	10.73	12.68
80.70	5.50	5.50	7.50	12.65	10.73	12.67
80.80	5.50	5.51	7.50	12.67	10.74	12.69
80.90	5.50	5.54	7.50	12.68	10.75	12.71
81.00	5.50	5.56	7.50	12.67	10.71	12.69
81.10	5.50	5.56	7.50	12.64	10.76	12.72
81.20	5.50	5.59	7.51	12.70	10.77	12.45
81.30	5.52	5.61	7.51	12.71	10.79	12.76
81.40	5.54	5.64	7.54	12.71	10.80	12.77
81.50	5.58	5.67	7.56	12.64	10.81	12.78
81.60	5.58	5.70	7.59	12.75	10.82	12.75
AVERAGE	5.51	5.56	7.51	12.65	10.73	12.68
CHANGE FROM REF., %		0.80	36.26		-15.20	0.22

## TABLE DEFINITIONS

Reference:

Tchw,set = 6 C

Tasup,set = 12 C

CASE 1:

Tchw,set = 6 C

Tasup,set = 10 C

CASE 2:

Tchw,set = 8 C

Tasup,set = 12 C

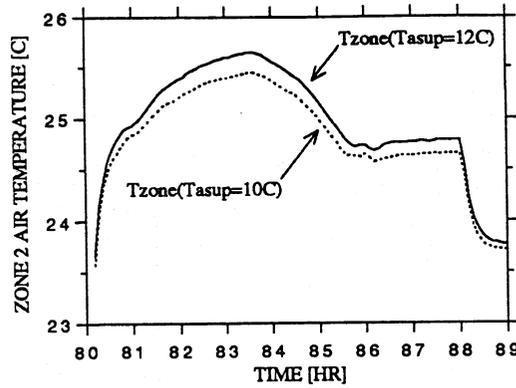


FIGURE 3.9: Zone 2 Air Temperature vs Tasup (day 4)

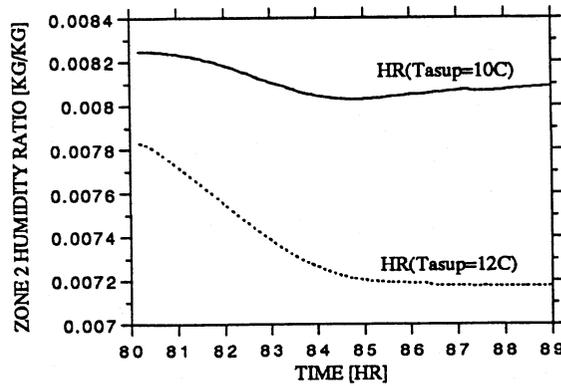


FIGURE 3.10: Zone 2 Humidity Ratio vs Tasup (day 4)

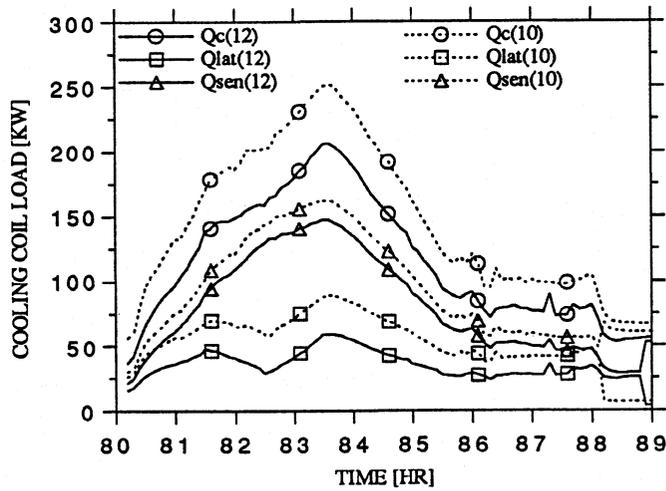


FIGURE 3.11: Cooling Coil Loads vs Tasup (day 4)

air temperature produce lower average room temperature and humidity. The reduced humidity results from greater dehumidification at the cooling coil as supply air temperature is lowered.

FIGURE 3.11 shows the total ( $Q_c$ ), latent ( $Q_{lat}$ ) and sensible ( $Q_{sen}$ ) components of the cooling coil load as  $T_{sup,set}$  is changed from 12 C to 10 C. Lowering  $T_{sup}$  has increased the cooling load. Most of this load increase was latent condensation on the cooling coil that does not contribute to cooling the zone.

In conclusion, supply air temperature,  $Q_c$  and  $Q_h$  are coupled variables in this particular system and therefore are not acceptable predictor variables for the system cost function. Their use invalidates the control optimization results. The imperfect controls in the reference system model, like any real building HVAC controls, allow interaction between system variables. A thorough understanding of the relation between system variables is important in defining the best cost function for use in optimizing the supervisory control. A revised version of the System cost function was needed.

### **3.3 REVISED COST FUNCTION**

The following simple criteria were used to select new cost function predictor variables to replace  $Q_c$  and  $Q_h$ :

1. Strict independence from other cost function predictor variables
2. Some correlation with system cooling and heating loads

The two variables selected were the average outside sol-air temperature ( $T_{solair}$ ) and the sum of zone internal gains from lights, people and other equipment (GAINS). The revised system cost function was then:

$$P_{total} = f(T_{asup}, T_{chw}, T_{wb}, T_{solair}, GAINS) \quad \text{\{Eq. 3.11\}}$$

The same optimization STEPS from Section 3.1 were repeated to produce a new optimized controller.

### 3.3.1 *Check of cost function*

The MINITAB regression on the bi-quadratic form of the revised cost function {Eq. 3.11} can be seen in Appendix D (No. 3 - 100% O.A. and No. 4 - MIN O.A.). The initial regression run for the 100% O.A. mode produced a poor cost function fit with  $s = 17.9$  KW and a fit of 32.9%. The cost function fit to the actual system power is shown in FIGURE 3.12. The cost function plots in FIGURE 3.13 predict that as  $T_{chw}$  increases  $T_{asup}$  decreases to minimize system power. The plots indicated that  $T_{chw}$  should be set to the high constraint value (8 C) to minimize power. With  $T_{chw, opt} = 8$  C,  $T_{asup, opt}$  decreases with increasing GAINS and increases slightly with  $T_{solair}$  and  $T_{wb}$  In FIGURE 3.14.

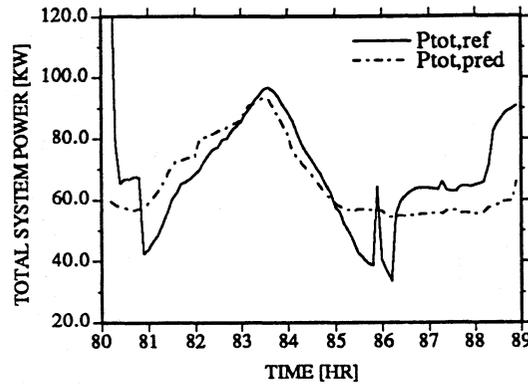


FIGURE 3.12: Revised Cost Function Fit (100% O.A., day 4)

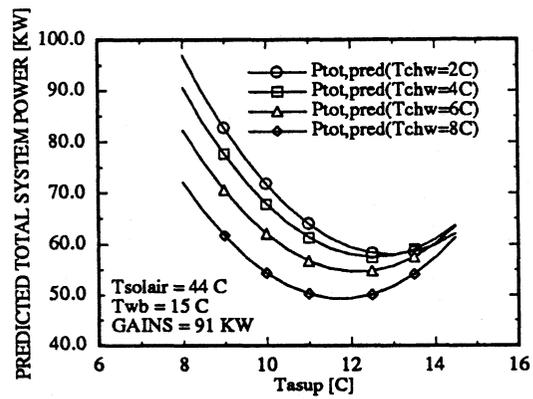


FIGURE 3.13: Revised Cost Function (100% O.A., day 4)

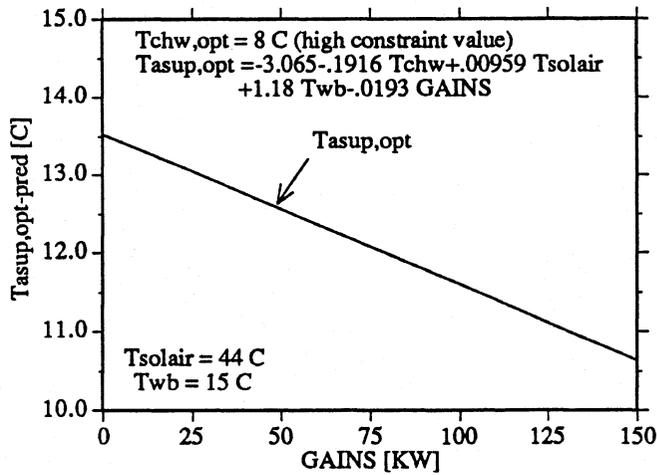


FIGURE 3.14: Revised Control Functions (100% O.A., day 4)

The cost function fit for the MIN O.A. was 89.5% with a 12.32 KW standard deviation. The fit for the last day of the simulation is shown in FIGURE 3.15. Example cost function plots in FIGURE 3.16 predict that both Tch<sub>w</sub> and Tas<sub>up</sub> should be increased to minimize system power. It is interesting to note that the individual cost function plots all intersect at one point suggesting that system power shows zero sensitivity to Tch<sub>w</sub> at that control point. FIGURE 3.17 shows the same behavior more clearly at a different system state (higher cooling load). It was found that the control functions (FIGURE 3.18) predict this intercept point. But this is not the control point for the minimum system power as can be seen in FIGURE 3.17. For this reason, the control functions were not usable in the optimization, and an alternate approach to finding new control functions was pursued.

### ***3.3.2 Revised regression database***

A new regression database was generated (STEP 2, SECTION 3.2) in attempt to obtain usable control functions and to examine the effect, if any, that changing databases might have on the optimization results.

The original database (OPT1) had been generated using a cyclic forcing function that gradually incremented the control variables (Tch<sub>w</sub>, Tas<sub>up</sub>) across their design operating ranges (see database sample, Appendix E [No.2]).

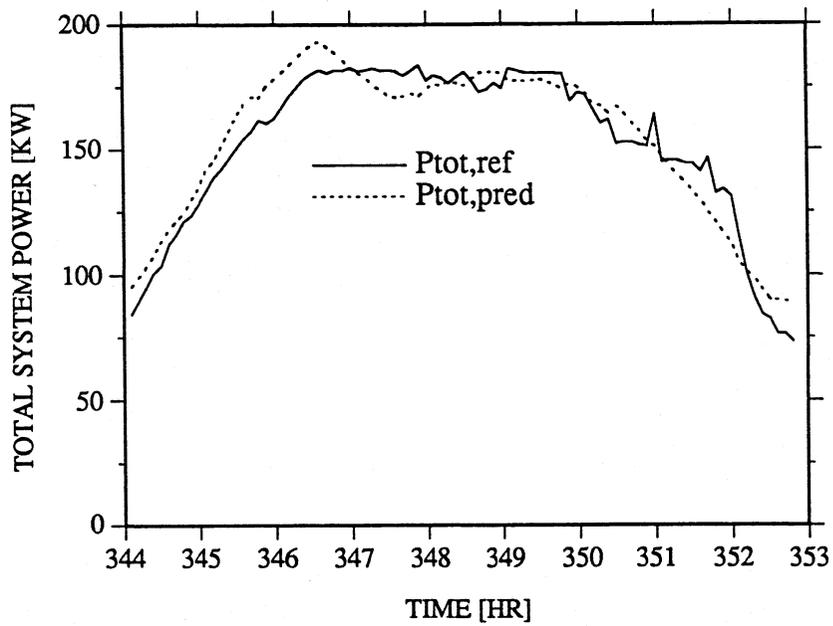


FIGURE 3.15: Revised Cost Function Fit (MIN O.A., final day)

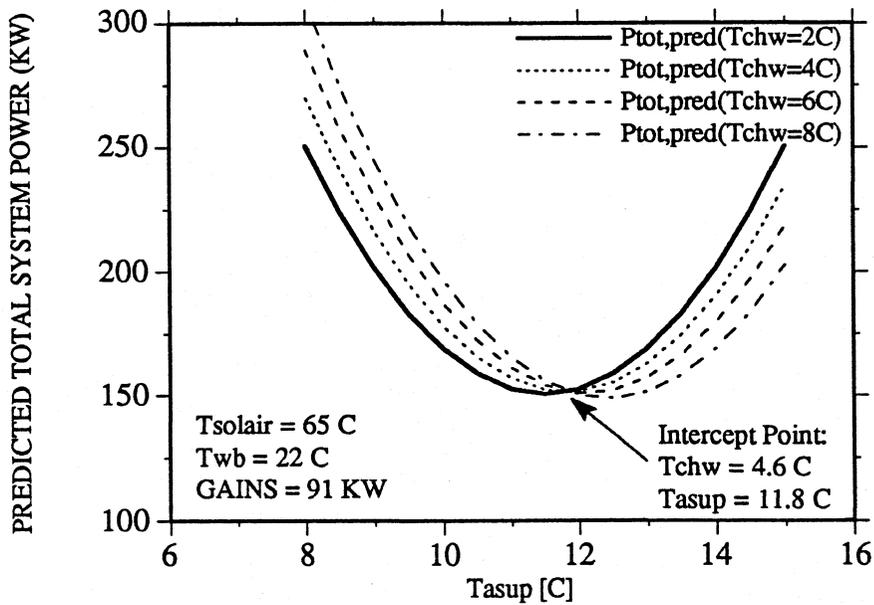


FIGURE 3.16: Revised Cost Function (MIN O.A., final day, avg. load)

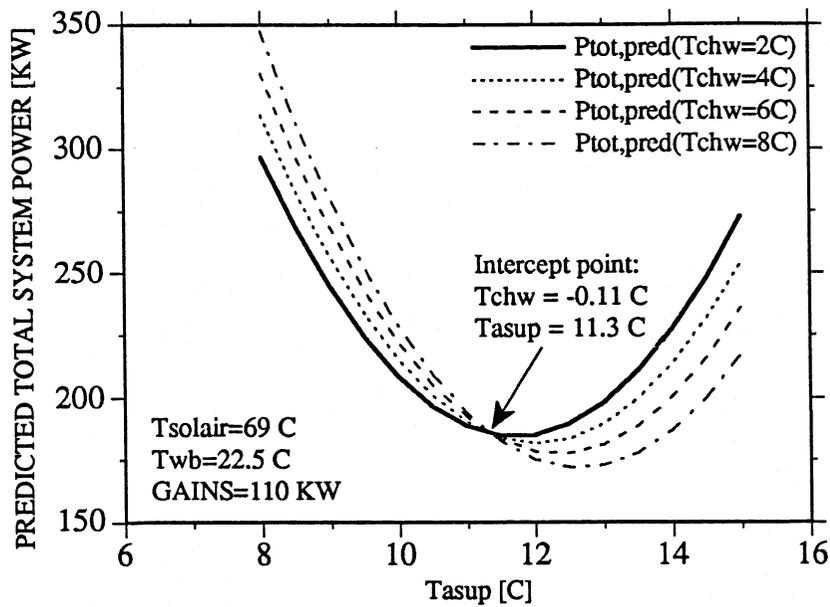


FIGURE 3.17: Revised Cost Function (MIN O.A., final day, high load)

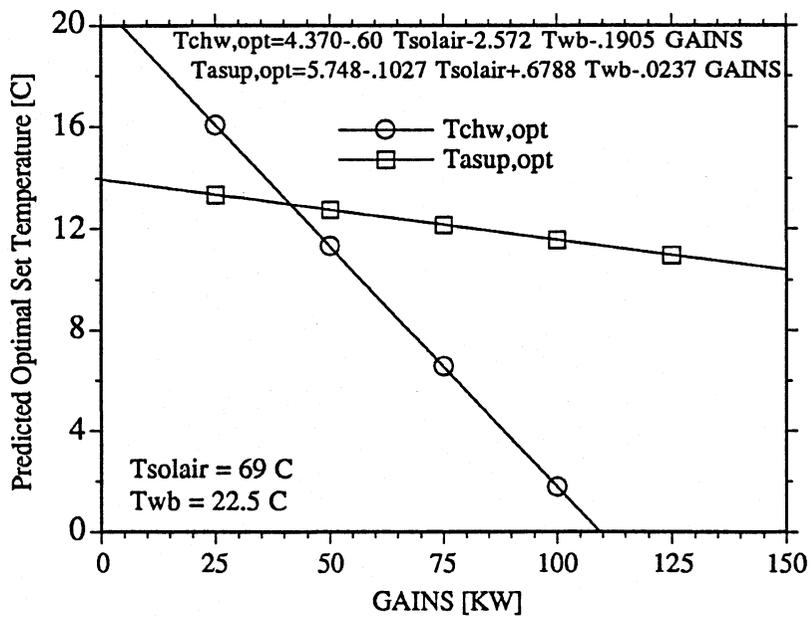


FIGURE 3.18: Revised Control Functions (MIN O.A., final day, high load)

The new database was formed using a random function to reset the control variables randomly within their operating ranges. This approach could also help reduce possible bias in the control functions that may have resulted from the repetitive nature of the old database. Appendix E (No. 3) is a sample of the new input file of random control variables values used to generate the new database.

### 3.4 SECOND OPTIMIZATION

The optimization STEPS (see Section 3.1) were repeated using the new cost function regression database from Section 3.3.2

#### 3.4.1 Check of cost function

Regressing the cost function {Eq. 3.11} on the new database gave a fit of 28.9% with  $s = 18.07$  KW in the 100% O.A. mode. This compares with  $R^2 = 32.9\%$  from the old database. There was basically no change in the cost function fit for the MIN O.A. mode.

A sample plot of the cost function fit to actual system power is shown for the 100 % O.A. mode in FIGURES 3.19. The poor fit in the 100% O.A. mode is due to both the selected predictor variables and the particular design and operating characteristics of sample HVAC system. The zone reheat subsystem is one design feature of this HVAC system model that is not predicted well by the cost function. The fit improves significantly in

the MIN O.A. mode where the reheat operation is minimal (FIGURE 3.22). The system model also uses a step forcing function to model the building internal GAINS. The step profile for the GAINS predictor variable strongly influences the shape of the cost function fit in FIGURE 3.19. A more continuous GAINS function may have produced a better fit.

The cost function characteristic plots in FIGURE 3.20 are almost the inverse of the results using the old database (see FIGURE 3.13). The widely different cost function results must be due in part to the changed regression database. The new fitted cost function predicts that raising  $T_{sup}$  up to the maximum constraint value while reducing  $T_{chw}$  will minimize system power. The (100% O.A.) control functions in FIGURE 3.21 predicts that  $T_{chw,opt}$  should decrease with increasing GAINS and  $T_{wb}$ , and increase with  $T_{solair}$ .

Plotting the cost function for the MIN O.A. mode (FIGURE 3.23) shows a basic similarity to the results with the old database (see FIGURE 3.16). The change in the regression again appears to have had some influence on the fitted cost function and, therefore, the optimized controller performance.

It is notable that the MIN O.A. cost function plots (FIGURE 3.23) do not intersect at a single point as with the old database (FIGURE 3.16, 3.17). Changing the database has eliminated the intersect problem, in this case, and produced usable control functions which are illustrated in FIGURE 3.24.

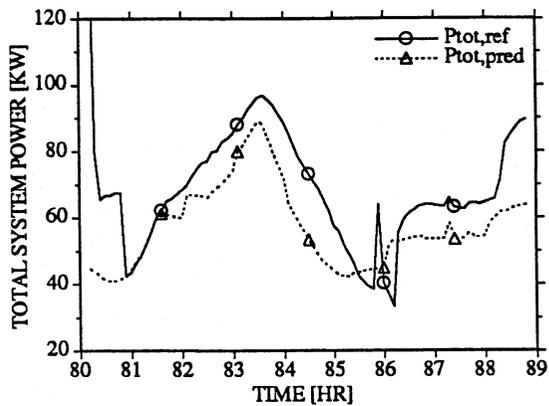


FIGURE 3.19: OPT 2 Cost Function Fit (100% O.A., day 4)

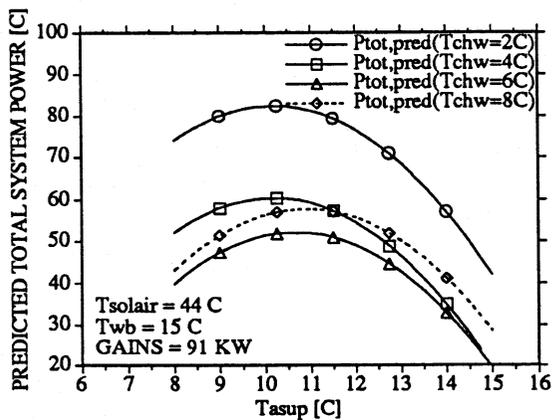


FIGURE 3.20: OPT 2 Cost Function (100% O.A.)

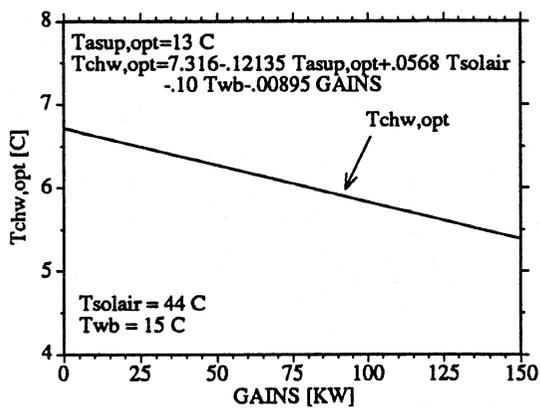


FIGURE 3.21: OPT 2 Control Functions (100% O.A., day 4)

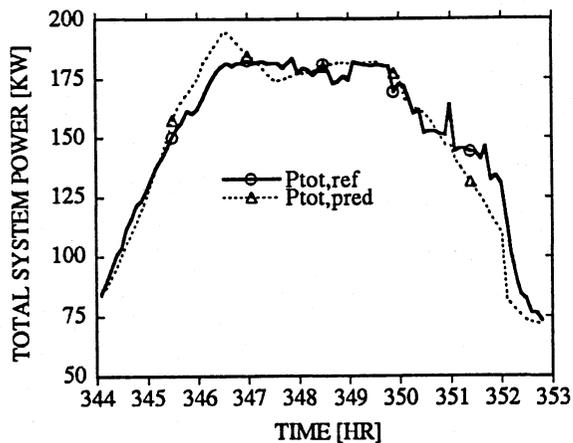


FIGURE 3.22: OPT 2 Cost Function fit (MIN O.A., final day)

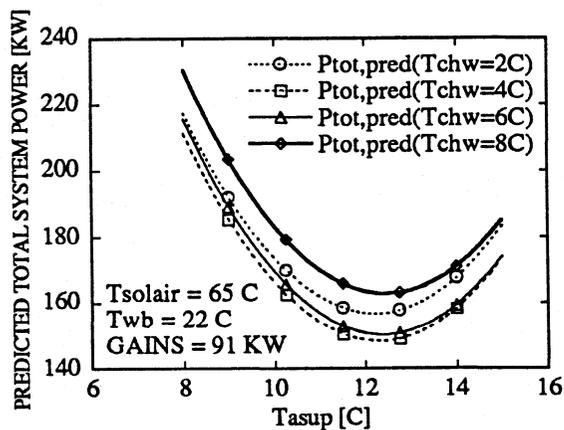


FIGURE 3.23: OPT 2 Cost Function (MIN O.A., final day)

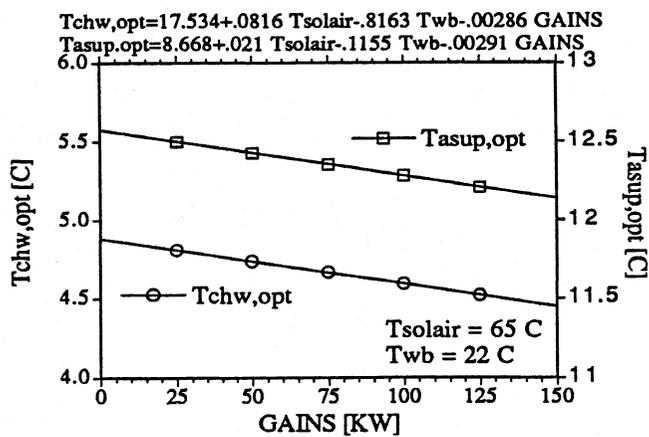


FIGURE 3.24: OPT 2 Control Functions (MIN O.A.)

