SIMULATION AND OPTIMIZATION IN THE REAL TIME CONTROL OF BUILDING ENVIRONMENTAL SYSTEMS.

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ABSTRACT

Some details of the optimization work conducted over the last five years in a high rise office complex are described. The solution of the many nonlinear equations representing the building environmental system in real time necessitates very fast algorithms and complete mapping of the feasible regions. The authors experiments in this area are outlined. Models for a chilled water system and an unusual application to an existing dual duct system are given as examples of a general nonlinear approach.

INTRODUCTION

The real time global optimization techniques described in the paper were applied to a high rise office retail complex in San Francisco CA. A general outline of the research and application work was presented in reference one. In this project existing pneumatic HVAC system controls were updated to direct digital controls with the acquisition of an Energy Management and Control System(EMCS). Based on simple payback rules, decisions were made to incorporate adjustable speed drives in almost all parts of the systems. A separate computer was installed to communicate with the EMCS vendor's monitoring computer to obtain current system operating data and to send optimal operating strategies. The optimization computer was selected to be fast enough to solve the class of nonlinear optimization problems in real time for the four high rise towers and retails areas of the complex.

In the following a model of a building chilled water system is described. It includes only the essential components to simplify the presentation. For example the air side VAV system is shown as an energy and rate balance using the effectiveness of the coils. Some of the components are not given specific functional form except for the dependencies. The solution techniques we have used are not limited to quadratic forms as outlined in reference four, any one of polynomial, exponential not limited to quadratic forms , any one of polynomial, exponential or mixed expressions of arbirtary complexity may be employed.

The second model gives the details of an HVAC air side system, i. e. old fashioned constant volume dual duct sysem found in many existing buildings. The challenge in this case was to operate the system as a partial variable volume system without changing the end controls at the mixing boxes.

In the project two or more models, such as the ones outlined, are combined into a large model for each one of the buildings. For example, there are fifty-six dual duct systems and one major chilled water system in one of the towers. The details of the distribution systems are also considered in the models. They will be presented in a forthcoming paper.

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MODEL I

This model represents the HVAC system of a high rise building in San Francisco CA. The system consists of four variable volume air handling systems, three chillers and four cooling towers. The system variables are:

m(i) : the air flow rate for air handling system i.
L(i) : the water flow rate through the (i)th coil.
Ts(i) : supply air temperature for the (i)th air handling system.
Tc(i) : chilled water supply temperature from the (i)th chiller.
Tcr : chilled water return temperature.
Lc(i) : evaporator side water flow rate for the the (i)th chiller.
Lt(i) : condenser side water flow rate for the (i)th chiller.
Te(i) : (i)th chiller evaporator temperature.
Tco(i): (i)th chiller condenser temperature.
Tts : tower supply temperature.
Ttr : tower return temperature.
G : air flow through an operating cooling tower(lb/hr).

Predictions for the following are supplied every period to the model:

Q(i) : load for the zone served by the (i)th air handing system.
Tr(i) : return temperature form the (i)th zone.
To : outside air temperature.
Twb : wet bulb temperature.

The system is represented by the following sets of equations:

Air handling system heat balance equations,

$$m(i)Tr(i) - (Q(i) + m(i)Ts(i)) = 0 \quad \text{for } i = 1,....,4 \qquad (1)$$

Coil rate equations,

$$(Tecon(i) - Tc).\, CminEff(i) - Q(i) - Efan(i) + (Tr(i) - Tecon(i)).\, m(i) = 0 \quad \text{for } i = 1,....,4 \qquad (2)$$

where

Tecon(i) : temperature of air after the economizer for the (i)th system.
= min { Tr(i),To }

CminEff(i) : effectiveness . m(i) for the (i)th coil
= f (m(i),L(i))

Efan(i) : energy consumption by the fans of the (i)th system
= f (m(i))