### 3.4.2 Performance results

The new control functions were programmed into the new optimized supervisory controller (OPT 2). The OPT 2 controller code appears in Appendix B (No.3).

Examples of total system power performance with the OPT 2 controller are presented for the two operating modes in FIGURE 3.25 and 3.26. The system total power was reduced by an average of 2.6% less than Reference for the 100% O.A. mode in FIGURE 3.25 (plot  $P_{tot,opt-act}$ ). This compares to an average 22% predicted power reduction ( $P_{tot,opt-pred}$ ). The optimized system power for the last day of the simulation (MIN O.A. mode) averaged about 1% less than the reference control case compared to a 4.5% predicted reduction (FIGURE 3.25). This 3.5% over prediction of the power reduction is much less than the 35% over-prediction seen in the first optimization (OPT 1).

Actual System energy consumption figures from the OPT 2 simulation are given in TABLE 3.3. Total System energy consumption with the optimized control was approximately 1% less than the Reference case. Most of the energy savings can be attributed to the reduced reheat energy resulting from the generally higher  $T_{asup}$  settings in the 100% O.A. mode and the fan energy savings attributed to slightly lower average  $T_{asup}$  settings in the MIN O.A. mode.

The marginal energy performance of the OPT 2 controller may be caused by a number of factors. The inability of the selected cost function to

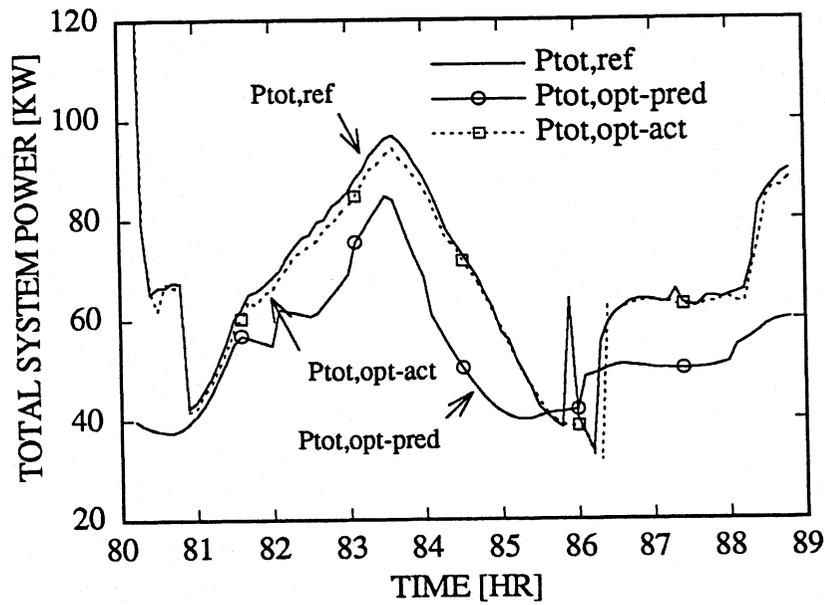


FIGURE 3.25: OPT 2 Optimized System Power (100% O.A., day 4)

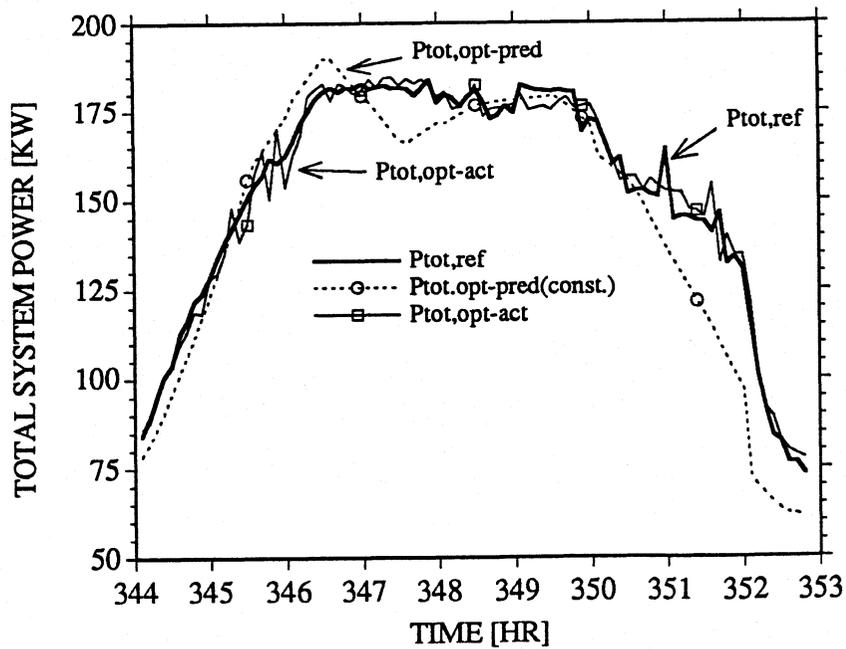


FIGURE 3.26: OPT 2 Optimized System Power (MIN O.A., final day)

TABLE 3.3

REFERENCE and OPTIMIZED (OPT 2) SYSTEM COMPONENT ENERGY CONSUMPTION DATA

Time(HR)	Wfans(MJ)			Wpumps(MJ)			Wchill(MJ)		
	Reference	OPT. (1)	OPT. (2)	Reference	OPT. (1)	OPT. (2)	Reference	OPT. (1)	OPT. (2)
24.00	407.60	392.50	409.80	190.10	186.70	190.70	239.40	321.10	225.20
48.00	879.70	875.20	899.80	159.30	168.20	159.30	579.70	610.50	521.70
72.00	896.70	831.80	908.60	167.90	172.10	167.70	564.30	639.20	526.50
96.00	894.60	838.90	908.90	170.10	175.30	169.40	641.90	694.80	594.60
120.00	593.00	549.90	603.40	169.60	171.40	170.20	410.00	487.90	391.30
144.00	1006.00	920.20	1017.00	165.80	172.00	165.40	711.30	777.50	671.90
168.00	802.80	736.00	818.50	169.50	174.30	169.60	653.50	709.10	650.40
192.00	756.60	709.70	767.00	167.40	173.00	167.10	536.70	598.00	512.70
216.00	946.60	880.70	950.70	163.50	170.60	162.80	628.40	692.60	600.00
240.00	513.60	477.90	524.30	181.60	184.80	181.70	432.40	500.00	437.60
264.00	822.60	746.30	777.50	170.60	174.00	169.90	910.20	850.50	1025.00
288.00	1558.00	1518.00	1486.00	164.80	170.20	165.40	2031.00	1824.00	2036.00
312.00	1589.00	1598.00	1516.00	166.10	171.10	167.60	2001.00	1829.00	1999.00
336.00	1766.00	1802.00	1682.00	164.60	169.40	166.40	2165.00	2008.00	2165.00
360.00	1961.00	2043.00	1906.00	166.20	169.60	165.10	2754.00	2447.00	2821.00
TOTALS	15393.80	14920.10	15175.50	2537.10	2602.70	2538.30	15258.80	14989.20	15177.90
CHANGE FROM REF., %		-3.08	-1.42		2.59	0.05		-1.77	-0.53

Time(HR)	Welect(MJ)			Wboil(MJ)			Wtotal(MJ)		
	Reference	OPT. (1)	OPT. (2)	Reference	OPT. (1)	OPT. (2)	Reference	OPT. (1)	OPT. (2)
24.00	837.00	900.20	825.70	2059.00	2202.00	2030.00	2896.00	3102.20	2855.70
48.00	1619.00	1654.00	1581.00	176.80	208.40	180.10	1795.80	1862.40	1761.10
72.00	1629.00	1643.00	1603.00	608.40	663.00	615.00	2237.40	2306.00	2218.00
96.00	1707.00	1709.00	1673.00	590.50	689.40	566.10	2297.50	2398.40	2239.10
120.00	1173.00	1209.00	1165.00	648.80	740.40	639.30	1821.80	1949.40	1804.30
144.00	1883.00	1870.00	1855.00	252.30	296.70	249.90	2135.30	2166.70	2104.90
168.00	1626.00	1619.00	1639.00	543.40	610.30	552.90	2169.40	2229.30	2191.90
192.00	1461.00	1481.00	1447.00	517.50	621.10	498.30	1978.50	2102.10	1945.30
216.00	1739.00	1744.00	1713.00	171.30	230.10	169.30	1910.30	1974.10	1882.30
240.00	1128.00	1163.00	1144.00	892.20	1075.00	873.20	2020.20	2238.00	2017.20
264.00	1903.00	1771.00	1973.00	346.10	383.30	338.50	2249.10	2154.30	2311.50
288.00	3754.00	3512.00	3688.00	40.54	45.96	41.97	3794.54	3557.96	3729.97
312.00	3757.00	3599.00	3682.00	79.60	92.17	80.92	3836.60	3691.17	3762.92
336.00	4096.00	3980.00	4013.00	0.00	0.00	0.00	4096.00	3980.00	4013.00
360.00	4881.00	4660.00	4893.00	0.00	0.00	0.00	4881.00	4660.00	4893.00
TOTALS	33193.00	32514.20	32894.70	6926.44	7857.83	6835.49	40119.44	40372.03	39730.19
CHANGE FROM REF., %		-2.05	-0.90		13.45	-1.31		0.63	-0.97

accurately model the system (poor fit) is one limiting factor. It was also demonstrated that the particular database used for fitting the cost function can affect the control functions and control performance. The undersizing of the system cooling plant is a poor design condition that also reduces system controllability regardless of the actual controller that is used.

### *3.4.3 Second optimization cycle (STEP 13)*

The final step of the proposed near-optimal control methodology called for repeating the cost function regression procedure after the current optimized controller has operated for some period of time to "tune" the control functions for improved control performance. This optimization cycle procedure was applied to the optimized controller (OPT 2). The database for the new optimization cycle was simply the output values for  $P_{total}$  and the other cost function variables from the OPT 2 simulation run.

The MINITAB regression results for this cycle are shown in Appendix D (No. 6, 7) for the two cooling operating modes. The resulting fitted cost function for both modes had a number of predictor variables that were automatically eliminated by the regression routine. This is because the database values for  $T_{chw}$  and  $T_{asup}$  did not vary by an amount sufficient to be significant in the regression analysis. With the loss of the interaction predictor variable ( $T_{chw} \times T_{asup}$ ) and other variables in the 100% O.A.

mode regression, it was not possible to derive a control function and optimization cycle had to be terminated at this point. The difficulty appeared to be in the method of generating the database used for the cost function regression. The control variable values were not forced over a sufficient range to properly apply the regression analysis. The resulting loss of key predictor variables invalidated the fitted cost function. Revising the optimization methodology to randomly perturb the control variables values about their set-points should eliminate the problem of lost cost function predictors and provide usable control functions.

### **3.5 SUMMARY**

A methodology for near-optimal control was introduced and applied to a sample HVAC system simulation model.

The cost function suggested by previous studies was modified to produce a better prediction of the HVAC system operation. Adding a new cost function variable to predict the heating load ( $Q_h$ ) significantly improved the cost function fit. Despite the near perfect cost function fit, the resulting "optimized" controller (OPT 1) exhibited behavior that was inconsistent with conventional control principles. The new controller did not produce the predicted reduction in system power and there was no net reduction in total system energy consumption. A check of the relationship between cost function variables indicated that the supply air temperature was coupled with other cost function cooling and heating load variables, which contributed to the poor predictability and performance results.

A new cost function with independent variables was proposed. The poor fit of the cost function may have contributed to the marginal (1%) System energy savings with the new optimized controller (OPT 2).

The procedure for generating the cost function regression database was revised and the influence of the database on the optimized control behavior was demonstrated.

The cost reducing performance of the optimization attempts in this study did not achieve the 4.5% energy savings demonstrated by a simple supply air reset control.

## CHAPTER 4

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### *SUMMARY CONCLUSIONS*

1. The higher pickup heating loads at initial HVAC system start-up have an undesirable influence on the initial optimized controller generation which can be easily avoided by removing start-up data from the controller generation database.
2. The presence of zone reheat in the sample HVAC system influenced the choice of cost function variables to provide maximum optimized controller performance.
3. The particular design of the reference HVAC system contains control functions or other unidentified constraints that result in the coupling of some System variables that were initially assumed to be independent.
4. The coupling of cost function predictor variables in first optimization attempt produced an unpredictable and invalid controller.
5. The System cooling plant was undersized and this poor design condition, by reducing the controllability of the System, had a negative effect on the optimized controller performance.

6. The HVAC system model in this study required individual evaluation to select the cost function variable for the controller optimization process.
7. The optimization attempts in this study did not achieve the available energy savings as demonstrated by the modified simple setpoint controller.
8. The particular factors that reduced the potential benefits of the near-optimal control methodology include:
  - a) the presence of the zone reheat system
  - b) under sizing of the cooling plant
  - c) limited chilled water and supply air temperature operating range allowed by the particular system component designs
  - d) the choice of cost function form and predictor variables
  - e) the procedure used to generate the cost function regression database and the regression method itself
  - f) the restricted range and quantity of optimization database due to the limited simulation time (2 weeks)
9. The factors affecting this simulated HVAC system control optimization are valid concerns in applying the near-optimal control methodology to real buildings.

While the actual performance achieved with the optimized controllers in

this study was marginal, the basic optimization methodology was not at fault.

This exercise illustrated that many factors determine the optimization effectiveness and that some of these are inherent in the controlled system design (and operation).

The ability to select *independent* cost function variables that provide a good fit for a particular HVAC system was the primary factor affecting the results of this study. Developing a systematic procedure for selecting cost function variables for a particular HVAC system should minimize complications and improve overall performance of the optimization.

This exercise in near-optimal control application was useful in providing a preview of the complicating factors that should be considered when applying near-optimal control methods to real buildings.

## **APPENDIX A**

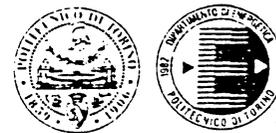
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### **IEA ANNEX - 17 EXERCISE SPECIFICATIONS**

APPENDIX A No. 1

# POLITECNICO DI TORINO

## Dipartimento di Energetica



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Torino

Prot. n.

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### I.E.A.-ANNEX 17-BUILDING ENERGY MANAGEMENT SYSTEMS

Exercises concerning the simulation of the Collins building

NEW SPECIFICATIONS FOR EXERCISES 2 - 3 - 4 (July 1990)

Vincenzo CORRADO

Augusto MAZZA

Doc. # AN17-900512-01

These specifications integrate the following documents:

- |   |                |
|---|----------------|
| - Specifications for exercise 2             | AN17-890906-02 |
| - Appendix to specifications for exercise 2 | AN17-891017-07 |
| - Specifications for exercise 3             | AN17-900206-01 |
| - New TRNSYS deck and TRNSYS types          | AN17-900321-08 |

Exercise 2RR is a common exercise for all the participants to Annex 17. With reference to the previous exercises about the Collins building, some modifications have been proposed in the system modeling, in order to have a more detailed simulation and to avoid some problems found in the previous exercises.

Exercise 3 is a diversified exercise, in which all the participants are allowed to develop new control strategies, according to some general guidelines concerning the control system. Zone control should be kept common to all participants, in order to have comparable comfort conditions. As far as the central plant control is concerned, different methods are allowed for solving optimization problems.

Exercise 4 is a diversified exercise, in which all the participants are allowed to develop new control strategies without any limitation. The goal of the exercise will be both to minimize energy consumption and to provide good comfort conditions in the occupied zones.

## 2. SYSTEM

The system is the same as that described in specifications AN17-890906-02.

## 3. CONTROL STRATEGY

### 3.1 Exercise 2RR

The control scheme to be used for running exercise 2RR is the same as that specified in specifications AN17-890906-02.

The only difference is that the room temperature set point is not modulated any more as a function of the outdoor temperature, but it is fixed during the whole simulation period depending on the climatic season.

The following values should be used for the room temperature set point:

TSET = 21	(winter season)
TSET = 23	(mid seasons)
TSET = 25	(summer season)

### 3.2 Exercise 3

The control scheme to be used for running exercise 3 is the same as that specified in document AN17-900206-01.

According to the this scheme, different optimum control methods can be used in order to define the following functions:

- criteria for changing the plant work condition;
- enthalpy economiser control;
- heating coil control;
- humidifier control;
- cooling coil control;
- boiler set point;
- chiller evaporator set point;
- cooling tower control.

The room temperature set points are fixed, as for the exercise 2RR.

### 3.3 Exercise 4

No guidelines are given for running the exercise 4. Every participant will be able to develop his own optimum control strategy to be applied to the standard building-plant system.

## 4. SIMULATION

With respect to the previous specifications, a new mid season weather file has been supplied by IKE. Therefore three simulations should be run for the following periods of fifteen days:

- from January 1 to January 15
- from April 29 to May 13
- from August 15 to August 29.

The first week of each period will be used for initializing the system.

### 4.1 General assumptions

The following values of clothing thermal resistances should be used for comfort calculations:

R = 180. m <sup>2</sup> ·°C/kW	(winter simulation)
R = 130. m <sup>2</sup> ·°C/kW	(mid season simulation)
R = 100. m <sup>2</sup> ·°C/kW	(summer simulation)

## 4.2 Input data

The required input variables are the same as for the previous exercises.

## 4.3 Output data

With reference to the previous specifications, the same daily and global results are required.

As far as hourly results are concerned, a more detailed set of output variables is required. A scheme of the complete set of hourly output variables is given in appendix 2.

The evaluation of the developed strategies will be made on the basis of the daily and total energy consumptions and costs from the 8th to the 15th day of simulation.

## 4.4 System

### 4.4.1 Correction of existing TRNSYS types

#### Chiller

The following corrections should be made to TRNSYS type 60 (chiller):

```
line 74 :      10 ICOMPR = NINT(PAR(1))
...
line 338:      GOTO (10,20,30,40),ICOMPR
```

#### Building

The following corrections should be made to TRNSYS type 62 (building):

```
line 215:      QRLIG1 = FLIG1*3600.*0.484
line 216:      QPLIG1 = FLIG1*3600.*0.516
...
line 219:      QRLIG2 = FLIG2*3600.*0.484
line 220:      QPLIG2 = FLIG2*3600.*0.516
...
line 223:      QRLIG3 = FLIG3*3600.*0.484
line 224:      QPLIG3 = FLIG3*3600.*0.516
```

### 4.4.2 Improvement of existing TRNSYS types

Some slight modifications have been made in the system modeling with reference to previous specifications.

Supervisor

The output no. 11, representing the cooling tower fan speed control (CTOWER), should now vary from 0 to 1.

Therefore, the following three conditions are possible:

```
CTOWER = 0.          tower fan switched off
CTOWER = 0.5        tower fan at low speed
CTOWER = 1.          tower fan at full speed
```

Moreover, in order to consider a fixed room temperature set point for each simulation, the following lines from 212 to 224 should be so modified:

```
C -----
C CALCULATES INDOOR TEMPERATURE SET POINT
C -----
C
      TRSET = 23.
      IF (MONTH.LE.3.OR MONTH.GE.12) TRSET = 21.
      IF (MONTH.GE.6.AND.MONTH.LE.9) TRSET = 25.
```

Building

On the base of a review of the building model made by UL, it was suggested to multiply the zone and plenum capacitances by 2.5. Therefore, the following corrections should be made to TRNSYS type 62 (building):

```
line 111:      CR = 2.6530E+4*2.5
...
line 113:      CP = 1.2505E+4*2.5
```

4.4.3 TYPE 53: Axial fan

An analysis of the fan model made by UL pointed out the following reasons for the unsatisfactory results found in the previous exercises:

- underestimate of pressure drops across the fan;
- unrealistic extrapolation of pitch blade control function in the range of low pressures;
- optimistic assumption of constant engine and transmission efficiencies at partial load.

On the base of the conclusions of the above analysis, a new TRNSYS type has been implemented by PT. Anyway, the assumption of constant efficiencies has been kept in order to avoid excessive overheating of supply air. In the following lines a scheme is shown of the new fan module (TRNSYS type

## INPUTS 8

- |                                   |            |
|-----------------------------------|------------|
| 1) Fan on/off switch              | (0/1)      |
| 2) Inlet air dry bulb temperature | [°C]       |
| 3) Inlet air humidity ratio       | [kg/kg]    |
| 4) Inlet air total pressure       | [Pa]       |
| 5) Dry air mass flow rate         | [kg/s]     |
| 6) Outlet air total pressure      | [Pa]       |
| 7) Fan speed                      | [rounds/s] |
| 8) Fan blade angle                | [deg]      |

## PARAMETERS

- |   |   |
|---|---|
| 1) Design engine efficiency               | (0-1)   |
| 2) Design transmission efficiency         | (0-1)   |
| 3) Kind of efficiency law at partial load | (1/2)   |
| 4) Engine position                        | (1/2)   |
| 5) Fan impeller diameter                  | [m]   |
| 6) Nominal air volume flow rate           | [m <sup>3</sup> /s]   |
| 7) Nominal fan absorbed power             | [kW]  |
| 8) Nominal connection pressure            | [Pa]  |
| 9) I1 = kind of fan control law           | (0-3)   |
| 10) M0 = degree of the first variable     |   |
| 11) N0 = degree of the second variable    |   |
| 12) I2 = kind of law for absorbed power   | (0-3)   |
| 13) P0 = degree of the first variable     |   |
| 14) Q0 = degree of the second variable    |   |
| **)                                       | if (I1.ne.0) ==>  |
|   | Coefficients of the polynomial fitting the fan control law ((m0+1)*(n0+1) coefficients)               |
| **)                                       | if (I2.ne.0) ==>  |
|   | Coefficients of the polynomial fitting the normalised fan absorbed power ((p0+1)*(q0+1) coefficients) |

## OUTPUTS 17

- |                                    |            |
|------------------------------------|------------|
| 1) Outlet air dry bulb temperature | [°C]       |
| 2) Outlet air humidity ratio       | [kg/kg]    |
| 3) Outlet air total pressure       | [Pa]       |
| 4) Dry air mass flow rate          | [kg/s]     |
| 5) Outlet air specific enthalpy    | [kJ/kg]    |
| 6) Outlet air relative humidity    | [%]        |
| 7) Outlet humid air mass flow rate | [kg/s]     |
| 8) Heat transfer to the air        | [kW]       |
| 9) Air pressure rise               | [Pa]       |
| 10) Fan absorbed power             | [kW]       |
| 11) Electrical absorbed power      | [kW]       |
| 12) Fan efficiency                 | (0-1)      |
| 13) Transmission efficiency        | (0-1)      |
| 14) Engine efficiency              | (0-1)      |
| 15) Global efficiency              | (0-1)      |
| 16) Fan speed                      | [rounds/s] |
| 17) Fan blade angle                | [degrees]  |

#### 4.4.3 TYPE 60: Cooling tower

A new TRNSYS type has been implemented for the simulation of a cooling tower according to the standard model developed within Annex 10.

In the following lines a scheme is shown of the new cooling tower module (TRNSYS type 61):

##### INPUTS 6

- |                                 |                     |        |
|---------------------------------|---------------------|--------|
| 1) On/off switch                |                     | (0/1)  |
| 2) Supply water temperature     |                     | [°C]   |
| 3) Ambient wet bulb temperature |                     | [°C]   |
| 4) Atmospheric pressure         |                     | [Pa]   |
| 5) Water mass flow rate         | (if P16=1 or P16=2) | [kg/s] |
| Outlet water temperature        | (if P16=3 or P16=4) | [°C]   |
| 6) Fan speed control            | (if P16=1)          | (0-1)  |
| Air mass flow rate              | (if P16=2 or P16=4) | [kg/s] |
| Water mass flow rate            | (if P16=3)          | [kg/s] |

##### PARAMETERS 16

- |  |  |                     |
|--|--|---------------------|
| 1) Modeling method                                     | (1=standard method, 2=simplified method) |                     |
| 2) Option for the calculation of tower characteristics | (1=values given, 2=values calculated)    |                     |
| 3) Altitude of tower site                              |  | [m]                 |
| 4) Design supply air wet bulb temperature              |  | [°C]                |
| 5) Design supply water temperature                     |  | [°C]                |
| - if (P1=1) ==>  |  |                     |
| 6) Outlet water temperature at condition 1             |  | [°C]                |
| 7) Air volume flow rate at condition 1                 |  | [m <sup>3</sup> /s] |
| 8) Water volume flow rate at condition 1               |  | [m <sup>3</sup> /s] |
| 9) Outlet water temperature at condition 2             |  | [°C]                |
| 10) Air volume flow rate at condition 2                |  | [m <sup>3</sup> /s] |
| 11) Water volume flow rate at condition 2              |  | [m <sup>3</sup> /s] |
| 12) C1 (if P2=1)                                       |  |                     |
| 13) C2 (if P2=1)                                       |  |                     |
| - if (P1=2) ==>  |  |                     |
| 6) Design outlet water temperature                     |  | [°C]                |
| 7) Design air volume flow rate                         |  | [m <sup>3</sup> /s] |
| 8) Design water volume flow rate                       |  | [m <sup>3</sup> /s] |
| 9) CK (if P2=2)  |  |                     |
| 10) unassigned   |  |                     |
| 11) unassigned   |  |                     |
| 12) unassigned   |  |                     |
| 13) unassigned   |  |                     |
| 14) Design fan absorbed power                          |  | [kW]                |
| 15) Design fan volume flow rate                        |  | [kW]                |
| 16) Kind of simulation                                 |  | (1,2,3,4)           |

## OUTPUTS 13

1) Outlet water temperature	[°C]
2) Water mass flow rate	[kg/s]
3) Water volume flow rate	[m <sup>3</sup> /s]
4) Atmospheric pressure	[Pa]
5) Air mass flow rate	[kg/s]
6) Air volume flow rate	[m <sup>3</sup> /s]
7) Heat removed from the air	[kW]
8) Fan electrical power consumption	[kW]
9) Mass flow rate ratio (air/water)	
10) Water side effectiveness	(0-1)
11) Air side effectiveness	(0-1)
12) Effectiveness related to NTU	(0-1)
13) Approximated effectiveness (by linearization)	(0-1)

**APPENDIX B**

---

**TRNSYS COMPONENT CODES**



- C \* 5. ON/OFF CHILLER (0/1)
- C \* 6. ON/OFF COOLING TOWER FAN (0/1)
- C \* 7. SUPPLY FAN STATIC PRESSURE [PA]
- C \* 8. EXTRACT/SUPPLY FLOW RATE RATIO (0-1)
- C \* 9. BOILER OUTLET WATER TEMPERATURE SET POINT
- C \* 10. EVAPORATOR OUTLET WATER TEMPERATURE SET
- C \* 11. COOLING TOWER FAN SPEED CONTROL (0-1)
- C \* 12. AIR MASS FLOW RATE THROUGH UAU BOX 1 [KG/S]
- C \* 13. AIR MASS FLOW RATE THROUGH UAU BOX 2 [KG/S]
- C \* 14. AIR MASS FLOW RATE THROUGH UAU BOX 3 [KG/S]
- C \* 15. CONTROL SIGNAL TO MIXING BOX (0-1)
- C \* 16. ON/OFF BOILER PUMP (0/1)
- C \* 17. ON/OFF HEATING COIL PUMP (0/1)
- C \* 18. ON/OFF REHEAT COIL PUMP (0/1)
- C \* 19. ON/OFF HUMIDIFIER PUMP (0/1)
- C \* 20. ON/OFF COOLING COIL PUMP (0/1)
- C \* 21. ON/OFF COOLING TOWER PUMP (0/1)
- C \* 22. CONTROL SIGNAL TO HEATING COIL THREE-WAY VALVE (0-1)
- C \* 23. CONTROL SIGNAL TO HUMIDIFIER THREE-WAY VALVE (0-1)
- C \* 24. CONTROL SIGNAL TO COOLING COIL THREE-WAY VALVE (0-1)
- C \* 25. CONTROL SIGNAL TO COOLING TOWER THREE-WAY VALVE (0-1)
- C \* 26. CONTROL SIGNAL TO REHEAT COIL 1 THREE-WAY VALVE (0-1)
- C \* 27. CONTROL SIGNAL TO REHEAT COIL 2 THREE-WAY VALVE (0-1)
- C \* 28. CONTROL SIGNAL TO REHEAT COIL 3 THREE-WAY VALVE (0-1)

C \*\*\*\*\*  
C

IMPLICIT REAL(X)

```

C*****CHANGE
DIMENSION XIN(42),OUT(31),INFO(10)
DIMENSION XIN98(3),PAR98(5),OUT98(5),INFO98(10)
COMMON /SIM/ TIME0,TFINAL,DELTA
COMMON /STORE/ NSTORE,IAU,S(5000)
COMMON /PID/ IPID(40),IND

```

```

C IF (INFO(7).GT.-1) GO TO 100

```

```

C *****
C * FIRST CALL OF THE SIMULATION *
C *****
C

```

```

C*****CHANGE
INFO(6) = 31
INFO(10) = 10
CALL TYPECK(1,INFO,42,0,0)
DO 98 I=1,10
98 S(INFO(10)+I-1) = 0.

```

```

C DO 99 I=1,20
IPID(I) = -1
IPID(I+20) = 1
99 IPID(I+40) = 0

```

```

C *****
C * FIRST CALL OF EACH TIME STEP *
C *****
C

```

```

100 CONTINUE
IF (INFO(7).GT.0) GO TO 100
DO 101 I=1,20

```

```
101 IF (IPID(I).NE.-1) IPID(I) = 0
```

```
ind = 0
```

```
C
```

```
C *****
```

```
C * INITIALIZATION OF VARIABLES *
```

```
C *****
```

```
C
```

```
120 CONTINUE
```

```
ISTORE = INFO(10)-1
```

```
INFO98(2) = 98
```

```
INFO98(3) = 3
```

```
INFO98(4) = 5
```

```
INFO98(5) = 0
```

```
INFO98(6) = 5
```

```
INFO98(9) = 1
```

```
C
```

```
C *****
```

```
C VALUES OF INPUTS *
```

```
C *****
```

```
C
```

```
YEAR = XIN(1)
```

```
MONTH = XIN(2)
```

```
DAY = XIN(3)
```

```
HOURL = XIN(4)
```

```
TOUT = XIN(5)
```

```
TROOM1 = XIN(6)
```

```
TROOM2 = XIN(7)
```

```
TROOM3 = XIN(8)
```

```
TLEN1 = XIN(9)
```

```
TLEN2 = XIN(10)
```

```
TLEN3 = XIN(11)
```

```
TEX = XIN(12)
```

```
TFE = XIN(13)
```

```
TM = XIN(14)
```

```
TH = XIN(15)
```

```
THUM = XIN(16)
```

```
TC = XIN(17)
```

```
TFS = XIN(18)
```

```
TB1 = XIN(19)
```

```
TB2 = XIN(20)
```

```
TB3 = XIN(21)
```

```
TH1 = XIN(22)
```

```
TH2 = XIN(23)
```

```
TH3 = XIN(24)
```

```
TUR = XIN(25)
```

```
TUEUAP = XIN(26)
```

```
TCOND = XIN(27)
```

```
RHOUT = XIN(28)
```

```
RHR1 = XIN(29)
```

```
RHR2 = XIN(30)
```

```
RHR3 = XIN(31)
```

```
RHR4 = XIN(32)
```

```
RHR5 = XIN(33)
```

```
RHR6 = XIN(34)
```

```
RHFE = XIN(35)
```

```
RHM = XIN(36)
```

```
RHPUM = XIN(37)
```

```
RHC = XIN(38)
```

```
POUF = XIN(39)
```

```
PROOM = XIN(40)
```

PFE = XIN(41)  
PFS = XIN(42)

88

```
C
C =====
C !!! LOGIC FOR THE ENERGY MANAGEMENT SYSTEM BEGINS HERE
C =====
C
C *****
C * CONTROL STRATEGY FOR EXERCISE 2 *
C *****
C
C   CMMIN = 0.1
C
C   HOUR = TIME-24.*INT(TIME/24.)
C   GMSYS = 0.
C   IF (HOUR.GT.0.AND.HOUR.LE.17.) GMSYS = 1.
C   IF (GMSYS.EQ.1.) THEN
C     GAMFS = 1.
C     GAMFE = 1.
C     GAMB = 1.
C   ELSE
C     S(ISTORE+1) = 0.
C     GO TO 200
C   ENDIF
C
C -----
C CALCULATES SUPPLY FAN STATIC PRESSURE AND EXTRACT/SUPPLY FLOW RATE R4
C -----
C
C   PFANS = PRDM+1000.
C   RFANE = 0.9
C
C -----
C CALCULATES INDOOR TEMPERATURE SET POINT
C -----
C
C   TRSET = 23.
C   IF (MONTH.LE.3.OR.MONTH.GE.12) TRSET = 21.
C   IF (MONTH.GE.6.OR.MONTH.LE.9) TRSET = 25.
C   TRSET2 = TRSET-1.5
C
C -----
C CALCULATES INDOOR RELATIVE HUMIDITY SET POINT
C -----
C
C   RHRSET = 50.
C
C -----
C CALCULATES SET POINTS OF HYDRONIC SYSTEM
C -----
C
C   TWSET = 80.
C   TWESET = 6.
C   TWCDW = 18.
C   TWCUP = 24.
C   TWCSET = (TWCDW+TWCUP)/2.
C
C -----
C CALCULATES THE HEATING/COOLING/FREE COOLING CONDITION
```

```

C -----
C ICOND = 0    ==> FREE COOLING
C ICOND = 1    ==> COOLING
C ICOND = 2    ==> HEATING
C
  IF (TOUT.GT.20.) THEN
    ICOND = 1
    S(ISTORE+1) = ICOND
    GO TO 400
  ENDIF
C
  ICOND = S(ISTORE+1)
  IF (INFO(7).GT.0) GO TO 150
  IF (ICOND.FQ.0.AND.(TROOM1.GT.22..OR.TROOM2.GT.22..OR.TROOM3.GT.
+ 22.)) ICOND=1
  IF (ICOND.FQ.0.AND.TROOM1.LT.20..AND.TROOM2.LT.20..AND.TROOM3.LT.
+ 20.) ICOND=2
  IF (ICOND.EQ.1.AND.TROOM1.LT.20..AND.TROOM2.LT.20..AND.TROOM3.LT.
+ 20.) THEN
    IF (TOUT.GF.10.) ICOND=0
    IF (TOUT.LT.10.) ICOND=2
  ENDIF
  IF (ICOND.EQ.2.AND.(TROOM1.GT.22..OR.TROOM2.GT.22..OR.TROOM3.GT.
+ 22.)) THEN
    IF (TOUT.GF.10.) ICOND=0
    IF (TOUT.LT.10.) ICOND=1
  ENDIF
150 S(ISTORE+1) = ICOND
    GO TO (300,400,500),ICOND+1
C
C -----
C FREE COOLING CONDITION
C -----
C
300 CONTINUE
  GAMCH = 0.
  GAMCT = 0.
  CTOWER = 0.
  GAMPHC = 0.
  GAMPCC = 0.
  GAMPCT = 0.
C
  CMBOX = 1.
  CHEAT = 0.
  CCOOL = 0.
  CCOND = 0.
C
  S(ISTORE+2) = CTOWER
  GO TO 700
C
C -----
C COOLING CONDITION
C -----
C
400 CONTINUE
  GAMCH = 1.
  GAMCT = 1.
C
  TSSET = 10.
  TSSET1 = 10.665

```

TSET2 = 9.335

90

ITP98 = 1

GO TO 2000

410 CCOOL = OUT98(1)

IF (CCOOL.EQ.0..and.tout.lt.12.33) THEN

GAMPCC = 0.

GAMPCT = 0.

CTOWER = 0.

CCOND = 0.

S(ISTORE+2) = CTOWER

GO TO 450

ENDIF

GAMPCC = 1.

GAMPCT = 1.

CTOWER = S(ISTORE+2)

IF (CTOWER.NE.1..AND.TWCOND.IF.TWCDW) THEN

CTOWER = 0.

CCOND = 0.

GO TO 430

ENDIF

IF (CTOWER.EQ..5.AND.TWCOND.GE.TWCDUP.and.ind.ne.1.and.info(7).st.0  
+ .OR.CTOWER.EQ.1..AND.TWCOND.GE.TWCDW) THEN

CTOWER = 1.

CCOND = 1.

GO TO 430

ENDIF

if (ctower.eq.1.and.info(7).st.100) ind = 1

CTOWER = .5

ITP98 = 2

GO TO 2000

420 CCOND = OUT98(1)

430 CONTINUE

S(ISTORE+2) = CTOWER

450 CONTINUE

WOUT = FWPFI(TOUT,RHOUT,POUT)

WRET = FWPFI(TFE,RHFE,POUT)

HOUT = FHAIR(TOUT,WOUT)

HRET = FHAIR(TFE,WRET)

IF (HOUT.LT.HRET) THEN

IECON = 1

ELSE

IECON = .2

ENDIF

if (tout.ge.12.33) then

gampcc = 0.

cheat = 0.

if (iecon.eq.1) cmbow = 1

if (iecon.eq.2) cmbow = cmin

go to 700

endif

```

C
  ITP98 = 3
  GO TO 2000
170 CMBOX = OUT98(1)
  GO TO 600

C
C -----
C HEATING CONDITION
C -----
C
500 CONTINUE
  GAMCH = 0.
  GAMCT = 0.
  CTOWER = 0.
  GAMPCO = 0.
  GAMPCT = 0.
  CMBOX = CMMIN
  CCOOL = 0.
  CCOND = 0.
  S(ISTORE+2) = CTOWER

C
  TSET2 = 26.335

C
600 CONTINUE
  ITP98 = 4
  GO TO 2000
650 CHEAT = OUT98(1)

C
  GAMPHC = 0.
  IF (CHEAT.GT.0.) GAMPHC = 1.

C
700 CONTINUE
C -----
C CALCULATES HUMIDIFIER WORKING
C -----
C
  IF (TOUT.EQ.14) THEN
    CHUMID = 0.
    GO TO 750
  ENDIF

C
  ITP98 = 5
  GO TO 2000
720 CHUMID = OUT98(1)

C
750 CONTINUE
C -----
C CALCULATES MASS FLOW RATES THROUGH UAV BOXES
C -----
C
  IF (ICOND.EQ.2) THEN
    IVAV = 2.
  ELSE
    IVAV = 1.
  ENDIF

C
  ITP98 = 6

```

GO TO 2000  
 810 CVAU1 = OUT98(1)

ITP98 = 7

GO TO 2000  
 820 CVAU2 = OUT98(1)

ITP98 = 8

GO TO 2000  
 830 CVAU3 = OUT98(1)

MVAU1 = 1.488+5.952\*CVAU1  
 MVAU2 = 1.488+5.952\*CVAU2  
 MVAU3 = 1.488+5.952\*CVAU3

-----  
 CALCULATES CONTROL SIGNALS TO REHEAT COILS  
 -----

ITP98 = 9

GO TO 2000  
 910 CHEAT1 = OUT98(1)

ITP98 = 10

GO TO 2000  
 920 CHEAT2 = OUT98(1)

ITP98 = 11

GO TO 2000  
 930 CHEAT3 = OUT98(1)

GAMPRH = 0.

GAMPB = 0.

GAMPHU = 0.

IF (CHEAT1.GT.0..OR.CHEAT2.GT.0..OR.CHEAT3.GT.0.) GAMPRH = 1.

IF (GAMPHC.EQ.1..OR.GAMPRH.EQ.1.) GAMPB = 1.

IF (CHUMID.GT.0.) GAMPHU = 1.

=====  
 !!! LOGIC FOR THE ENERGY MANAGEMENT SYSTEM FNDIS HERE  
 =====

\*\*\*\*\*

\* VALUES OF OUTPUTS \*

\*\*\*\*\*

OUT(1) = GAMSYS  
 OUT(2) = GAMFS  
 OUT(3) = GAMFE  
 OUT(4) = GAMB  
 OUT(5) = GAMCH  
 OUT(6) = GAMCT  
 OUT(7) = PFANS  
 OUT(8) = RFANE  
 OUT(9) = TWRSET  
 OUT(10) = TWESET  
 OUT(11) = CTOWER  
 OUT(12) = MVAU1  
 OUT(13) = MVAU2

```

OUT(14) = MVAU3
OUT(15) = CMBOX
OUT(16) = GAMPB
OUT(17) = GAMPHC
OUT(18) = GAMPRH
OUT(19) = GAMPHU
OUT(20) = GAMFCC
OUT(21) = GAMFCT
OUT(22) = CHEAT
OUT(23) = CHUMID
OUT(24) = CCOOL
OUT(25) = CCOND
OUT(26) = CHEAT1
OUT(27) = CHEAT2
OUT(28) = CHEAT3
C*****CHANGE
      out(29) = cheat3
      out(30) = icond
      out(31) = tsset
C
C 1000 RETURN
C
C *****
C * THE PLANT IS SWITCHED OFF *
C *****
C
C 200 DO 210 I=1,28
      OUT(I) = 0.
C 210 CONTINUE
      GO TO 1000
C
C *****
C *          PID CONTROLLERS          *
C *          -----                  *
C *          *                         *
C * 1) cooling coil      : CCOOL      *
C * 2) cooling tower    : CCOND      *
C * 3) mixing box      : CMBOX      *
C * 4) heating coil    : CHEAT      *
C * 5) humidifier      : CHUMID     *
C * 6) VAV box 1       : CVAU1      *
C * 7) VAV box 2       : CVAU2      *
C * 8) VAV box 3       : CVAU3      *
C * 9) Reheat coil 1   : CHEAT1     *
C * 10) Reheat coil 2  : CHEAT2     *
C * 11) Reheat coil 3  : CHEAT3     *
C *****
C
C 2000 CONTINUE
C
      INFO98(1) = ITP98
      INFO98(7) = IPID(ITP98)
      INFO98(8) = IPID(ITP98+20)
      INFO98(10) = IPID(ITP98+40)
      PAR98(2) = 0.
      PAR98(3) = 0.
      PAR98(4) = 0.
      PAR98(5) = 0.
      IF (ITP98.FI.3) PAR98(5) = CMMIN
C

```

```

IF (ITP98.EQ.1) THEN
  PAR98(1) = 2./0.67
  XIN98(1) = TSSET1
  XIN98(3) = 1.
ENDIF

```

```

IF (ITP98.EQ.2) THEN
  PAR98(1) = 2./6.
  XIN98(1) = TWCSSET
  XIN98(2) = TWCOND
  XIN98(3) = 1.
ENDIF

```

```

IF (ITP98.EQ.3) THEN
  PAR98(1) = 2./0.66
  XIN98(1) = TSSET
  XIN98(3) = IECON
ENDIF

```

```

IF (ITP98.EQ.4) THEN
  PAR98(1) = 2./0.67
  XIN98(1) = TSSET2
  XIN98(3) = 2.
ENDIF

```

```

IF (ITP98.FQ.5) THEN
  PAR98(1) = 0.1
  XIN98(1) = RHRSET
  XIN98(2) = RHR2
  XIN98(3) = 2.
ENDIF

```

```

IF (ITP98.FQ.1.OR.ITP98.FQ.3.OR.ITP98.FQ.4) XIN98(2) = TFS
IF (ITP98.EQ.6.OR.ITP98.EQ.9) XIN98(2) = TROOM1
IF (ITP98.EQ.7.OR.ITP98.FQ.10) XIN98(2) = TROOM2
IF (ITP98.EQ.8.OR.ITP98.EQ.11) XIN98(2) = TROOM3

```

```

IF (ITP98.FQ.6.OR.ITP98.FQ.7.OR.ITP98.FQ.8) THEN
  PAR98(1) = 1.
  XIN98(1) = TRSET
  XIN98(3) = IUAV
ENDIF

```

```

IF (ITP98.FQ.9.OR.ITP98.FQ.10.OR.ITP98.FQ.11) THEN
  PAR98(1) = 2.
  XIN98(1) = TRSET2
  XIN98(3) = 2.
ENDIF

```

```

2100 CALL TYPE67(TIME,XIN98,OUT98,NUM1,NUM2,PAR98,INF098)

```

```

IPID(ITP98) = INF098(7)+1
IPID(ITP98+20) = INF098(8)+1
IPID(ITP98+40) = INF098(10)
GO TO (410,420,470,650,720,810,820,830,910,920,930), ITP98
END

```

OPTIMIZED SUPERVISORY CONTROL (OPT 1)  
 TEA ANNEX 17 - EXERCISE 3 (07/90)  
 SUPPOT.FOR139

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C \*\*\*\*\*

C VALUES OF INPUTS \*

C \*\*\*\*\*

C

YEAR = XIN(1)  
 MONTH = XIN(2)  
 DAY = XIN(3)  
 HOUR = XIN(4)  
 TDUT = XIN(5)  
 TROOM1 = XIN(6)  
 TROOM2 = XIN(7)  
 TROOM3 = XIN(8)  
 TPLEN1 = XIN(9)  
 TPLEN2 = XIN(10)  
 TPLEN3 = XIN(11)  
 YEX = XIN(12)  
 TFE = XIN(13)  
 TM = XIN(14)  
 TH = XIN(15)  
 THUM = XIN(16)  
 TC = XIN(17)  
 TFS = XIN(18)  
 TD1 = XIN(19)  
 TD2 = XIN(20)  
 TD3 = XIN(21)  
 TH1 = XIN(22)  
 TH2 = XIN(23)  
 TH3 = XIN(24)  
 TWR = XIN(25)  
 TWEVAP = XIN(26)  
 TWCOND = XIN(27)  
 RHOUT = XIN(28)  
 RHR1 = XIN(29)  
 RHR2 = XIN(30)  
 RHR3 = XIN(31)  
 RHP1 = XIN(32)  
 RHP2 = XIN(33)  
 RHP3 = XIN(34)  
 RHFE = XIN(35)  
 RHM = XIN(36)  
 RHHUM = XIN(37)  
 RHC = XIN(38)  
 POUT = XIN(39)  
 PROOM = XIN(40)  
 PFE = XIN(41)  
 PFS = XIN(42)  
 Tsair = XIN(43)  
 Tweth = XIN(44)  
 Sgain = XIN(45)  
 TMAX = XIN(46)  
 TMIN = XIN(47)  
 QC = XIN(48)  
 QH = XIN(49)

C\*\*\*\*\*

C RFRIN OPTIMIZED CONTROL LOGIC - OPT 1

C\*\*\*\*\*

```

C
  IF (CMBOX.GT.0.5) THEN
    TWESET = 18.9709+2.3575*QC+3.345*QH+.4293*Tweth
    XTCHW = TWESET
    IF (TWESET.GT.8.0) TWESET=8.0
    IF (TWESET.LT.4.0) TWESET=4.0
    TSSET = -1.079-.02467*QC-.0108*QH-.005824*TWFRFT+.9067*Tweth
    XTSET = TSSET
    IF (TSSET.LT.TMIN) TSSET=TMIN
  ELSE
    TSSET = TMIN
    TWESET = 2.12-.00898*QC+.0388*QH+.291*TSSET+.334*Tweth
    XTCHW = TWESET
    IF (TWESET.GT.8.0) TWFRFT=8.0
    IF (TWESET.LT.4.0) TWESET=4.0
  ENDIF
  IF (TSSET.GT.TMAX) TSSET=TMAX

```

```

C
  TSSET1 = TSSET
  TSSET2 = TSSET-0.665
  TSSET3 = TSSET+0.335

```

C\*\*\*\*\*

C END OPTIMIZED CONTROL LOGIC

C\*\*\*\*\*

C

OPTIMIZED SUPERVISORY CONTROL (OPT 2)  
 IFA ANNEX 17 - EXERCISE 3 (07/90)  
 SUPPRT.FOR146

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C

C \*\*\*\*\*

C VALUES OF INPUTS \*

C \*\*\*\*\*

C

YEAR = XIN(1)  
 MONTH = XIN(2)  
 DAY = XIN(3)  
 HOUR = XIN(4)  
 TOUT = XIN(5)  
 TROOM1 = XIN(6)  
 TROOM2 = XIN(7)  
 TROOM3 = XIN(8)  
 TPLEN1 = XIN(9)  
 TPLEN2 = XIN(10)  
 TPLEN3 = XIN(11)  
 TEX = XIN(12)  
 TFE = XIN(13)  
 TM = XIN(14)  
 TH = XIN(15)  
 THUM = XIN(16)  
 TC = XIN(17)  
 TFS = XIN(18)  
 TD1 = XIN(19)  
 TD2 = XIN(20)  
 TD3 = XIN(21)  
 TH1 = XIN(22)  
 TH2 = XIN(23)  
 TH3 = XIN(24)  
 TWB = XIN(25)  
 TWEVAP = XIN(26)  
 TWCOND = XIN(27)  
 RHOUT = XIN(28)  
 RHR1 = XIN(29)  
 RHR2 = XIN(30)  
 RHR3 = XIN(31)  
 RHP1 = XIN(32)  
 RHP2 = XIN(33)  
 RHP3 = XIN(34)  
 RHFE = XIN(35)  
 RHM = XIN(36)  
 RHHUM = XIN(37)  
 RHC = XIN(38)  
 POUT = XIN(39)  
 PROOM = XIN(40)  
 PFE = XIN(41)  
 PFS = XIN(42)  
 Tsair = XIN(43)  
 Tueth = XIN(44)  
 Ssin = XIN(45)  
 TMAX = XIN(46)  
 TMIN = XIN(47)

C

C\*\*\*\*\*

C BEGIN OPTIMIZED CONTROL LOGIC OPT 2

C\*\*\*\*\*

```

C
IF (CMBOX.GT.0.5) THEN
  TSSET = TMAX
  TUESFT = 7.316+.0549*Teair-.00995*ssair-.12153*TSSET-.1*Twath
  IF (TSSET.LT.4.) TSSET=4.
ELSE
  TUESFT = 17.534+.0914*Teair-.00296*ssair-.9163*Twath
  IF (TUESFT.GT.9.0) TUESFT=9.0
  IF (TUESFT.LT.4.0) TUESFT=4.0
  TSSET = 9.668+.0014*Teair-.00091*ssair+.1155*Twath
ENDIF
XTSSET = TSSET
IF (TSSET.GT.TMAX) TSSET=TMAX
C
  TSSET1 = TSSET
  TSSET2 = TSSET-0.665
  TSSET3 = TSSET+0.335
C
C*****
C END OPTIMIZED CONTROL LOGIC
C*****
C

```

## APPENDIX C

---

TRNSYS DECKS

NOI 187

\*\*\*\*\*

\* APPENDIX C No. 1 \*

\* I.F.A. Annex 17 \*

\* ----- \*

\* COLI INS RUII RING SYSTEM SIMULATION \*

\* ----- \*

\* EXERCISE 2 \*

\* ----- \*

\* \*\*\*\*\* \*

\* SIMULATION 0. 360. .1 \*

\* TOLERANCES .0005 .0005 \*

\* LIMITS 300 30 \*

\* WIDTH 120 \*

\* CONSTANTS 4 \*

\* PATH = 101325. \*

\* XEXT = 0.8336 WPHUM = 0.3 \*

\* \* CLOTH (100 for summer, 130 for mid seasons, 180 for winter) \*

\* \* CLOTH = 100. \*

\* \*CLOTH = 130. \*

\* \*CLOTH = 180. \*

\* \*\*\*\*\* \*

\* ----- \*

\* INPUT BLOCK 1 \*

\* ----- \*

\* \*\*\*\*\* \*

\* UNIT 1 TYPE 9 METEOROLOGICAL DATA READER \*

\* \*\*\*\*\* \*

\* PARAMETERS 4 \*

\* 12 0.5 12 0 \*

\* \*\*\*\*\* \*

\* UNIT 2 TYPE 14 OCCUPANCY HOURLY PROFILE 1 \*

\* \*\*\*\*\* \*

\* PARAMETERS 24 \*

\* 0. 0. 8. 0. 8. \*

\* 4. 10. 4. 10. 12. \*

\* 12. 12. 12. 22. 14. \*

\* 22. 14. 4. 14. 4. \*

\* 16. 0. 24. 0. \*

\* \*\*\*\*\* \*

\* UNIT 3 TYPE 14 OCCUPANCY HOURLY PROFILE 2 \*

\* \*\*\*\*\* \*

\* PARAMETERS 20 \*

\* 0. 0. 8. 0. 8. \*

\* 18. 12. 18. 12. 14. \*

\* 14. 14. 16. 12. 17. \*

\* 12. 17. 0. 24. 0. \*

\* \*\*\*\*\* \*

\* UNIT 4 TYPE 14 OCCUPANCY HOURLY PROFILE 3 \*

\* \*\*\*\*\* \*

\* \*\*\*\*\* \*

\* UNIT 4 TYPE 14 OCCUPANCY HOURLY PROFILE 3 \*

\* \*\*\*\*\* \*

\* \*\*\*\*\* \*

\* \*\*\*\*\* \*

\* \*\*\*\*\* \*

\* \*\*\*\*\* \*

\* \*\*\*\*\* \*

\* \*\*\*\*\* \*

\* \*\*\*\*\* \*

\* \*\*\*\*\* \*

PARAMETERS 20

0.	0.	8.	0.	8.
20.	12.	20.	12.	4.
14.	4.	14.	14.	16.
14.	16.	0.	24.	0.

\*

\*\*\*\*\*

UNIT 5 TYPE 14 LIGHTING HOURLY PROFILE 1

\*\*\*\*\*

PARAMETERS 24

0.	0.	8.	0.	8.
10.	10.	10.	10.	20.
12.	20.	12.	35.	14.
35.	14.	10.	16.	10.
16.	0.	24.	0.	

\*

\*\*\*\*\*

UNIT 6 TYPE 14 LIGHTING HOURLY PROFILE 2

\*\*\*\*\*

PARAMETERS 12

0.	0.	8.	0.	8.
35.	16.	35.	16.	0.
24.	0.			

\*

\*\*\*\*\*

UNIT 7 TYPE 14 LIGHTING HOURLY PROFILE 3

\*\*\*\*\*

PARAMETERS 20

0.	0.	8.	0.	8.
35.	12.	35.	12.	15.
14.	15.	14.	20.	16.
20.	16.	0.	24.	0.

\*

\*\*\*\*\*

UNIT 8 TYPE 14 EQUIPMENT HOURLY PROFILE 1

\*\*\*\*\*

PARAMETERS 24

0.	0.	8.	0.	8.
2.	11.	2.	11.	7.5
12.	7.5	12.	10.	14.
10.	14.	2.	16.	2.
16.	0.	24.	0.	

\*

\*\*\*\*\*

UNIT 9 TYPE 14 EQUIPMENT HOURLY PROFILE 2

\*\*\*\*\*

PARAMETERS 12

0.	0.	8.	0.	8.
7.5	16.	7.5	16.	0.
24.	0.			

\*

\*\*\*\*\*

UNIT 10 TYPE 14 EQUIPMENT HOURLY PROFILE 3

\*\*\*\*\*

PARAMETERS 20

0.	0.	8.	0.	8.
5.	12.	5.	12.	1.5
14.	1.5	14.	3.	16.
3.	16.	0.	24.	0.

\*

```

*****
UNIT 11      TYPE 33      PSYCHROMETRICS (outdoor)
*****

```

```

PARAMETERS  1
1
INPUTS      3
1.5         1.6         0.0
12.85      99.         PATM

```

```

*
*****
*
*           -----
*           | BUILDING BLOCK 1 |
*           -----
*
*****
*

```

```

*****
UNIT 13      TYPE 10      BUILDING
*****

```

```

INPUTS      34
39.1        40.1        41.1        39.2        40.2
41.2        39.4        40.4        41.4        0.0
1.7         1.8         1.9         1.10        1.11
1.12        2.1         3.1         4.1         5.1
6.1         7.1         8.1         9.1         10.1
33.8        34.8        35.8        1.5         11.2
0.0         0.0         0.0         50.8
0.          0.          0.          0.          0.
0.          0.          0.          0.          PATM
11.78       11.78       11.78       11.78       11.78
11.78       0.          0.          0.          0.
0.          0.          0.          0.          0.
0.          0.          0.          12.85       9.131F-03
0.5         0.5         0.5         0.9
DERIVATIVES 18
20.         21.         20.         21.         20.
21.         20.         21.         20.         21.
20.         21.         9.F-03      9.F-03      9.F-03
9.F-03      9.F-03      9.E-03

```

```

*
*****
UNIT 14      TYPE 33      PSYCHROMETRICS (room 1)
*****

```

```

PARAMETERS  1
2
INPUTS      3
13.1        13.13       0.0
21.         - 9.F-03    PATM

```

```

*
*****
UNIT 15      TYPE 33      PSYCHROMETRICS (room 2)
*****

```

```

PARAMETERS  1
2
INPUTS      3
13.5        13.15       0.0
21.         9.F-03     PATM

```

```

*
*****
UNIT 16      TYPE 33      PSYCHROMETRICS (room 3)
*****

```

```

PARAMETERS 1
2
INPUTS      3
13.9        13.17      0.0
21.         9.F-03     PATH

```

```

*
*****
UNIT 17      TYPE 33      PSYCHROMETRICS (plenum 1)
*****

```

```

PARAMETERS 1
2
INPUTS      3
13.3        13.14      0.0
21.         9.E-03     PATH

```

```

*
*****
UNIT 18      TYPE 33      PSYCHROMETRICS (plenum 2)
*****

```

```

PARAMETERS 1
2
INPUTS      3
13.7        13.16      0.0
21.         9.F-03     PATH

```

```

*
*****
UNIT 19      TYPE 33      PSYCHROMETRICS (plenum 3)
*****

```

```

PARAMETERS 1
2
INPUTS      3
13.11       13.18      0.0
21.         9.F-03     PATH

```

```

*
*****
*           -----
*           | CONTROLIER BLOCK I |
*           -----
*
*****

```

```

*****
UNIT 51      TYPE 44      CONVERGENCE PROMOTER
*****

```

```

PARAMETERS 1
0
INPUTS      2
13.1        51.1,
0.          0.

```

```

*
*****
UNIT 52      TYPE 44      CONVERGENCE PROMOTER
*****

```

```

PARAMETERS 1
0
INPUTS      2
13.5        52.1
0.          0.

```

```

*
*****
UNIT 53      TYPE 44      CONVERGENCE PROMOTER
*****

```

```

PARAMETERS 1
0
INPUTS 2
13.9 53.1
0. 0.

```

```

*
*****
UNIT 54 TYPE 44 CONVERGENCE PROMOTER
*****

```

```

PARAMETERS 1
0
INPUTS 2
32.1 54.1
0. 0.

```

```

*
*****
UNIT 55 TYPE 44 CONVERGENCE PROMOTER
*****

```

```

PARAMETERS 1
50
INPUTS 2
45.1 55.1
0. 0.

```

```

*
*****
UNIT 56 TYPE 44 CONVERGENCE PROMOTER
*****

```

```

PARAMETERS 1
0
INPUTS 2
15.4 56.1
0. 0.

```

```

*
*****
UNIT 50 TYPE 66 SUPERVISOR CONTROLLER
*****

```

```

INPUTS 42
1.1 1.2 1.3 1.4 1.5
51.1 52.1 53.1 13.3 13.7
13.11 21.1 23.1 22.1 29.1
30.1 31.1 54.1 33.1 34.1
35.1 36.1 37.1 38.1 43.1
44.1 55.1 1.6 14.4 56.1
16.4 17.4 18.4 19.4 23.6
22.4 30.6 31.8 0.0 0.0
23.3 32.3
61. 8. 15. 0. 12.85
21. 21. 21. 21. 21.
21. 0. 0. 0. 0.
0. 0. 0. 0. 0.
0. 0. 99. 58.10 58.10
58.10 58.10 58.10 58.10 0.
0. 0. 0. PATH PATH
PATH PATH

```

```

*trace 110.7 110.9
*****
* ----- *
* | PLANT BLOCK | *
* ----- *

```

\*\*\*\*\*

\*

\*\*\*\*\*

UNIT 20 TYPE 15 EXTRACT AIR PRESSURE AND

\*\*\*\*\*

PARAMETERS 21

0	0	0	0	3
3	-21	-31	-31	1
-1	XEXT	1	4	-4
0	0	0	3	3
-4				

INPUTS 7

0.0	13.19	13.20	13.21	50.12
50.13	50.14			
PATH	0.	0.	0.	0.
0.	0.			

\*

\*\*\*\*\*

UNIT 21 TYPE 58 FLOW MERGE

\*\*\*\*\*

PARAMETERS 1

3.				
INPUTS	10			
13.3	13.14	13.19	13.7	13.16
13.20	13.11	13.18	13.21	20.1
21.	9.E-03	0.	21.	9.E-03
0.	21.	9.E-03	0.	PATH

\*

\*\*\*\*\*

UNIT 22 TYPE 54 MIXING BOX

\*\*\*\*\*

PARAMETERS 13

0.	0.	0.	.23674E07	.23674E07
.23674E07	.47348E05	.47348E05	.47348E05	0.
0.	0.	0.		
INPUTS	8			
1.5	11.2	23.1	23.2	0.0
20.2	23.4	50.15		
12.85	9.131E-03	0.	0.	PATH
0.	0.	0.		

\*

\*\*\*\*\*

UNIT 23 TYPE 53 RETURN FAN

\*\*\*\*\*

PARAMETERS 18

.90	.90	1	1	.85
16.74	13.95	50.	0	0.
0	1	1	1	0.
0.	0.	1.6667		
INPUTS	8			
50.3	21.1	21.2	21.3	21.4
22.8	0.0	0.0		
0.	0.	0.	PATH	0.
PATH	49.1667	0.		

\*

\*\*\*\*\*

UNIT 24 TYPE 54 FILTER

\*\*\*\*\*

PARAMETERS 3

0.	0.	0.
----	----	----

INPUTS	4			
22.1	22.2	22.3	22.4	
0.	0.	PATH	0.	

\*

\*\*\*\*\*  
 UNIT 25 TYPE 57 HYDRAULIC CIRCUIT OF HEATING COIL  
 \*\*\*\*\*

PARAMETERS	23			
1.	1.	1.	0.	29.0
29.0	0.58	0.58	0.	0.384E9
0.386E9	0.386E9	7.2E-3	.15776F6	.27702F7
-.11089E10	.47677	.15114E3	-.63912E4	0.
0.	0.	0.		
INPUTS	4			
50.17	42.1	29.5	50.22	
0.	0.	0.	0.	

\*

\*\*\*\*\*  
 UNIT 26 TYPE 15 HYDRAULIC CIRCUIT OF HUMIDIFIER  
 \*\*\*\*\*

PARAMETERS	17			
0	-21	0	-1	80.
1	-1	10.	3	-31
1	-4	-1	WPHUM	-31
1	-4			
INPUTS	2			
50.19	50.23			
0.	0.			

\*

\*\*\*\*\*  
 UNIT 27 TYPE 57 HYDRAULIC CIRCUIT OF COOLING COIL  
 \*\*\*\*\*

PARAMETERS	23			
1.	1.	1.	0.	49.5
49.5	0.91	0.91	0.	0.132E+9
0.132E+9	0.132E+9	12.3E-3	.15776F6	0.16216F7
-.37997E9	.81449	.15114E3	-.37353F4	0.
0.	0.	0.		
INPUTS	4			
50.20	44.1	31.5	50.24	
0.	0.	0.	0.	

\*

\*\*\*\*\*  
 UNIT 28 TYPE 57 HYDRAULIC CIRCUIT OF REHEAT COILS  
 \*\*\*\*\*

PARAMETERS	51			
3.	1.	1.	0.	4.56
4.56	0.0912	0.0912	0.	0.156E11
0.156E11	1.	1.	0.	4.56
4.56	0.0912	0.0912	0.	0.156E11
0.156E11	1.	1.	0.	4.56
4.56	0.0912	0.0912	0.	0.156E11
0.156E11	0.173E10	3.4E-3	.15776F6	.58662F7
-.49728E10	.22514	.15114E3	-.13513E5	0.
0.	0.	0.	0.	0.
0.	0.	0.	0.	0.
0.				
INPUTS	8			
50.18	42.1	36.5	50.26	37.5
50.27	38.5	50.28		

0. 0. 0. 0. 0.  
0. 0. 0.

\*

\*\*\*\*\*  
UNIT 29 TYPE 51 HEATING COIL  
\*\*\*\*\*

PARAMETERS 16  
0. 2. 69. 69. 88.9E-3  
2.629 2.692 21.96E-3 1.0E-3 1.  
3.227E-3 0.406E-3 1. 0.1036 -0.35804  
0.28905  
INPUTS 6  
24,1 24,2 24,3 24,4 25,3  
25,4  
0. 0. PATH 0. 0.  
0.

\*

\*\*\*\*\*  
UNIT 30 TYPE 52 HUMIDIFIER  
\*\*\*\*\*

PARAMETERS 1  
0.  
INPUTS 5  
29,1 29,2 29,3 29,4 26,1  
0. 0. PATH 0. 0.

\*

\*\*\*\*\*  
UNIT 31 TYPE 51 COOLING COIL  
\*\*\*\*\*

PARAMETERS 16  
0. 6. 69. 69. 266.7E-3  
2.629 3.286 21.96E-3 1.0E-3 1.  
3.227E-3 0.406E-3 1. 0.1036 -0.35804  
0.92496  
INPUTS 6  
30,1 30,2 30,3 30,4 27,3  
27,4  
0. 0. PATH 0. 0.  
0.

\*

\*\*\*\*\*  
UNIT 32 TYPE 53 SUPPLY FAN  
\*\*\*\*\*

PARAMETERS 18  
.90 .90 1 1 .94  
18.6 46.5, 50. 0 0  
0 1 1 1 0.  
0. 0. 1.6667  
INPUTS 8  
50,2 31,1 31,2 31,3 31,4  
50,7 0,0 0,0  
0. 0. 0. PATH 0.  
PATH 49.1667 0.

\*

\*\*\*\*\*  
UNIT 33 TYPE 55 DUCT 1  
\*\*\*\*\*

PARAMETERS 5  
0.7 124. 9.F-3 5.77E-3 2.6015  
INPUTS 5

32,1	32,2	32,3	50,12	13,3
0.	0.	PATH	0.	21.

\*  
 \*\*\*\*\*

UNIT 34 TYPE 55 DUCT 2  
 \*\*\*\*\*

PARAMETERS	5			
0.7	124.	9.E-3	5.77E-3	2.6015
INPUTS	5			
32,1	32,2	32,3	50,13	13,7
0.	0.	PATH	0.	21.

\*  
 \*\*\*\*\*

UNIT 35 TYPE 55 DUCT 3  
 \*\*\*\*\*

PARAMETERS	5			
0.7	124.	9.E-3	5.77E-3	2.6015
INPUTS	5			
32,1	32,2	32,3	50,14	13,11
0.	0.	PATH	0.	21.

\*  
 \*\*\*\*\*

UNIT 36 TYPE 51 REHEATING COIL 1  
 \*\*\*\*\*

PARAMETERS	16			
0.	2.	40.	40.	88.9E-3
1.524	1.575	17.17E-3	1.0E-3	1
3.227E-3	0.406E-3	1.	0.1036	-0.35804
2.6015				
INPUTS	6			
33,1	33,2	33,3	33,4	28,3
28,4				
0.	0.	PATH	0.	0.
0.				

\*  
 \*\*\*\*\*

UNIT 37 TYPE 51 REHEATING COIL 2  
 \*\*\*\*\*

PARAMETERS	16			
0.	2.	40.	40.	88.9E-3
1.524	1.575	17.17E-3	1.0E-3	1
3.227E-3	0.406E-3	1.	0.1036	-0.35804
2.6015				
INPUTS	6			
34,1	34,2	34,3	34,4	28,6
28,7				
0.	0.	PATH	0.	0.
0.				

\*  
 \*\*\*\*\*

UNIT 38 TYPE 51 REHEATING COIL 3  
 \*\*\*\*\*

PARAMETERS	16			
0.	2.	40.	40.	88.9E-3
1.524	1.575	17.17E-3	1.0E-3	1
3.227E-3	0.406E-3	1.	0.1036	-0.35804
2.6015				
INPUTS	6			
35,1	35,2	35,3	35,4	28,9
28,10				

```

0.          0.          PATH          0.          0.
0.
*
*****
UNIT 39      TYPE 64      UAU BOX 1
*****
PARAMETERS   3
0.          .24955F6      .4991F4
INPUTS       5
36,1        36,2        36,3        36,4        0,0
0.          0.          PATH          0.          PATH
    
```

```

*
*****
UNIT 40      TYPE 64      UAU BOX 2
*****
PARAMETERS   3
0.          .24955E6      .4991F4
INPUTS       5
37,1        37,2        37,3        37,4        0,0
0.          0.          PATH          0.          PATH
    
```

```

*
*****
UNIT 41      TYPE 64      UAU BOX 3
*****
PARAMETERS   3
0.          .24955F6      .4991F4
INPUTS       5
38,1        38,2        38,3        38,4        0,0
0.          0.          PATH          0.          PATH
    
```

```

*
*****
UNIT 42      TYPE 45      HYDRAULIC CIRCUIT OF ROTLER
*****
PARAMETERS   2
15.7        0.450
INPUTS       6
50,16       43,1        25,1        28,1        25,2
28,2
0.          0.          0.          0.          0.
0.
    
```

```

*
*****
UNIT 43      TYPE 59      ROTLER
*****
PARAMETERS   18
8.2E-3      0.13      0.37194      0.5      0.005
0.03993     0.02289   0.5          8.2E-3    36.
0.13        3.294      2.10551     0.987     2.12514
4.187      1.880      42875.
INPUTS       5
50,4        42,2        42,3        0,0        50,9
0.          0.          0.          15.        0.
    
```

```

*
*****
UNIT 44      TYPE 60      CHILLER
*****
PARAMETERS   12
2.          0.25      370.P(450)  85.8      14.76
6.0         4.0      4.0        24.        36.
55.         1.
    
```

*Init Rev. 370.P(450)*  
*Design Cooling Capacity*  
*Init Rev. (0.0)*  
*Design Compressor Power*

INPUTS	6				
50.5	27.1	27.2	45.1	45.2	
50.10					110
0.	0.	0.	0.	0.	
0.					

\*trace 110.7 110.9

\*\*\*\*\*  
 UNIT 45 TYPE 57 HYDRAULIC CIRCUIT OF COOLING TOWER  
 \*\*\*\*\*

PARAMETERS	23				
1.	2.	1.	0.	72.9	
72.9	1.46	1.46	0.	0.610E8	
0.610E8	0.610E8	18.1E-3	.15774FA	.110194E7	
-.17547E9	.11984E1	.15114E3	-.25384E4	0.	
0.	0.	0.			
INPUTS	4				
50.21	44.3	46.1	50.25		
0.	0.	0.	0.		

\*  
 \*\*\*\*\*  
 UNIT 46 TYPE 61 COOLING TOWER  
 \*\*\*\*\*

PARAMETERS	16				
1.	2.	0.	22.	35.	
29.	12.	19.1E-3	26.	12.	
10.3E-3	0.	0.	6.5	12.	
1.					
INPUTS	6				
50.6	45.3	11.6	0.0	45.4	
50.11					
0.	0.	12.76	PATM	0.	
0.					

\*  
 \*\*\*\*\*  
 \*  
 \* ----- \*  
 \* I OUTPUT BLOCK I \*  
 \* ----- \*  
 \*\*\*\*\*

\*\*\*\*\*  
 \*UNIT 57 TYPE 63 PMU - PPD (room1)  
 \*\*\*\*\*

PARAMETERS	3				
0.070	0.0	CLRTH			
INPUTS	4				
13.1	13.1	0.0	14.7		
21.	21.	0.2	1445.25		

\*\*\*\*\*  
 \*UNIT 58 TYPE 63 PMU - PPD (room2)  
 \*\*\*\*\*

PARAMETERS	3				
0.070	0.0	CLRTH			
INPUTS	4				
13.5	13.5	0.0	15.7		
21.	21.	0.2	1445.25		

\*\*\*\*\*  
 \*UNIT 59 TYPE 63 PMU - PPD (room3)  
 \*\*\*\*\*

```

*      PARAMETERS      3
*      0.070          0.0          CLOTH
*      INPUTS          4
*      13.9           13.9          0.0          16.7
*      21.            21.            0.2          1445.25
*

```

```

*****
UNIT 60      TYPE 15      CALCULATION OF ELECTRICAL POWER [kW]
*****

```

```

PARAMETERS      22
0                0                0                0                3
3                -3               0                0                0
0                0                0                3                3
3                3                3                -3               3
3                -4
INPUTS           10
44.8            32.11            23.11            46.8            42.4
25.6            29.12            26.2             27.6            45.6
0.              0.              0.              0.              0.
0.              0.              0.              0.              0.

```

```

*
*****
UNIT 61      TYPE 15      CALCULATION OF TOTAL COST [CU/£]
*****

```

```

PARAMETERS      13
0                -1              27.F-06         1                0
-1              42875.           2               -1              .389
1                3               -4
INPUTS           2
60.3            43.4
0.              0.

```

```

*
*****
***** DAILY RESULTS *****
*****

```

```

*****
UNIT 63      TYPE 15      UNIT CONVERSION (from kW to M.J/h)
*****

```

```

PARAMETERS      43
-1              3.6             -31             0               -31
1                -4             0              -31             1
-4              0              -31            1              -4
0              -31            1              -4             0
-31            1              -4             0              -31
1                -4             0              -31             1
-4              0              -31            1              -4
0              -31            1              -4             0
-31            1              -4
INPUTS           10
29.12          31.12           36.12          37.12          38.12
44.7           44.9           46.7           43.3           43.4
0.             0.             0.             0.             0.
0.             0.             0.             0.             0.

```

```

*
*****
UNIT 64      TYPE 15      UNIT CONVERSION (from kW to M.J/h)
*****

```

```

PARAMETERS      43
-1              3.6             -21             0               -31

```

1	-4	0	-31	1
-4	0	-31	1	-4
0	-31	1	-4	0
-31	1	-4	0	-31
1	-4	0	-31	1
-4	0	-31	1	-4
0	-31	1	-4	0
-31	1	-4		
INPUTS	10			
44.8	32.11	23.11	46.8	42.4
25.6	28.12	26.2	27.6	45.6
0.	0.	0.	0.	0.
0.	0.	0.	0.	0.

\*\*\*\*\*

UNIT 65 TYPE 24 QUANTITY INTEGRATOR (daily results)

\*\*\*\*\*

PARAMETERS 1

24.

INPUTS 10

63.1	63.2	63.3	63.4	63.5
63.6	63.7	63.8	63.9	63.10
0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0

\*\*\*\*\*

UNIT 64 TYPE 24 QUANTITY INTEGRATOR (daily results)

\*\*\*\*\*

PARAMETERS 1

24.

INPUTS 10

64.1	64.2	64.3	64.4	64.5
64.6	64.7	64.8	64.9	64.10
0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0

\*\*\*\*\*

UNIT 67 TYPE 15 CALCULATION OF ELECTRICAL CONSUMPTION [MJ]

\*\*\*\*\*

PARAMETERS 22

0	0	0	0	3
3	-3	0	0	0
0	0	0	3	3
3	3	3	-3	3
3	-4			

INPUTS 10

66.1	66.2	66.3	66.4	66.5
66.6	66.7	66.8	66.9	66.10
0.	0.	0.	0.	0.
0.	0.	0.	0.	0.

\*\*\*\*\*

UNIT 68 TYPE 15 CALCULATION OF TOTAL COST [FCU]

\*\*\*\*\*

PARAMETERS 13

0	-1	27.F-03	1	0
-1	42.975	2	-1	.389
1	3	-4		

INPUTS 2

67,3            65,10  
0.                0.

\*  
\*\*\*\*\*  
\*\*\*\*\* MEAN HOURLY RESULTS \*\*\*\*\*  
\*\*\*\*\* ----- \*\*\*\*\*

\*\*\*\*\*  
\*UNIT 70            TYPE 24            QUANTITY INTEGRATOR (hourly results)  
\*\*\*\*\*  
\*            PARAMETERS            1  
\*            1.  
\*            INPUTS                10  
\*            29,12            31,12            36,12            37,12            38,12  
\*            44,7            44,9            46,7            43,3            43,4  
\*            0.            0.            0.            0.            0.  
\*            0.            0.            0.            0.            0.  
\*

\*\*\*\*\*  
\*UNIT 71            TYPE 24            QUANTITY INTEGRATOR (hourly results)  
\*\*\*\*\*  
\*            PARAMETERS            1  
\*            1.  
\*            INPUTS                10  
\*            44,8            32,11            23,11            46,8            42,4  
\*            25,6            28,12            26,2            27,6            45,6  
\*            0.            0.            0.            0.            0.  
\*            0.            0.            0.            0.            0.  
\*

\*\*\*\*\*  
\*UNIT 72            TYPE 24            QUANTITY INTEGRATOR (hourly results)  
\*\*\*\*\*  
\*            PARAMETERS            1  
\*            1.  
\*            INPUTS                10  
\*            1,5            13,1            13,5            13,9            13,3  
\*            13,7            13,11            21,1            23,1            22,1  
\*            0.            0.            0.            0.            0.  
\*            0.            0.            0.            0.            0.  
\*

\*\*\*\*\*  
\*UNIT 73            TYPE 24            QUANTITY INTEGRATOR (hourly results)  
\*\*\*\*\*  
\*            PARAMETERS            1  
\*            1.  
\*            INPUTS                10  
\*            29,1            30,1<sup>7</sup>            31,1            32,1            33,1  
\*            34,1            35,1            36,1            37,1            38,1  
\*            0.            0.            0.            0.            0.  
\*            0.            0.            0.            0.            0.  
\*

\*\*\*\*\*  
\*UNIT 74            TYPE 24            QUANTITY INTEGRATOR (hourly results)  
\*\*\*\*\*  
\*            PARAMETERS            1  
\*            1.  
\*            INPUTS                10  
\*            11,2            13,13            13,15            13,17            13,14  
\*            13,16            13,18            22,2            30,2            31,2  
\*            0.            0.            0.            0.            0.  
\*

\* 0. 0. 0. 0. 0.

\*\*\*\*\*  
\*UNIT 75 TYPE 24 QUANTITY INTEGRATOR  
\*\*\*\*\*

\* PARAMETERS 1  
\* 1.  
\* INPUTS 10  
\* 60,3 61,1 14,4 15,4 16,4  
\* 50,12 50,13 50,14 20,2 23,2  
\* 0. 0. 0. 0. 0.  
\* 0. 0. 0. 0. 0.  
\*

\*\*\*\*\*  
\*UNIT 74 TYPE 24 QUANTITY INTEGRATOR  
\*\*\*\*\*

\* PARAMETERS 1  
\* 1.  
\* INPUTS 9  
\* 14,3 15,3 16,3 17,3 18,3  
\* 19,3 17,4 18,4 19,4  
\* 0. 0. 0. 0. 0.  
\* 0. 0. 0. 0.  
\*

\*\*\*\*\*  
\*UNIT 77 TYPE 24 QUANTITY INTEGRATOR  
\*\*\*\*\*

\* PARAMETERS 1  
\* 1.  
\* INPUTS 10  
\* 57,1 58,1 59,1 57,2 58,2  
\* 59,2 60,1 60,2 21,4 22,9  
\* 0. 0. 0. 0. 0.  
\* 0. 0. 0. 0.  
\*

UNIT 58 TYPE 15 CALCULATION OF SYSTEM LOAD

\*\*\*\*\*  
PARAMETERS 22  
0 7 -4 0 0 3 0 3 -3 0 3 -4 0 0 3 -4 0 0 3 0 3 -4  
INPUTS 10  
31,12 36,12 37,12 38,12 29,12 43,4 60,3 13,22 13,24 13,26  
0. 0. 0. 0. 0. 0. 0. 0. 0. 0.  
\*

\*\*\*\*\*  
UNIT 59 TYPE 15 CALCULATION OF COMPONENT POWERS  
\*\*\*\*\*

PARAMETERS 22  
0 0 3 0 3 -4 0 0 3 0 3 0 3 0 3 -4 0 7 -4 0 7 -4  
INPUTS 10  
32,11 23,11 46,8 42,4 25,6 28,12 27,6 45,6 31,13 31,14  
0. 0. 0. 0. 0. 0. 0. 0. 0.  
\*\*\*\*\*

\*\*\*\*\*  
\*\*\*\*\* PRINTERS \*\*\*\*\*  
\*\*\*\*\* ----- \*\*\*\*\*  
\*

\*\*\*\*\*  
\*UNIT 57 TYPE 25 PRINTER 2 (graphs)  
\*\*\*\*\*

\* PARAMETERS 4  
\* 0,1 80 91 20

```

*      INPUTS          9
*      40,1    40,2    40,4    13,20    13,32    13,35
*      13,38    21,4    21,1
*      Tain2    HRin2    Min2    Maxt2    Flux2    Sens2
*      Lat2    Mext    Text
*

```

```

*****

```

```

*UNIT 59      TYPE 25      PRINTER 3 (graphs)

```

```

*****

```

```

*      PARAMETERS      4
*      0,1      144.      168.      81
*      INPUTS      10
*      44,8      32,11      23,11      43,4      42,4
*      25,6      28,12      43,4      27,6      45,6
*      Wchill      Wfans      Wpane      Wboil      Wchill
*      Wwheat      Wwht      Wboil      Wcool      Wtowe
*

```

```

*****

```

```

*UNIT 57      TYPE 25      PRINTER 5 (hourly results)

```

```

*****

```

```

*      PARAMETERS      4
*      1      144.      360.      82
*      INPUTS      10
*      70,1      70,2      70,3      70,4      70,5
*      70,6      70,7      70,8      70,9      70,10
*      HEATH0      HEATH0      HEATH1      HEATH2      HEATH3
*      HEATEv      HEATEd      HEATet      HEATb      Wboil
*

```

```

*****

```

```

*UNIT 74      TYPE 25      PRINTER 6 (hourly results)

```

```

*****

```

```

*      PARAMETERS      4
*      1      168.      360.      51
*      INPUTS      10
*      71,1      71,2      71,3      71,4      71,5
*      71,6      71,7      71,8      71,9      71,10
*      Wchill      Wfans      Wpane      Wtower      Wboil
*      Wwheat      Wwht      Wwumi      Wcool      Wtowe
*

```

```

*****

```

```

*UNIT 74      TYPE 25      PRINTER 7 (hourly results)

```

```

*****

```

```

*      PARAMETERS      4
*      1      336.      360.      71
*      INPUTS      10
*      72,1      72,2      72,3      72,4      73,4
*      72,6      72,7      72,8      72,9      72,10
*      Tout      Troom1      Troom2      Troom3      Tsup
*      Tain2      Tain3      Textr      Tfans      Tmix
*

```

```

*****

```

```

*UNIT 83      TYPE 25      PRINTER 8 (hourly results)

```

```

*****

```

```

*      PARAMETERS      4
*      1      337.      360.      9
*      INPUTS      10
*      73,1      73,2      73,3      73,4      73,5
*      73,6      73,7      73,8      73,9      73,10
*      Theat      Thumid      Tcool      Tfans      Tduct1
*      Tduct2      Tduct3      Theat1      Theat2      Theat3
*

```

```

*
*****
*UNIT 80      TYPE 25      PRINTER 9 (hourly results)
*****
*   PARAMETERS      4
*   1                337.      360.      6
*   INPUTS          10
*   74,1             74,2      74,3      74,4      74,5
*   74,6             74,7      74,8      74,9      74,10
*   HUMR0            HUMRr1     HUMRr2     HUMRr3     HUMRr1
*   HUMR=2           HUMR=3     HUMR=      HUMR=      HUMR=0
*

```

```

*****
*UNIT 81      TYPE 25      PRINTER 10 (hourly results)
*****
*   PARAMETERS      4
*   1                337.      360.      7
*   INPUTS          10
*   75,1             75,2      75,3      75,4      75,5
*   75,6             75,7      75,8      75,9      75,10
*   Hselect          Cost       RHr=1     RHr=2     RHr=3
*   Hvac1            Hvac2      Hvac3     Hsupply   HUMRr=
*

```

```

*****
*UNIT 82      TYPE 25      PRINTER 11 (hourly results)
*****
*   PARAMETERS      4
*   1                337.      360.      8
*   INPUTS          9
*   76,1             76,2      76,3      76,4      76,5
*   76,6             76,7      76,8      76,9
*   ENTHr1           ENTHr2     ENTHr3     FNTHr1     ENTHr2
*   ENTH=3           RH=1       RH=2       RH=3
*

```

```

*****
*UNIT 83      TYPE 25      PRINTER 12 (hourly results)
*****
*   PARAMETERS      4
*   1                337.      360.      9
*   INPUTS          10
*   77,1             77,2      77,3      77,4      77,5
*   77,6             77,7      77,8      77,9      77,10
*   PMUr1            PMUr2     PMUr3     PPDn1     PPDn2
*   PPDn3            Wfantot    Wpumptot  Mextract  Mfresh
*

```

```

*****
*UNIT 74      TYPE 25      PRINTER 13 (daily results)
*****
*   PARAMETERS      4
*   74                192.      360.      61
*   INPUTS          10
*   65,1             65,2      65,3      65,4      65,5
*   65,6             65,7      65,8      65,9      65,10
*   HEATH0           HEATc0     HEATH1     HEATH2     HEATH3
*   HEATev           HEATcd    HEATct     HEATH      Wboil
*

```

```

*****
*UNIT 75      TYPE 25      PRINTER 14 (daily results)
*****
*   PARAMETERS      4

```

```

*      24      192.      360.      62
*      INPUTS      10
*      66,1      66,2      66,3      66,4      66,5      117
*      66,6      66,7      66,8      66,9      66,10
*      Wchill      Wfans      Wpane      Wtower      Wboil
*      Wwheat      Wwrt      Wwumi      Wwcool      Wwtove

```

```

*****
UNIT 74      TYPE 25      PRINTER 1 (graphs)
*****

```

```

PARAMETERS      4
0.1      80      360      41
*FORMAT
*(F10.4,9 F9.4)
INPUTS      8
58,1 59,3 59,4 44,1 32,1 13,5 13,15 50,13
Gc      Qhcoil Qscoil Tchv      Tausale Tz2      RH22      Muav2

```

```

*****

```

```

UNIT 73      TYPE 25      PRINTER 4 (graphs)
*****

```

```

PARAMETERS      4
0.1      80      360      40
INPUTS      9
58,4 44,8 43,4 59,1 59,2 58,1 29,12 58,2 37,12
POWER      Pchill Pcoil Pfans Ppump Gc      Qhcoil Qrh      Qrh2

```

```

*****

```

```

UNIT 57      TYPE 25      PRINTER 15 (daily results)
*****

```

```

PARAMETERS      4
24      0.      360.      42
INPUTS      6
67,1      67,2      66,1      67,3      65,10      68,1
Wpantot      Wpumptot      Wchill      Wwlect      Wboil      Cost

```

```

*
END

```

APPENDIX C No. 2

OPT 1 TRNSYS DECK MODIFICATIONS TO REFERENCE DECK  
 IEA ANNEX 17 EXERCISE 3 (07/90)  
 DECK.OPT1140

\*\*\*\*\*  
 UNIT 50        TYPE 6A        SUPERVISOR CONTROLLER  
 \*\*\*\*\*

INPUTS		49		
1,1	1,2	1,3	1,4	1,5
51,1	52,1	53,1	13,3	13,7
13,11	21,1	23,1	22,1	29,1
30,1	31,1	54,1	33,1	34,1
35,1	36,1	37,1	38,1	43,1
44,1	55,1	1,6	14,4	56,1
16,4	17,4	18,4	19,4	23,6
22,6	30,6	31,8	0,0	0,0
23,3	32,3	1,7	11,6	58,4
0,0	0,0	58,3	58,1	
61.	8.	15.	0.	12.85
21.	21.	21.	21.	21.
21.	0.	0.	0.	0.
0.	0.	0.	0.	0.
0.	0.	0.	0.	0.
0.	0.	99.	58.10	58.10
58.10	58.10	58.10	58.10	0.
0.	0.	0.	PATM	PATM
PATM	PATM	20.	13.	0.
13.	10.5	0.	0.	

\*\*\*\*\*  
 UNIT 58        Type 15    Calculation of QC, QH  
 \*\*\*\*\*

PARAMETERS		21																		
0	0	3	0	3	-0	3	-4	0	0	3	-4	0	7	-4	0	0	3	0	3	-4
INPUTS		10																		
29,12	36,12	37,12	38,12	43,4	60,3	31,12	13,22	13,24	13,26											
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.											

\*  
 \*\*\*\*\*

OPT 2 TRNSYS DECK MODIFICATIONS TO REFERENCE DECK  
 IEA ANNEX 17 - EXERCISE 3 (07/90)

\*

\*\*\*\*\*

UNIT 50 TYPE 66 SUPERVISOR CONTROLLER

\*\*\*\*\*

INPUTS	47				
1,1	1,2	1,3	1,4	1,5	
51,1	52,1	53,1	13,3	13,7	
13,11	21,1	23,1	22,1	29,1	
30,1	31,1	54,1	33,1	34,1	
35,1	36,1	37,1	38,1	43,1	
44,1	55,1	1,6	14,4	56,1	
16,4	17,4	18,4	19,4	23,6	
22,6	30,6	31,8	0,0	0,0	
23,3	32,3	1,7	11,6	58,4	
0,0	0,0				
61.	8.	15.	0.	12.85	
21.	21.	21.	21.	21.	
21.	0.	0.	0.	0.	
0.	0.	0.	0.	0.	
0.	0.	0.	0.	0.	
0.	0.	99.	58.10	58.10	
58.10	58.10	58.10	58.10	0.	
0.	0.	0.	PATM	PATM	
PATM	PATM	20.	13.	0.	
13.	10.				

\*trace 180. 181.

\*\*\*\*\*

UNIT 58 Type 15 Calculation of BUILDING GAINS

\*\*\*\*\*

PARAMETERS	21																			
0	0	3	0	3	0	3	-4	0	0	3	-4	0	7	-4	0	0	3	0	3	-4
INPUTS	10																			
29,12	36,12	37,12	38,12	43,4	60,3	31,12	13,22	13,24	13,26											
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.											

\*

**APPENDIX D**

---

***MINITAB COMMAND FILES and OUTPUTS***

## APPENDIX D No. 1

```
MTB > read 'c:\bob\reg41.max' c1-c10
      716 ROWS READ
* 6444 NUMBERS READ IN EXPONENTIAL NOTATION
```

ROW	C1	C2	C3	C4	C5	C6	C7	C8	C9
1	32.3	1	1	241.60	226.10	51.3600	4.500	10.87	1.329
2	32.4	1	1	241.80	224.30	50.9900	4.500	10.87	1.412
3	32.5	1	1	180.70	173.30	49.5300	4.500	10.87	1.436
4	32.6	1	1	110.20	113.90	26.5800	4.567	10.88	1.509

```
C10
 12.49  12.59  12.69  12.80  .  .  .
```

```
MTB > erase c1-c3
MTB > execute 'c:\bob\reg4com'
MTB > LET C11=C5*C5
MTB > LET C12=C7*C7
MTB > LET C13=C8*C8
MTB > LET C14=C10*C10
MTB > LET C15=C5*C7
MTB > LET C16=C5*C8
MTB > LET C17=C5*10
MTB > LET C18=C7*C8
MTB > LET C19=C7*C10
MTB > LET C20=C8*C10
MTB > END
MTB > regress c4 on 14 c5 c7 c8 c10-c20;
SUBC> residuals=c21.
```

```
*      C17 is highly correlated with other X variables
*      C17 has been removed from the equation
```

```
* NOTE *      C5 is highly correlated with other predictor variables
* NOTE *      C7 is highly correlated with other predictor variables
* NOTE *      C8 is highly correlated with other predictor variables
* NOTE *      C10 is highly correlated with other predictor variables
* NOTE *      C12 is highly correlated with other predictor variables
* NOTE *      C13 is highly correlated with other predictor variables
* NOTE *      C14 is highly correlated with other predictor variables
* NOTE *      C15 is highly correlated with other predictor variables
* NOTE *      C16 is highly correlated with other predictor variables
* NOTE *      C18 is highly correlated with other predictor variables
* NOTE *      C19 is highly correlated with other predictor variables
* NOTE *      C20 is highly correlated with other predictor variables
```

```
The regression equation is
C4 = 503 + 2.06 C5 - 64.3 C7 + 181 C8 - 189 C10 + 0.00236 C11 + 1.37 C12
      - 5.48 C13 + 3.98 C14 - 0.520 C15 + 0.0631 C16 - 7.26 C18
      + 12.6 C19 - 0.95 C20
```

Predictor	Coef	Stdev	t-ratio	p
Constant	503.4	410.3	1.23	0.220
C5	2.0585	0.5107	4.03	0.000
C7	-64.27	28.24	-2.28	0.023
C8	181.14	37.41	4.84	0.000
C10	-188.81	35.15	-5.37	0.000
C11	0.0023593	0.0004992	4.73	0.000
C12	1.373	1.454	0.94	0.345
C13	-5.481	1.459	-3.76	0.000
C14	3.982	1.062	3.75	0.000
C15	-0.51956	0.03689	-14.08	0.000
C16	0.06313	0.02723	2.32	0.021
C18	-7.257	1.336	-5.43	0.000
C19	12.624	1.516	8.33	0.000
C20	-0.955	1.617	-0.59	0.555

s = 14.48

R-sq = 87.7%

R-sq(adj) = 87.5%

## Analysis of Variance

SOURCE	DF	SS	MS	F	p
Regression	13	1052134	80933	385.90	0.000
Error	702	147229	210		
Total	715	1199363			

SOURCE	DF	SEQ SS
C5	1	644370
C7	1	27025
C8	1	23241
C10	1	243120
C11	1	48947
C12	1	2
C13	1	9314
C14	1	2372
C15	1	33553
C16	1	3855
C18	1	1691
C19	1	14569
C20	1	73

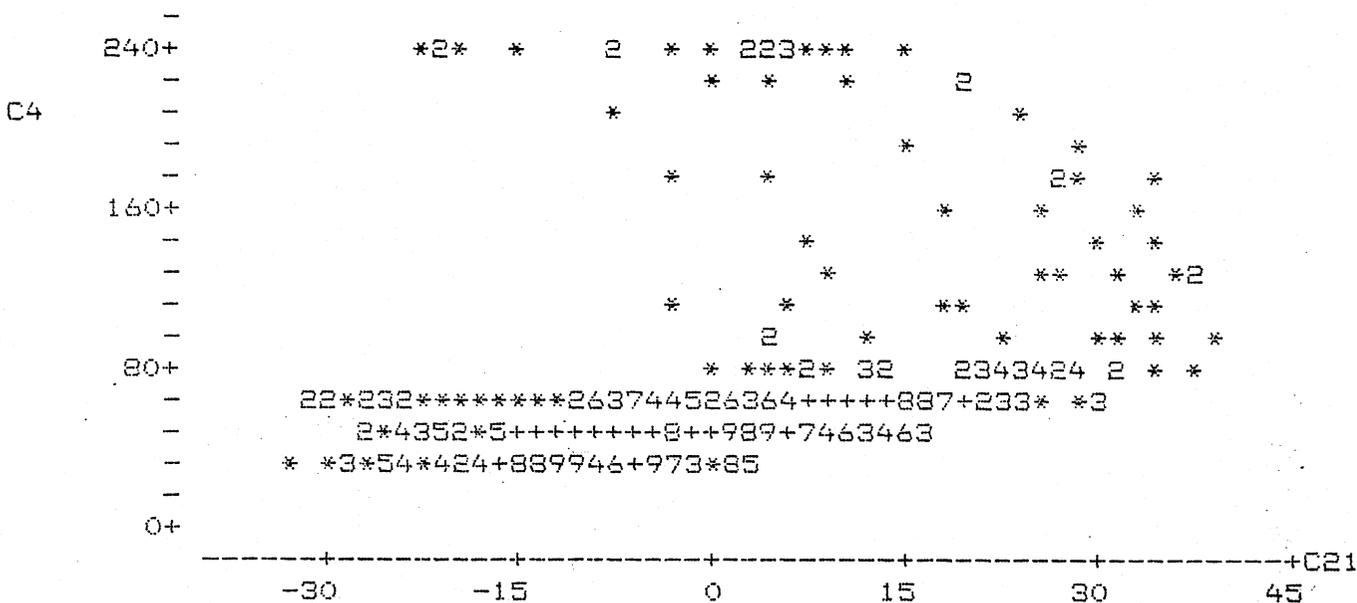
## Unusual Observations

Obs.	C5	C4	Fit	Stdev.Fit	Residual	St.Resid
1	226	241.600	263.832	5.200	-22.232	-1.64 X
2	224	241.800	256.935	4.919	-15.135	-1.11 X
3	173	180.700	184.177	4.909	-3.477	-0.26 X
4	114	110.200	113.611	4.236	-3.411	-0.25 X

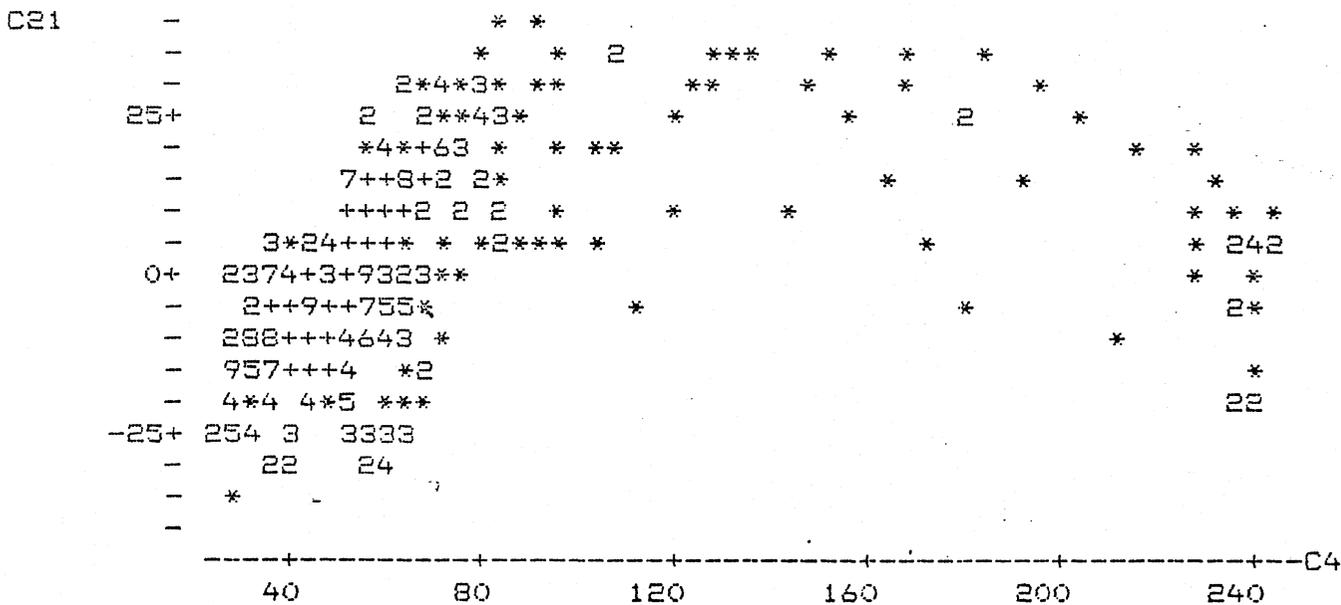
5	82	70.570	79.876	3.606	-9.306	-0.66 X
78	81	37.830	67.220	1.816	-29.390	-2.05R
89	220	239.300	258.266	3.525	-18.965	-1.35 X
93	181	196.300	167.927	2.911	28.373	2.00R
94	159	168.200	139.341	2.913	28.859	2.03R
95	144	149.600	119.958	2.899	29.642	2.09R
170	219	236.100	233.052	4.855	3.048	0.22 X
171	220	237.900	231.926	4.907	5.974	0.44 X
172	211	226.500	215.800	4.339	10.700	0.77 X
174	132	133.300	97.994	2.204	35.306	2.47R
175	99	96.090	61.870	1.508	34.220	2.38R
209	132	61.510	90.434	2.261	-28.924	-2.02R
210	133	61.210	92.370	2.105	-31.160	-2.17R
211	129	58.510	88.638	1.990	-30.128	-2.10R
212	130	58.410	90.399	1.958	-31.989	-2.23R
249	99	79.700	44.655	1.789	35.045	2.44R
250	105	85.630	47.504	1.858	38.126	2.65R
251	113	90.840	51.666	1.975	39.174	2.73R
339	241	243.100	233.401	4.619	9.699	0.71 X
340	230	233.700	218.979	3.799	14.721	1.05 X
342	138	124.300	92.218	2.455	32.082	2.25R
419	85	63.260	33.903	1.887	29.357	2.04R
421	89	67.490	38.132	1.642	29.358	2.04R
422	91	70.580	39.837	1.556	30.743	2.14R
423	93	72.570	40.994	1.568	31.576	2.19R
424	93	72.620	41.035	1.645	31.585	2.20R
425	230	241.200	237.978	3.577	3.222	0.23 X
426	232	241.200	237.275	3.674	3.925	0.28 X
427	236	241.100	234.884	3.826	6.216	0.45 X
429	182	183.200	148.462	2.043	34.738	2.42R
430	159	150.200	115.074	1.918	35.126	2.45R
431	136	126.300	89.007	1.749	37.293	2.59R
432	119	107.300	72.707	1.520	34.593	2.40R
433	109	95.450	64.170	1.376	31.280	2.17R
472	219	236.500	243.441	3.530	-6.941	-0.49 X
473	214	235.900	239.370	4.643	-3.470	-0.25 X
474	208	228.000	227.893	4.327	0.107	0.01 X
475	176	191.500	177.022	3.535	14.478	1.03 X
532	57	26.670	59.457	2.140	-32.787	-2.29R
598	140	56.120	86.634	1.962	-30.514	-2.13R
649	238	243.000	237.387	4.093	5.613	0.40 X
650	238	243.100	236.307	4.136	6.793	0.49 X
651	234	237.600	227.483	3.923	10.117	0.73 X
653	174	166.500	133.239	2.594	33.261	2.33R
654	145	135.200	97.708	2.216	37.492	2.62R
655	123	108.500	74.785	1.791	33.715	2.35R

R denotes an obs. with a large st. resid.  
 X denotes an obs. whose X value gives it large influence.

MTB > plot c4 c21



MTB > plot c21 c4



APPENDIX D No. 2

MTR > regress c4 on 20 c7-c26;  
 SUBC> residuals=c27.

- \* NOTE \* C7 is highly correlated with other predictor variables
- \* NOTE \* C8 is highly correlated with other predictor variables
- \* NOTE \* C9 is highly correlated with other predictor variables
- \* NOTE \* C10 is highly correlated with other predictor variables
- \* NOTE \* C11 is highly correlated with other predictor variables
- \* NOTE \* C12 is highly correlated with other predictor variables
- \* NOTE \* C14 is highly correlated with other predictor variables
- \* NOTE \* C15 is highly correlated with other predictor variables
- \* NOTE \* C16 is highly correlated with other predictor variables
- \* NOTE \* C18 is highly correlated with other predictor variables
- \* NOTE \* C19 is highly correlated with other predictor variables
- \* NOTE \* C20 is highly correlated with other predictor variables
- \* NOTE \* C21 is highly correlated with other predictor variables
- \* NOTE \* C22 is highly correlated with other predictor variables
- \* NOTE \* C23 is highly correlated with other predictor variables
- \* NOTE \* C24 is highly correlated with other predictor variables
- \* NOTE \* C25 is highly correlated with other predictor variables
- \* NOTE \* C26 is highly correlated with other predictor variables

The regression equation is  $C4 = 48.1 + 0.495 C7 + 1.34 C8 - 0.066 C9 + 2.13 C10 - 7.78 C11 + 0.000730 C12 - 0.000165 C13 + 0.0021 C14 + 0.987 C15 + 1.04 C16 + 0.00231 C17 - 0.00946 C18 + 0.0487 C19 - 0.0527 C20 - 0.0137 C21 + 0.0213 C22 - 0.0296 C23 + 0.0115 C24 - 0.0122 C25 - 1.79 C26$

*Power*

Predictor	Coef	Stdev	t-ratio	P
Constant	48.11	14.21	3.39	0.001
C7 <i>Qc</i>	0.49465	0.02685	18.42	0.000
C8 <i>Qh</i>	1.33796	0.04401	30.40	0.000
C9 <i>Tchw</i>	-0.0657	0.5693	-0.12	0.908
C10 <i>Tarp</i>	2.133	1.538	1.39	0.166
C11 <i>Tub</i>	-7.780	1.537	-5.06	0.000
C12 <i>Qc2</i>	0.00073032	0.00003049	23.95	0.000
C13 <i>Qc2</i>	-0.00016537	0.00004023	-4.11	0.000
C14 <i>Tchw2</i>	0.00213	0.02202	0.10	0.923
C15 <i>Tarp2</i>	0.98692	0.06498	15.19	0.000
C16 <i>Tub2</i>	1.03941	0.06984	14.88	0.000
C17 <i>Qc Qh</i>	0.0023142	0.0001345	17.20	0.000
C18 <i>QcTchw</i>	-0.009465	0.001077	-8.79	0.000
C19 <i>Qc Tarp</i>	0.048655	0.001386	35.11	0.000
C20 <i>Qc Tub</i>	-0.052662	0.002536	-20.77	0.000
C21 <i>Qh Tchw</i>	-0.013674	0.002811	-4.86	0.000
C22 <i>Qh Tarp</i>	0.021317	0.002606	8.18	0.000
C23 <i>Qh Tub</i>	-0.029625	0.003885	-7.62	0.000
C24 <i>Tchw Tarp</i>	0.01154	0.03345	0.34	0.730
C25 <i>Tchw Tub</i>	-0.01215	0.05524	-0.22	0.826
C26 <i>Tarp Tub</i>	-1.79287	0.07433	-24.12	0.000

s = 0.7673

R-sq = 99.9%

R-sq(adj) = 99.9%

126

## Analysis of Variance

SOURCE	DF	SS	MS	F	P
Regression	20	345774	17289	29364.29	0.000
Error	767	452	1		
Total	787	346226			

SOURCE	DF	SEQ SS
C7	1	374
C8	1	326673
C9	1	3696
C10	1	7557
C11	1	4517
C12	1	121
C13	1	1207
C14	1	13
C15	1	184
C16	1	2
C17	1	350
C18	1	47
C19	1	609
C20	1	77
C21	1	13
C22	1	28
C23	1	0
C24	1	2
C25	1	14
C26	1	343

## Unusual Observations

Obs.	C7	C4	Fit	Stdev. Fit	Residual	St. Resid
1	43	243.084	243.008	0.531	0.076	0.14 X
4	85	63.050	60.630	0.183	2.420	3.25R
5	92	37.672	37.717	0.229	-0.044	-0.06 X
72	157	54.379	57.616	0.107	-3.237	-4.26R
88	56	59.817	56.552	0.147	3.265	4.34R
91	28	229.046	229.233	0.490	-0.186	-0.32 X
92	29	149.577	151.031	0.311	-1.454	-2.07RX
93	29	120.729	123.175	0.264	-2.446	-3.40RX
100	42	68.035	70.767	0.152	-2.732	-3.63R
109	65	61.044	62.695	0.125	-1.651	-2.18R
112	68	60.491	57.464	0.117	3.027	3.99R
150	140	65.497	63.592	0.125	1.904	2.52R
179	39	167.377	168.072	0.276	-0.696	-0.97 X
184	83	64.722	63.009	0.095	1.713	2.25R
213	218	101.171	102.662	0.196	-1.491	-2.01R
235	97	65.701	63.518	0.081	2.184	2.86R
237	98	65.851	63.507	0.078	2.344	3.07R
260	60	73.979	75.967	0.178	-1.988	-2.66R
262	49	216.155	214.639	0.374	1.516	2.26RX
263	50	119.441	118.548	0.233	0.894	1.22 X
264	57	80.495	78.185	0.145	2.311	3.07R

314	108	64.138	65.752	0.088	-1.614	-2.12R
315	108	67.136	65.160	0.085	1.976	2.59R
318	113	68.035	66.078	0.084	1.958	2.57R
342	89	60.645	58.539	0.120	2.106	2.78R
351	40	236.508	236.376	0.422	0.132	0.21 X
358	109	41.950	44.144	0.098	-2.194	-2.88R
432	74	59.082	56.529	0.128	2.553	3.37R
439	54	60.797	62.534	0.199	-1.737	-2.34R
440	55	60.649	62.153	0.215	-1.504	-2.04R
441	38	209.522	208.876	0.388	0.646	0.98 X
443	51	80.570	78.127	0.124	2.443	3.23R
460	96	68.810	67.274	0.096	1.535	2.02R
520	57	198.280	197.124	0.417	1.156	1.80 X
521	58	105.527	106.793	0.229	-1.266	-1.73 X
582	103	63.326	60.822	0.092	2.503	3.29R
586	113	66.179	64.148	0.102	2.031	2.67R
587	117	67.095	64.702	0.106	2.393	3.15R
598	119	70.158	67.925	0.098	2.233	2.93R
599	103	65.105	63.118	0.101	1.987	2.61R
602	67	71.049	68.351	0.152	2.698	3.59R
607	66	88.173	90.169	0.216	-1.996	-2.71R
608	67	91.158	92.751	0.240	-1.593	-2.19RX
609	44	183.189	183.119	0.273	0.070	0.10 X
610	55	69.535	66.250	0.096	3.285	4.31R
611	87	63.723	61.726	0.094	1.997	2.62R
675	76	59.983	57.136	0.092	2.847	3.74R
677	80	61.030	58.115	0.091	2.916	3.83R
699	34	191.336	192.444	0.294	-1.108	-1.56 X
730	65	60.341	58.090	0.153	2.251	2.99R
732	64	59.478	57.350	0.172	2.128	2.85R
741	74	62.352	59.802	0.123	2.550	3.37R
758	87	62.678	60.705	0.076	1.972	2.58R
759	79	56.544	54.757	0.090	1.787	2.35R
760	79	59.737	57.048	0.098	2.689	3.53R
772	129	73.017	70.473	0.137	2.544	3.37R
774	129	73.223	70.766	0.146	2.457	3.26R
778	145	85.002	85.737	0.226	-0.734	-1.00 X
779	149	84.286	85.291	0.219	-1.005	-1.37 X
784	167	82.093	85.976	0.201	-3.883	-5.24R
787	178	87.320	87.783	0.227	-0.463	-0.63 X
788	180	87.890	88.102	0.241	-0.212	-0.29 X

R denotes an obs. with a large st. resid.

X denotes an obs. whose X value gives it large influence.



## APPENDIX D No. 3

MTR &gt; regress c4 on 20 c7-c26;

SURC&gt; residuals=c27.

\* NOTE \* C7 is highly correlated with other predictor variables  
 \* NOTE \* C8 is highly correlated with other predictor variables  
 \* NOTE \* C9 is highly correlated with other predictor variables  
 \* NOTE \* C10 is highly correlated with other predictor variables  
 \* NOTE \* C11 is highly correlated with other predictor variables  
 \* NOTE \* C12 is highly correlated with other predictor variables  
 \* NOTE \* C14 is highly correlated with other predictor variables  
 \* NOTE \* C15 is highly correlated with other predictor variables  
 \* NOTE \* C16 is highly correlated with other predictor variables  
 \* NOTE \* C18 is highly correlated with other predictor variables  
 \* NOTE \* C19 is highly correlated with other predictor variables  
 \* NOTE \* C20 is highly correlated with other predictor variables  
 \* NOTE \* C21 is highly correlated with other predictor variables  
 \* NOTE \* C22 is highly correlated with other predictor variables  
 \* NOTE \* C23 is highly correlated with other predictor variables  
 \* NOTE \* C24 is highly correlated with other predictor variables  
 \* NOTE \* C25 is highly correlated with other predictor variables  
 \* NOTE \* C26 is highly correlated with other predictor variables

The regression equation is

$$C4 = -56.4 + 0.130 C7 + 0.869 C8 - 0.831 C9 + 0.42 C10 + 5.93 C11 + 0.000103 C12 - 0.000328 C13 + 0.196 C14 + 0.083 C15 + 0.166 C16 + 0.00103 C17 + 0.00352 C18 + 0.00798 C19 + 0.00441 C20 - 0.0152 C21 + 0.00980 C22 + 0.0185 C23 - 0.114 C24 - 0.131 C25 + 0.169 C26$$

Predictor	Coef	Stdev	t-ratio	P
Constant	-56.39	18.08	-3.12	0.002
C7	0.13043	0.01423	9.17	0.000
C8	0.8685	0.1369	6.35	0.000
C9	-0.8313	0.9692	-0.86	0.391
C10	0.418	3.048	0.14	0.891
C11	5.932	1.180	5.03	0.000
C12	0.00010334	0.00001393	7.42	0.000
C13	-0.0003285	0.0001411	-2.33	0.020
C14	0.19632	0.05570	3.52	0.000
C15	-0.0834	0.1594	-0.52	0.601
C16	-0.16578	0.03892	-4.26	0.000
C17	0.0010292	0.0003392	3.03	0.003
C18	0.003520	0.001103	3.19	0.002
C19	0.007978	0.001190	6.70	0.000
C20	0.0044065	0.0007400	5.95	0.000
C21	-0.015212	0.009831	-1.55	0.122
C22	0.009800	0.009894	0.99	0.323
C23	0.01854	0.01275	1.45	0.147
C24	-0.11415	0.09546	-1.20	0.232
C25	-0.13149	0.04971	-2.64	0.008
C26	0.16895	0.08556	1.97	0.049

s = 1.365

R-sq = 99.9%

R-sq(adi) = 99.9%

130

## Analysis of Variance

SOURCE	DF	SS	MS	F	P
Regression	20	667201	33360	17892.42	0.000
Error	444	828	2		
Total	464	668029			

SOURCE	DF	SEQ SS
C7	1	512443
C8	1	143720
C9	1	623
C10	1	6583
C11	1	2428
C12	1	822
C13	1	43
C14	1	34
C15	1	71
C16	1	3
C17	1	25
C18	1	37
C19	1	264
C20	1	55
C21	1	0
C22	1	13
C23	1	7
C24	1	13
C25	1	10
C26	1	7

## Unusual Observations

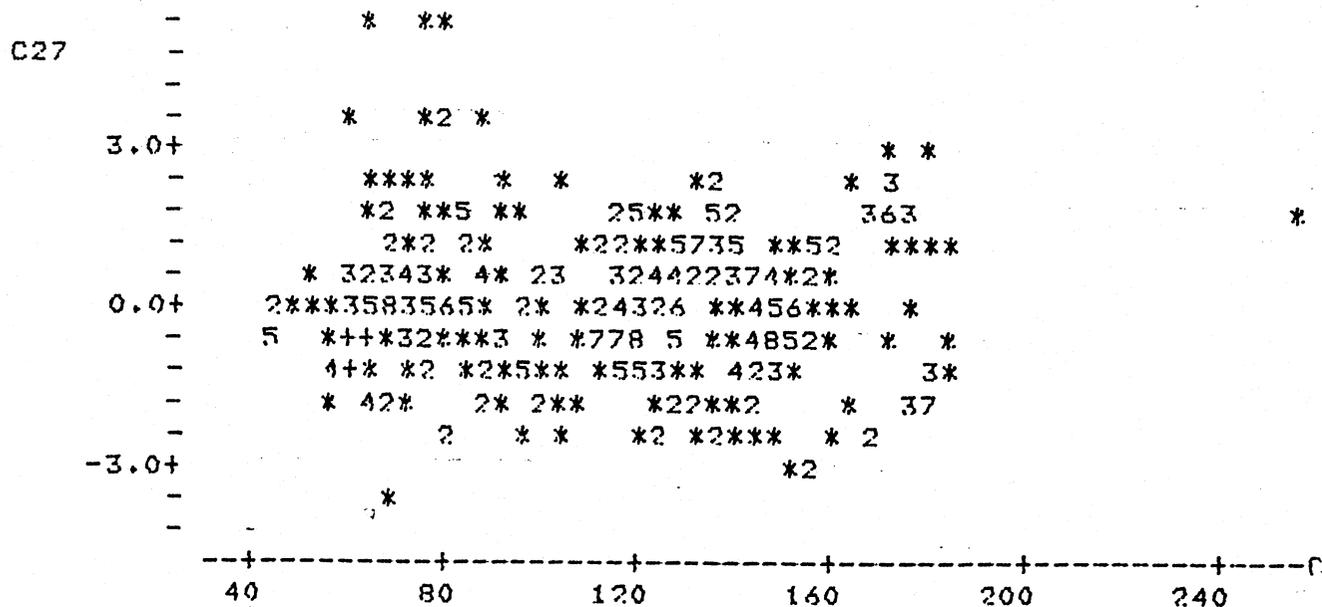
Obs.	C7	C4	Fit	Stdev.Fit	Residual	St.Resid
1	62	86.269	87.729	0.566	-1.461	-1.18 X
2	62	92.280	92.841	0.552	-0.561	-0.45 X
3	62	94.135	94.197	0.525	-0.062	-0.05 X
4	62	95.890	97.354	0.535	-1.465	-1.17 X
5	62	95.291	96.336	0.508	-1.045	-0.82 X
6	62	99.456	100.777	0.576	-1.321	-1.07 X
9	76	65.611	60.376	0.295	5.235	3.93R
11	66	75.594	70.259	0.267	5.336	3.98R
12	66	79.777	76.137	0.281	3.640	2.72R
16	66	88.522	89.099	0.612	-0.577	-0.47 X
19	80	61.915	58.581	0.317	3.334	2.51R
25	66	68.219	71.639	0.343	-3.420	-2.59R
27	90	254.045	252.499	1.313	1.546	4.11RX
28	95	174.193	176.219	1.101	-2.025	-2.51RX
29	90	103.055	100.655	0.676	2.400	2.02RX
31	127	81.834	84.458	0.499	-2.624	-2.06R
32	133	83.090	83.705	0.511	-0.615	-0.49 X
33	140	84.719	84.988	0.534	-0.269	-0.21 X
34	181	88.404	90.231	0.547	-1.827	-1.46 X
35	183	89.411	90.804	0.560	-1.393	-1.12 X
36	181	89.437	88.791	0.531	0.646	0.51 X

40	171	86.223	85.587	0.559	0.636	0.51 X
71	166	84.497	84.287	0.527	0.210	0.17 X
106	64	123.968	123.221	0.737	0.747	0.65 X
196	62	164.239	166.266	1.181	-2.027	-2.96RX
286	216	75.520	71.817	0.404	3.703	2.84R
376	199	79.374	74.134	0.190	5.239	3.87R
377	206	80.545	76.680	0.191	3.865	2.86R
378	221	86.226	82.591	0.175	3.635	2.68R
393	386	151.277	154.123	0.162	-2.846	-2.10R
394	394	155.144	157.961	0.169	-2.818	-2.08R
395	397	156.958	159.690	0.167	-2.732	-2.02R
417	425	181.397	178.576	0.292	2.821	2.11R
425	407	171.768	169.038	0.222	2.730	2.03R

R denotes an obs. with a large st. resid.

X denotes an obs. whose X value gives it large influence.

MTR > plot c27 c4



## APPENDIX D No. 4

```

MTB > read 'randb.max' c3-c11
1 773 ROWS READ
2
3  ROW      C3      C4      C5      C6      C7      C8      C9      C10
4
5  1      32.1      1      1.0      240.681      51.7770      98.49      3.8064      10.3936
6  2      32.2      1      1.0      93.788      53.5310      98.49      4.3446      10.8036
7  3      32.3      1      1.0      60.524      55.2850      98.49      4.8827      11.2714
8  4      32.4      1      1.0      55.942      57.0390      98.49      5.4209      11.7801
9
10
11
12 C11
13 12.2896 12.3922 12.4927 12.5910 . . .
14
15 MTB > let c7=25-c7
16 MTB > print c7
17
18 C7
19 -26.7770 -28.5310 -30.2850 -32.0390 -33.7930 -35.0070 -35.6810
20 -36.3550 -37.0290 -37.7030 -38.3770 -39.0510 -39.7250 -40.3990
21 -41.0720 -41.1840 -40.7320 -40.2800 -39.8280 -39.3760 -38.9230
22 -38.4690 -38.0150 -37.5610 -37.1070 -36.3550 -35.3050 -34.2550
23 -33.2050 -32.1550 -31.1050 -30.0550 -29.0050 -27.9550 -26.9050
24 -26.3370 -26.2510 -26.1650 -26.0790 -25.9930 -25.9070 -25.8210
25 -25.7350 -25.6490 -25.5630 -25.9370 -26.7710 -27.6050 -28.4390
26 -29.2730 -30.1060 -30.9380 -31.7700 -32.6020 -33.4340 -33.8510
27 -33.8530 -33.8550 -33.8570 -33.8590 -33.8610 -33.8630 -33.8650
28 -33.8670 -33.8690 -33.6180 -33.1140 -32.6100 -32.1060 -31.6020
29 -31.0970 -30.5910 -30.0850 -29.5790 -29.0730 -28.1690 -26.8670
30 -25.5650 -24.2630 -22.9610 -21.6590 -20.3570 -19.0550 -17.7530
31 -16.4510 -14.8330 -12.8990 -10.9650 -9.0310 -7.0970 8.0000
32 7.6320 7.2640 6.3270 4.8210 3.3150 1.8090 0.3030
33 -1.2020 -2.7060 -4.2100 -5.7140 -7.2180 -8.2840 -8.9120
34 -9.5400 -10.1680 -10.7960 -11.4230 -12.0490 -12.6750 -13.3010
35 -13.9270 -14.8200 -15.9800 -17.1400 -18.3000 -19.4600 -20.6200
36 -21.7800 -22.9400 -24.1000 -25.2600 -26.4200 -27.7060 -28.9500
37 -30.1940 -31.4380 -32.6810 -33.9230 -35.1650 -36.4070 -37.6490
38 -38.3280 -38.4440 -38.5600 -38.6760 -38.7920 -38.9070 -39.0210
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MTB > execute 'nreg.com'
1 MTB > let c12=c7*c7
2 MTB > let c13=c8*c8
3 MTB > let c14=c9*c9
4 MTB > let c15=c10*c10
5 MTB > let c16=c11*c11
6 MTB > let c17=c7*c8
7 MTB > let c18=c7*c9
8 MTB > let c19=c7*c10
9 MTB > let c20=c7*c11
10 MTB > let c21=c8*c9
11 MTB > let c22=c8*c10
12 MTB > let c23=c8*c11
13 MTB > let c24=c9*c10
14 MTB > let c25=c9*c11
15 MTB > let c26=c10*c11
16 MTB > end
17 MTB > regress c6 on 20 c7-c26;
18 SUBC> residuals=c27.
19 * NCTE *      C7 is highly correlated with other predictor variables
20 * NCTE *      C8 is highly correlated with other predictor variables
21 * NCTE *      C9 is highly correlated with other predictor variables
22 * NCTE *      C10 is highly correlated with other predictor variables
23 * NOTE *      C11 is highly correlated with other predictor variables
24 * NCTE *      C14 is highly correlated with other predictor variables
25 * NCTE *      C15 is highly correlated with other predictor variables
26 * NCTE *      C16 is highly correlated with other predictor variables
27 * NCTE *      C19 is highly correlated with other predictor variables
28 * NOTE *      C20 is highly correlated with other predictor variables
29 * NOTE *      C22 is highly correlated with other predictor variables
30 * NOTE *      C23 is highly correlated with other predictor variables
31 * NCTE *      C24 is highly correlated with other predictor variables
32 * NCTE *      C25 is highly correlated with other predictor variables
33 * NCTE *      C26 is highly correlated with other predictor variables
34
35 The regression equation is
36 C6 = 2201 + 10.3 C7 - 1.00 C8 - 29.7 C9 - 24.3 C10 - 246 C11 + 0.0306 C12
37 - 0.00230 C13 + 1.70 C14 - 1.74 C15 + 6.60 C16 - 0.0258 C17
38 + 0.193 C18 + 0.0660 C19 - 0.598 C20 + 0.0301 C21 + 0.0527 C22
39 + 0.0219 C23 + 0.42 C24 + 0.34 C25 + 3.69 C26
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```

Predictor	Coef	Stdev	t-ratio	P
Constant	2200.7	345.7	6.37	0.000
C7	10.268	1.517	6.77	0.000
C8	-1.0044	0.8125	-1.24	0.217
C9	-29.71	21.82	-1.36	0.174
C10	-24.35	38.78	-0.63	0.530
C11	-245.73	28.43	-8.64	0.000
C12	0.030601	0.004943	6.19	0.000
C13	-0.0022982	0.0008767	-2.62	0.009
C14	1.7046	0.8554	1.99	0.047
C15	-1.737	1.441	-1.20	0.229
C16	6.6047	0.8892	7.43	0.000
C17	-0.025760	0.003699	-6.96	0.000
C18	0.19257	0.06882	2.80	0.005
C19	0.06601	0.08680	0.76	0.447
C20	-0.59779	0.08363	-7.15	0.000
C21	0.03011	0.02698	1.12	0.265
C22	0.05271	0.04282	1.23	0.219
C23	0.02191	0.03995	0.55	0.584
C24	0.419	1.195	0.35	0.726
C25	0.345	1.247	0.28	0.782
C26	3.692	1.530	2.41	0.016

s = 18.07      R-sq = 30.7%      R-sq(adj) = 28.9%

#### Analysis of Variance

SOURCE	DF	SS	MS	F	P
Regression	20	109057.2	5452.9	16.69	0.000
Error	752	245670.7	326.7		
Total	772	354728.0			

SOURCE	DF	SEQ SS
C7	1	971.1
C8	1	2773.7
C9	1	324.9
C10	1	5168.2
C11	1	1.2
C12	1	37795.3
C13	1	742.1
C14	1	906.0
C15	1	188.9
C16	1	26093.7
C17	1	11161.2
C18	1	2449.1
C19	1	82.5
C20	1	17438.0
C21	1	310.3
C22	1	312.7
C23	1	116.9
C24	1	225.6
C25	1	93.8
C26	1	1901.9

## Unusual Observations

Obs.	C7	C6	Fit	Stdev.Fit	Residual	St.Resid
1	-26.8	240.681	97.800	7.330	142.881	8.65RX
2	-28.5	93.788	85.721	5.550	8.062	0.47 X
5	-33.8	33.721	54.087	5.763	-20.366	-1.19 X
6	-35.0	36.515	50.583	5.911	-14.067	-0.82 X
16	-41.2	62.643	69.558	5.491	-6.915	-0.40 X
81	-21.7	42.543	37.221	5.357	5.322	0.31 X
89	-9.0	53.860	49.689	5.809	4.171	0.24 X
90	-7.1	58.848	53.023	6.795	5.825	0.35 X
91	8.0	227.114	120.465	4.351	106.650	6.08R
169	-20.8	47.458	27.307	6.314	20.151	1.19 X
170	-19.7	37.480	31.013	5.449	6.467	0.38 X
179	-9.6	173.989	62.079	1.823	111.909	6.22R
266	1.7	94.934	74.540	5.799	20.394	1.19 X
267	1.8	92.995	71.861	7.064	21.135	1.27 X
268	-0.1	213.407	89.957	2.672	123.450	6.91R
347	-11.6	38.768	39.892	6.880	-1.124	-0.07 X
348	-9.7	56.211	44.830	5.189	11.381	0.66 X
355	-3.3	73.605	77.373	5.920	-3.768	-0.22 X
356	-3.3	73.761	79.946	7.673	-6.185	-0.38 X
357	-11.2	240.631	64.562	3.002	176.069	9.88R
358	-13.1	118.878	60.817	2.063	58.060	3.23R
441	-1.9	65.973	69.862	5.385	-3.890	-0.23 X
442	-1.7	75.386	70.358	5.283	5.028	0.29 X
447	2.9	210.689	68.610	1.971	142.079	7.91R
448	2.1	121.308	68.264	1.840	53.043	2.95R
511	-0.0	196.835	76.953	2.617	119.881	6.70R
512	-1.2	108.077	71.292	1.791	36.785	2.05R
598	1.2	74.855	73.612	5.785	1.243	0.07 X
599	1.6	77.810	76.102	7.540	1.708	0.10 X
600	-17.8	185.477	55.925	1.732	129.552	7.20R
690	-0.6	191.386	76.731	3.608	114.655	6.47R
765	-5.4	81.548	78.536	5.168	3.013	0.17 X

35 R denotes an obs. with a large st. resid.

36 X denotes an obs. whose X value gives it large influence.

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## APPENDIX D No. 5

```
MTB > read 'randb.min' c3-c11
```

```
480 ROWS READ
```

ROW	C3	C4	C5	C6	C7	C8	C9	C10
1	158.6	1	0.1	61.086	43.1630	80.54	5.5886	12.8878
2	158.7	1	0.1	61.463	42.4890	80.54	5.4713	12.7479
3	158.8	1	0.1	61.890	41.8150	80.54	5.3537	12.6163
4	158.9	1	0.1	61.625	41.1411	80.54	5.2312	12.4760

```
C11
```

```
16.1186 16.1244 16.1302 16.1360 . . .
```

```
MTB > let c7=25-c7
```

```
MTB > print c7
```

```
C7
```

19	-18.1630	-17.4890	-16.8150	-16.1411	-15.4670	-14.7930	-14.1190
20	-13.4450	-12.7711	-12.0970	-11.1610	-9.9631	-8.7650	-7.5671
21	-6.3690	-5.1710	-3.9731	-2.7750	-1.5771	-0.3790	0.2700
22	0.3700	0.4700	0.5700	0.6700	-7.5570	-7.4510	-7.3450
23	-7.2390	-7.1330	-7.0270	-6.9210	-6.8150	-6.7090	-6.6030
24	-6.0890	-5.1671	-4.2450	-3.3231	-2.4010	0.4110	-0.0270
25	-0.4650	-0.9030	-1.3410	-1.9910	-2.8529	-3.7150	-8.8710
26	-8.4970	-8.1230	-7.7490	-7.3750	-7.0010	-6.6270	-6.5010
27	-6.6230	-6.7450	-6.8670	-6.9890	-7.1100	-7.2300	-7.3500
28	-7.4700	-7.5900	-8.2340	-9.4019	-10.5700	-11.7379	-12.9060
29	-14.0730	-15.2389	-16.4050	-17.5709	-18.7370	-18.4369	-16.6711
30	-14.9050	-13.1392	-11.3731	-9.6059	-7.8381	-6.0700	-4.3022
31	-2.5341	-2.3680	-3.8039	-5.2400	-6.6759	-8.1120	-9.5490
32	-10.9869	-12.4250	-13.8629	-15.3010	-16.0090	-15.9870	-15.9650
33	-15.9430	-15.9210	-15.8980	-15.8740	-15.8500	-15.8260	-15.8020
34	-16.0780	-16.6540	-17.2300	-17.8059	-18.3820	-18.9571	-19.5311
35	-20.1050	-20.6790	-21.2531	-21.3379	-20.9339	-20.5300	-20.1260
36	-19.7220	-16.5275	-19.1616	-21.7950	-24.4292	-27.0633	-28.5371
37	-28.8511	-29.1650	-29.4790	-29.7930	-30.1071	-30.4211	-30.7350
38	-31.0490	-31.3630	-31.9752	-32.8852	-33.7950	-34.7051	-35.6151

```
MTB > regress c6 on 20 c7-c26;
1 SUBC> residuals=c27.
2
3 * ERROR * No data in column
4
5 MTB > execute 'nreg.com'
6 MTB > let c12=c7*c7
7 MTB > let c13=c8*c8
8 MTB > let c14=c9*c9
9 MTB > let c15=c10*c10
10 MTB > let c16=c11*c11
11 MTB > let c17=c7*c8
12 MTB > let c18=c7*c9
13 MTB > let c19=c7*c10
14 MTB > let c20=c7*c11
15 MTB > let c21=c8*c9
16 MTB > let c22=c8*c10
17 MTB > let c23=c8*c11
18 MTB > let c24=c9*c10
19 MTB > let c25=c9*c11
20 MTB > let c26=c10*c11
21 MTB > end
22 MTB > regress c6 on 20 c7-c26;
23 SUBC> residuals=c27.
24 * NOTE *      C7 is highly correlated with other predictor variables
25 * NOTE *      C8 is highly correlated with other predictor variables
26 * NOTE *      C9 is highly correlated with other predictor variables
27 * NOTE *      C10 is highly correlated with other predictor variables
28 * NOTE *      C11 is highly correlated with other predictor variables
29 * NOTE *      C14 is highly correlated with other predictor variables
30 * NOTE *      C15 is highly correlated with other predictor variables
31 * NOTE *      C16 is highly correlated with other predictor variables
32 * NOTE *      C17 is highly correlated with other predictor variables
33 * NOTE *      C18 is highly correlated with other predictor variables
34 * NOTE *      C19 is highly correlated with other predictor variables
35 * NOTE *      C20 is highly correlated with other predictor variables
36 * NOTE *      C22 is highly correlated with other predictor variables
37 * NOTE *      C23 is highly correlated with other predictor variables
38 * NOTE *      C24 is highly correlated with other predictor variables
39 * NOTE *      C25 is highly correlated with other predictor variables
40 * NOTE *      C26 is highly correlated with other predictor variables
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```

1 The regression equation is  
 2  $C6 = 306 + 4.92 C7 + 0.430 C8 - 48.8 C9 - 57.6 C10 + 22.7 C11 + 0.0784 C12$   
 3  $- 0.00212 C13 + 1.31 C14 + 3.42 C15 - 0.561 C16 - 0.0119 C17$   
 4  $+ 0.208 C18 + 0.122 C19 - 0.229 C20 + 0.0067 C21 + 0.0190 C22$   
 5  $- 0.0250 C23 - 0.27 C24 + 2.17 C25 - 1.01 C26$

Predictor	Coef	Stdev	t-ratio	P
Constant	306.0	294.4	1.04	0.299
C7	4.917	2.200	2.24	0.026
C8	0.4299	0.5885	0.73	0.465
C9	-48.79	22.26	-2.19	0.029
C10	-57.60	34.24	-1.68	0.093
C11	22.75	14.41	1.58	0.115
C12	0.078386	0.008466	9.26	0.000
C13	-0.0021239	0.0008264	-2.57	0.010
C14	1.3062	0.7675	1.70	0.089
C15	3.421	1.316	2.60	0.010
C16	-0.5612	0.3007	-1.87	0.063
C17	-0.011903	0.003746	-3.18	0.002
C18	0.2083	0.1062	1.96	0.050
C19	0.1220	0.1187	1.03	0.304
C20	-0.22890	0.08709	-2.63	0.009
C21	0.00667	0.02231	0.30	0.765
C22	0.01904	0.03636	0.52	0.601
C23	-0.02505	0.02257	-1.11	0.268
C24	-0.266	1.223	-0.22	0.828
C25	2.1653	0.7195	3.01	0.003
C26	-1.0111	0.8344	-1.21	0.226

30  $s = 12.61$        $R\text{-sc} = 90.1\%$        $R\text{-sq(adj)} = 89.6\%$

### 32 Analysis of Variance

SOURCE	DF	SS	MS	F	p
Regression	20	661660	33083	208.12	0.000
Error	459	72964	159		
Total	479	734624			

	SOURCE	DF	SEQ SS
1	C7	1	507148
2	C8	1	31019
3	C9	1	131
4	C10	1	1160
5	C11	1	21887
6	C12	1	85623
7	C13	1	1423
8	C14	1	263
9	C15	1	398
10	C16	1	330
11	C17	1	3998
12	C18	1	0
13	C19	1	1112
14	C20	1	1171
15	C21	1	266
16	C22	1	308
17	C23	1	234
18	C24	1	19
19	C25	1	1937
20	C26	1	233

22 Unusual Observations

Obs.	C7	C6	Fit	Stdev.Fit	Residual	St.Resid	
24	25	0.7	91.489	80.854	4.671	10.635	0.91 X
25	35	-6.6	63.432	64.858	5.022	-1.426	-0.12 X
26	36	-6.1	64.017	65.622	4.914	-1.605	-0.14 X
27	41	0.4	241.920	94.238	4.384	147.682	12.49R
28	42	-0.0	161.295	88.822	3.431	72.473	5.97R
29	65	-7.6	68.394	74.498	4.717	-6.104	-0.52 X
30	121	-16.5	119.528	78.925	2.550	40.602	3.29R
31	211	-2.8	169.540	80.905	3.680	88.635	7.35R
32	291	-27.0	96.734	62.893	3.220	33.841	2.78R
33	315	-43.6	137.578	145.506	5.294	-7.928	-0.69 X
34	316	-44.1	137.146	147.560	4.938	-10.414	-0.90 X
35	382	-23.9	84.750	81.524	6.186	3.227	0.29 X
36	386	-20.5	58.606	61.556	4.611	-2.951	-0.25 X
37	389	-19.4	53.875	62.387	4.709	-8.513	-0.73 X
38	390	-19.1	50.001	64.650	5.824	-14.648	-1.31 X
39	411	-45.2	153.631	178.798	1.661	-25.168	-2.01R
40	480	-21.7	74.374	74.275	4.811	0.099	0.01 X

42 R denotes an obs. with a large st. resid.

43 X denotes an obs. whose X value gives it large influence.

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809 ROWS READ

\* 6472 NUMBERS READ IN EXPONENTIAL NOTATION

ROW	C3	C4	C5	C6	C7	C8	C9	C10	C11
1	32.1	1	1	228.40	51.78	98.49	6.396	12.720	12.29
2	32.2	1	1	87.40	53.53	98.49	6.166	12.860	12.39
3	32.3	1	1	53.75	55.23	98.49	6.255	12.840	12.49
4	32.4	1	1	56.08	57.04	98.49	6.345	12.880	12.59

MTB &gt; let c7=25-c7

MTB &gt; print c7

C7

-26.78	-28.53	-30.28	-32.04	-33.79	-35.01	-35.68	-36.35	-37.03
-37.70	-38.38	-39.05	-39.73	-40.40	-41.07	-41.18	-40.73	-40.28
-39.83	-39.38	-38.92	-38.47	-38.02	-37.56	-37.11	-36.36	-35.30
-34.26	-33.20	-32.15	-31.11	-30.05	-29.01	-27.95	-26.90	-26.34
-26.25	-26.17	-26.08	-25.99	-25.91	-25.82	-25.74	-25.65	-25.56
-25.94	-26.77	-27.60	-28.44	-29.27	-30.11	-30.94	-31.77	-32.60
-33.43	-33.85	-33.85	-33.85	-33.86	-33.86	-33.86	-33.86	-33.87
-33.87	-33.87	-33.62	-33.11	-32.61	-32.11	-31.60	-31.10	-30.59
-30.08	-29.58	-29.07	-28.17	-26.87	-25.57	-24.26	-22.96	-21.66
-20.36	-19.06	-17.75	-16.45	-14.83	-12.90	-10.97	-9.03	-7.10
8.00	7.63	7.26	6.33	4.82	3.31	1.81	0.30	-1.20
-2.71	-4.21	-5.71	-7.22	-8.28	-8.91	-9.54	-10.17	-10.80
-11.42	-12.05	-12.68	-13.30	-13.93	-14.82	-15.98	-17.14	-18.30
-19.46	-20.62	-21.78	-22.94	-24.10	-25.26	-26.46	-27.71	-28.95
-30.19	-31.44	-32.68	-33.92	-35.17	-36.41	-37.65	-38.33	-38.44
-38.56	-38.68	-38.79	-38.91	-39.02	-39.14	-39.25	-39.36	-38.96
-38.03	-37.10	-36.17	-35.24	-34.32	-33.39	-32.47	-31.54	-30.61
-30.00	-29.69	-29.39	-29.08	-28.77	-28.47	-28.16	-27.85	-27.55
-27.24	-26.52	-25.38	-24.24	-23.09	-21.95	-20.81	-19.66	-18.52
-17.38	-16.23	-14.70	-12.78	-10.65	-8.93	-7.01	-9.60	-10.84

MTB &gt; execute 'nreg.com'

MTB &gt; let c12=c7\*c7

MTB &gt; let c13=c8\*c8

MTB &gt; let c14=c9\*c9

MTB &gt; let c15=c10\*c10

MTB &gt; let c16=c11\*c11

MTB &gt; let c17=c7\*c8

MTB &gt; let c18=c7\*c9

MTB &gt; let c19=c7\*c10

MTB &gt; let c20=c7\*c11

MTB &gt; let c21=c8\*c9

MTB &gt; let c22=c8\*c10

MTB &gt; let c23=c8\*c11

MTB &gt; let c24=c9\*c10

MTB &gt; let c25=c9\*c11

MTB &gt; let c26=c10\*c11

MTB &gt; end

1 SUBC> residuals=c27.

2  
3 \* C18 is highly correlated with other X variables

4 \* C18 has been removed from the equation

5  
6  
7 \* C19 is highly correlated with other X variables

8 \* C19 has been removed from the equation

9  
10  
11 \* C21 is highly correlated with other X variables

12 \* C21 has been removed from the equation

13  
14  
15 \* C22 is highly correlated with other X variables

16 \* C22 has been removed from the equation

17  
18  
19 \* C24 is highly correlated with other X variables

20 \* C24 has been removed from the equation

21  
22  
23 \* C25 is highly correlated with other X variables

24 \* C25 has been removed from the equation

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26  
27 \* C26 is highly correlated with other X variables

28 \* C26 has been removed from the equation

29  
30 \* NOTE \* C7 is highly correlated with other predictor variables

31 \* NOTE \* C8 is highly correlated with other predictor variables

32  
33 \* C9 is highly correlated with other X variables

34 \* C9 has been removed from the equation

35  
36 \* NOTE \* C7 is highly correlated with other predictor variables

37 \* NOTE \* C8 is highly correlated with other predictor variables

38 \* NOTE \* C10 is highly correlated with other predictor variables

39 \* NOTE \* C11 is highly correlated with other predictor variables

40 \* NOTE \* C14 is highly correlated with other predictor variables

41 \* NOTE \* C15 is highly correlated with other predictor variables

42 \* NOTE \* C16 is highly correlated with other predictor variables

43 \* NOTE \* C20 is highly correlated with other predictor variables

44 \* NOTE \* C23 is highly correlated with other predictor variables

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1 The regression equation is  
 2  $C6 = 316 + 12.2 C7 + 2.16 C8 - 32.5 C10 - 63.5 C11 - 0.0368 C12 - 0.00297$   
 3  $+ 14.6 C14 + 0.75 C15 + 2.69 C16 - 0.0290 C17 - 0.105 C20$   
 4  $- 0.0471 C23$

Predictor	Coef	Stdev	t-ratio	p
Constant	315.8	217.4	1.45	0.147
C7	12.188	1.077	11.32	0.000
C8	2.1593	0.4842	4.46	0.000
C10	-32.45	21.50	-1.51	0.132
C11	-63.47	21.63	-2.93	0.003
C12	-0.036774	0.007674	-4.79	0.000
C13	-0.0029732	0.0007188	-4.14	0.000
C14	14.648	1.519	9.65	0.000
C15	0.755	1.120	0.67	0.501
C16	2.6871	0.6881	3.91	0.000
C17	-0.029029	0.003074	-9.44	0.000
C20	-0.10499	0.08091	-1.30	0.195
C23	-0.04706	0.02896	-1.62	0.105

21  $s = 16.27$        $R\text{-sc} = 40.0\%$        $R\text{-sq(adj)} = 39.0\%$

### 23 Analysis of Variance

SOURCE	DF	SS	MS	F	p
Regression	12	140281	11690	44.14	0.000
Error	796	210830	265		
Total	808	351111			

SOURCE	DF	SEC SS
C7	1	443
C8	1	5946
C10	1	43519
C11	1	3059
C12	1	24437
C13	1	981
C14	1	29088
C15	1	16
C16	1	4596
C17	1	27095
C20	1	402
C23	1	699

## Unusual Observations

Obs.	C7	C6	Fit	Stdev.Fit	Residual	St.Resid
1	-26.8	228.400	135.435	8.085	92.965	6.58RX
2	-28.5	87.400	73.765	4.225	13.635	0.87 X
3	-30.3	53.750	72.580	4.078	-18.830	-1.20 X
4	-32.0	56.080	70.791	3.965	-14.711	-0.93 X
5	-33.8	32.630	69.339	3.872	-36.709	-2.32RX
6	-35.0	35.270	68.518	3.694	-33.248	-2.10RX
81	-21.7	39.560	29.352	4.494	10.208	0.65 X
82	-20.4	31.080	32.190	4.208	-1.110	-0.07 X
83	-19.1	26.520	34.925	3.976	-8.405	-0.53 X
84	-17.8	23.350	37.702	3.799	-14.352	-0.91 X
85	-16.5	46.120	40.268	3.675	5.852	0.37 X
86	-14.8	48.610	47.369	4.193	1.241	0.08 X
88	-11.0	45.550	50.596	3.586	-5.046	-0.32 X
89	-9.0	51.010	53.954	3.739	-2.944	-0.19 X
90	-7.1	52.110	57.707	4.017	-5.597	-0.35 X
91	8.0	248.500	207.831	11.535	40.669	3.54RX
92	7.6	167.500	206.659	11.476	-39.159	-3.39RX
93	7.3	125.300	75.995	4.744	49.305	3.17RX
94	6.3	87.700	128.400	4.789	-40.700	-2.62RX
95	4.8	82.890	77.266	3.676	5.624	0.35 X
96	3.3	70.030	139.041	5.828	-69.011	-4.54RX
169	-20.8	44.320	26.126	4.430	18.194	1.16 X
170	-19.7	36.550	28.501	4.045	8.045	0.51 X
171	-18.5	30.990	30.688	3.690	0.302	0.02 X
179	-9.6	162.800	57.666	1.309	105.134	6.48R
268	-0.1	198.200	133.896	5.939	64.304	4.24RX
269	-1.0	109.900	71.361	2.402	38.539	2.39R
339	-20.4	56.900	65.095	4.184	-8.195	-0.52 X
357	-11.2	230.900	60.680	1.516	170.220	10.50R
358	-13.1	105.900	59.154	1.510	46.746	2.88R
447	2.9	202.500	64.290	1.687	138.610	8.56R
448	2.1	113.300	63.900	1.733	49.400	3.05R
526	-5.2	42.180	59.850	4.565	-17.670	-1.13 X
527	-4.0	66.210	62.872	4.502	3.338	0.21 X
528	-0.0	185.400	65.443	1.529	119.957	7.40R
593	-3.8	37.530	68.682	4.723	-31.152	-2.00RX
617	-17.8	174.400	55.815	1.521	118.585	7.32R
707	-0.6	183.100	64.742	1.438	118.358	7.30R
708	-1.6	98.270	63.782	1.354	34.488	2.13R
767	4.8	31.360	66.202	2.271	-34.842	-2.16R
781	-7.6	53.020	93.594	9.587	-40.574	-3.09RX
786	-7.0	66.550	56.252	4.724	10.698	0.69 X
787	-6.9	62.540	56.904	4.682	6.036	0.39 X
788	-6.8	61.230	57.435	4.684	3.795	0.24 X

MTB > read "cpt3.min" c3-c11

1 \* ERROR \* Requested file does not exist

3 MTB > read "opt3min.dat" c3-c11

4 444 ROWS READ

5 \* 3552 NUMBERS READ IN EXPONENTIAL NOTATION

ROW	C3	C4	C5	C6	C7	C8	C9	C10	C11
1	160.3	0.1	1	65.60	27.78	1.14	6.023	11.050	16.26
2	160.4	0.1	1	70.92	26.58	1.14	5.915	9.805	16.27
3	160.5	0.1	1	74.38	25.38	1.14	5.808	11.020	16.29
4	160.6	0.1	1	77.85	24.73	1.14	5.719	10.900	16.33

15 MTB > let c7=25-c7

16 MTB > execute "nreg.com"

17 MTB > let c12=c7\*c7

18 MTB > let c13=c8\*c8

19 MTB > let c14=c9\*c9

20 MTB > let c15=c10\*c10

21 MTB > let c16=c11\*c11

22 MTB > let c17=c7\*c8

23 MTB > let c18=c7\*c9

24 MTB > let c19=c7\*c10

25 MTB > let c20=c7\*c11

26 MTB > let c21=c8\*c9

27 MTB > let c22=c8\*c10

28 MTB > let c23=c8\*c11

29 MTB > let c24=c9\*c10

30 MTB > let c25=c9\*c11

31 MTB > let c26=c10\*c11

32 MTB > end

33 MTB > regress c6 on 20 c7-c26;

34 SUBC> residuals=c27.

36 \* C19 is highly correlated with other X variables

37 \* C19 has been removed from the equation

40 \* C20 is highly correlated with other X variables

41 \* C20 has been removed from the equation

14 \* C25 is highly correlated with other X variables

15 \* C25 has been removed from the equation

18 \* C26 is highly correlated with other X variables

19 \* C26 has been removed from the equation

1 \* NOTE \* C7 is highly correlated with other predictor variables

3 \* C8 is highly correlated with other X variables

4 \* C8 has been removed from the equation

6 \* NOTE \* C7 is highly correlated with other predictor variables

\* NOTE \* C9 is highly correlated with other predictor variables  
 1 \* NCTE \* C10 is highly correlated with other predictor variables  
 2 \* NCTE \* C11 is highly correlated with other predictor variables  
 3 \* NOTE \* C12 is highly correlated with other predictor variables  
 4 \* NCTE \* C14 is highly correlated with other predictor variables  
 5 \* NCTE \* C15 is highly correlated with other predictor variables  
 6 \* NCTE \* C16 is highly correlated with other predictor variables  
 7 \* NOTE \* C18 is highly correlated with other predictor variables  
 8 \* NCTE \* C21 is highly correlated with other predictor variables  
 9 \* NCTE \* C22 is highly correlated with other predictor variables  
 10 \* NCTE \* C23 is highly correlated with other predictor variables  
 11 \* NCTE \* C24 is highly correlated with other predictor variables

12  
 13 The regression equation is  
 14  $C6 = 1994 + 1.57 C7 - 44.7 C9 - 296 C10 - 28.1 C11 + 0.0684 C12 - 0.00386 C13$   
 15  $- 3.76 C14 + 11.9 C15 + 0.863 C16 + 0.00145 C17 + 0.374 C18$   
 16  $+ 0.361 C21 - 0.478 C22 + 0.229 C23 + 7.97 C24$

Predictor	Coef	Stdev	t-ratio	p
19 Constant	1994.4	495.3	4.03	0.000
20 C7	1.569	1.090	1.44	0.151
21 C9	-44.65	39.41	-1.13	0.258
22 C10	-295.62	68.72	-4.30	0.000
23 C11	-28.12	17.43	-1.61	0.107
24 C12	0.06843	0.01029	6.65	0.000
25 C13	-0.0038633	0.0008051	-4.80	0.000
26 C14	-3.7618	0.8647	-4.35	0.000
27 C15	11.930	3.069	3.89	0.000
28 C16	0.8629	0.3764	2.29	0.022
29 C17	0.001453	0.002882	0.50	0.614
30 C18	0.3739	0.2438	1.53	0.126
31 C21	0.36064	0.05786	6.23	0.000
32 C22	-0.47835	0.08573	-5.58	0.000
33 C23	0.22903	0.04142	5.53	0.000
34 C24	7.971	3.239	2.46	0.014

35  
 36  $s = 12.34$        $R\text{-sq} = 89.8\%$        $R\text{-sq(adj)} = 89.4\%$

Analysis of Variance

SOURCE	DF	SS	MS	F
Regression	15	572699	38247	251.22
Error	428	65161	152	
Total	443	638859		

SOURCE	DF	SEC SS
C7	1	412488
C9	1	4003
C10	1	18043
C11	1	2045
C12	1	103017
C13	1	11576
C14	1	5832
C15	1	1745
C16	1	1642
C17	1	2386
C18	1	184
C21	1	3741
C22	1	5
C23	1	4069
C24	1	922

Unusual Observations

Obs.	C7	C6	Fit	Stdev.Fit	Residual	St.Resid
2	-1.6	70.920	75.704	9.723	-4.784	-0.63 X
16	0.4	250.700	107.902	4.673	142.798	12.50RX
17	-0.0	167.200	98.881	4.079	68.319	5.87RX
18	-7.0	96.410	97.921	12.331	-1.511	-3.51RX
65	-15.9	71.310	97.649	4.437	-26.339	-2.29RX
78	-20.7	46.930	37.334	6.683	9.596	0.93 X
85	-16.5	119.900	76.489	2.203	43.411	3.58R
123	-34.7	135.600	148.426	5.076	-12.826	-1.14 X
165	-32.6	113.900	104.026	4.419	9.874	0.86 X
175	-2.8	163.600	77.029	3.336	86.571	7.29R
255	-27.0	107.100	70.683	3.925	36.417	3.11R
345	-24.9	101.000	70.409	2.026	30.591	2.51R
351	-20.2	62.300	54.898	4.404	7.402	0.64 X
430	-33.0	154.500	164.545	7.818	-10.045	-1.05 X
433	-29.7	134.700	137.285	4.169	-2.585	-0.22 X
434	-28.6	134.500	136.864	4.576	-2.364	-0.21 X
435	-27.6	121.000	89.725	5.297	31.275	2.81RX
438	-24.3	89.080	81.052	5.882	8.028	0.74 X
444	-21.7	75.280	89.515	4.063	-14.235	-1.22 X

R denotes an obs. with a large st. resid.  
 X denotes an obs. whose X value gives it large influence.

***APPENDIX E***

---

***MISCELLANEOUS***

C APPENDIX E NO. 1: INITIAL COST FUNCTION DATABASE INPUT FILE  
GENERATING CODE (NDATGEN.FOR)

C

```
REAL TCHW,TAS
OPEN(UNIT=21,FILE='INAN17.DAT',STATUS='UNKNOWN')
NCOUNT=1
```

C

C SET Tchw, Tasup setpoint range

C

```
DATA XINT,TCHW1,TCHW2,TAS1,TAS2/5.,4.,8.,13.,10./
```

C

```
DTCHW=(TCHW2-TCHW1)/XINT
DTAS=(TAS2-TAS1)/XINT
Xdtchw=0.- dtchw
Xdtas=0.- dtas
```

20 CONTINUE

C

C Increment Tasup across setpoint range, outer do loop

C

```
DO 100 TAS=TAS1,TAS2,DTAS
```

C

C Increment Tchw across setpoint range, inner do loop

C

```
DO 10 TCHW=TCHW1,TCHW2,DTCHW
WRITE(21,*)TAS,TCHW
```

C 200 FORMAT(2F7.6)

```
NCOUNT=NCOUNT+1
IF(NCOUNT.GT.721)GO TO 40
```

10 CONTINUE

```
DO 100 TCHW=TCHW2,TCHW1,XDTCHW
NCOUNT=NCOUNT+1
WRITE(21,*)TAS,TCHW
IF(NCOUNT.GT.721)GO TO 40
```

100 CONTINUE

```
DO 300 TAS=TAS2,TAS1,XDTAS
DO 30 TCHW=TCHW1,TCHW2,DTCHW
WRITE(21,*)TAS,TCHW
IF(NCOUNT.GT.721)GO TO 40
```

30 CONTINUE

```
DO 300 TCHW=TCHW2,TCHW1,XDTCHW  
NCOUNT=NCOUNT+1  
  WRITE(21,*)TAS,TCHW  
  IF(NCOUNT.GT.721)GO TO 40  
300 CONTINUE  
  NCOUNT=NCOUNT+1  
  IF(NCOUNT.LT.721) GO TO 20  
40 END
```

## No. 2 - Initial Cost Function Database Sample (100% O.A.)

<u>Tasup,set(cyclic)</u>	<u>Tchw,set(cyclic)</u>
10.00	4.00
10.00	4.80
10.00	5.60
10.00	6.40
10.00	7.20
10.00	8.00
10.00	8.00
10.00	7.20
10.00	6.40
10.00	5.60
10.00	4.80
10.00	4.00
10.60	4.00
10.60	4.80
10.60	5.60
10.60	6.40
10.60	7.20
10.60	8.00
10.60	8.00
10.60	7.20
10.60	6.40
10.60	5.60
10.60	4.80
10.60	4.00
11.20	4.00
11.20	4.80
11.20	5.60
11.20	6.40
11.20	7.20
11.20	8.00
11.20	8.00
11.20	7.20
11.20	6.40
11.20	5.60
11.20	4.80
11.20	4.00
11.80	4.00
11.80	4.80
11.80	5.60

<u>Tasup,set(rand.#)</u>	<u>Tchw,set(rand.</u>
11.5361671	4.67337368
10.7914541	5.97090011
12.3799862	5.03923511
10.0336163	6.48846345
10.275963	6.15574001
12.5458693	7.34329999
11.9487703	6.51153172
11.0362743	4.94904148
11.0728111	6.09801294
12.1343997	4.22176973
12.1834368	7.04267039
10.2381273	4.67279016
12.556142	7.0125815
10.2970803	4.95830881
10.9515411	6.90646812
11.782257	4.11501181
12.6410195	4.74317035
12.2354061	4.50159202
12.4287488	6.4896032
11.6948613	4.02050855
12.4607862	6.25052803
12.3152483	6.26394885
11.7840407	4.59439298
12.3917943	4.90849646
12.3695191	5.40375869
12.8390611	4.90692802
10.2947812	5.83927785
10.5798539	4.82149759
10.7575585	4.63457538
11.7842218	5.46436551
12.6279874	5.59888593
10.2853645	6.02744478
12.974431	5.50810718
11.8728742	4.0172744
11.2364707	6.35462818
12.4863183	6.50997554
11.1245544	5.66995765
11.7904102	6.22681416
10.4048504	4.74856883

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