Conservation of mass,

$$\sum_{i=1}^{3} Lc(i) - \sum_{i=1}^{4} L(i) = 0 \qquad (3)$$

Heat balance of water side of coils,

$$\sum_{i=1}^{3} Lc(i) .\, (Tcr - Tc) - \sum_{i=1}^{4} (TotQ(i) + Efan(i)) = 0 \qquad (4)$$

where

$$TotQ(i) = Q(i) - (Tr(i) - Tecon(i)).\, m(i)$$

Evaporator rate equations,

$$(TcrS(i) - Te(i)) .\, Lc(i).EffEvap(i) - (Tcr - Tc(i)) .\, Lc(i) - EChillerPump(i) = 0 \quad \text{for } i = 1,....,3 \qquad (5)$$

where

TcrS(i) = Tcr + EChillerPump(i) / Lc(i)
EffEvap : evaporator effectiveness for the (i)th chiller
= f (Lc(i))
EChillerPump(i) : energy consumption by t he (i)th chiller pump
= f (Lc(i))

Condenser rate equations,

$$(Tco(i) - Tts) \cdot EffCond(i) \cdot Lt(i) - (Tcr - Te(i)) \cdot EffEvap(i) \cdot Lc(i) - EChiller(i) = 0 \quad (6)$$

for i = 1,....,3

where

EffCond(i) : condenser effectiveness of the (i)th chiller = f (Lt(i))

EChiller(i) : energy consumption by the chiller = f (Lc(i),Te(i),Tco(i),Tcr)

Condenser heat balance equation,

$$\sum_{i=1}^{3} Lt(i) \cdot (Ttr - Tts) - \sum_{i=1}^{3} (Lt(i) \cdot EffCond(i)) - \sum_{i=1}^{3} Etp(i) = 0 \quad (7)$$

where

Etp(i) : energy consumption by the (i)th tower pump = f (Lt(i))

Tower equation,

$$f (L/G,Tts,Ttr,Twb) = 0 \quad (8)$$

where

$$L = \sum_{i=1}^{3} Lt(i)/n$$

n = number of towers operating.

It can be shown that it is optimal to run as many towers as possible with equal loads on each.

Optimization of Model I

The above model of equations and variables presents a mixed integer non-linear programming problem. Not only are optimal setpoints searched for, but also the optimal combination of operating equipment. This task is approached by pre-determining feasible combinations of equipment and, for each of these combinations, solving a non-linear optimization problem. The generalized reduced gradient method is used to solve these non-linear equations. For model I the objective function to be minimized is:

$$\sum_{i=1}^{4} Efan(i) + \sum_{i=1}^{3} EChiller(i) + \sum_{i=1}^{3} EChillerPump(i) + \sum_{i=1}^{3} ETowerPump(i) + \sum_{i=1}^{n} ETower(i) \quad (9)$$

where

ETower(i) = f (G)

Once the solution is reached, the values for Ts(i), Tc(i), GPMc(i),GPMt(i) and Tts are assigned as setpoints to the computer control system and equipment is switched on and off as prescribed by the solution.

Model II

This model represents one of the air handling systems, serving half a floor, located at another high rise building in San Francisco CA. This system is essentially a dual-duct system and consists of a fan, a hot water coil, a cold water coil and n air mixing valves each controlled by a zone thermostat. The system variables used are:

P : fan head.

mh(i) : flow of hot air into the (i)th mixing valve.

mc(i) : flow of cold air into the (i)th mixing valve.

Th : hot air supply temperature.
Tc : cold air supply temperature.
Tm : mixed air temperature entering the fan.
Tr : return air temperature.
dPc(i) : pressure differential through the cold branch of the (i)th mixing box.
dPh(i) : pressure differential through the hot branch of the (i)th mixing box.
Qc : heat removed by the cold coil.
Qh : heat added by the hot coil.
S : speed of the fan.

Predicted inputs are:

q(i) : load for zone i.
t(i) : zone i temperature.
To : outside temperature.

The system is represented by the following equations:

Fan head,

$$P - K1 . (1 - (M/K2)^2) = 0 \qquad (10)$$

where K1 and K2 are fan specific constants.

$$M = \sum_{i=1}^{n} (mh(i) + mc(i)) \qquad (11)$$

Head loss equations,

$$Ks . (\sum_{i=1}^{n} (mh(i) + mc(i)))^2 - P$$
$$+ Kh . (\sum_{i=1}^{n} (mh(i))^2$$
$$+ Kh(i) . (mh(i))^2$$
$$+ Ks(i) . (mh(i) + mc(i))^2$$
$$+ Kr . (\sum_{i=1}^{n} (mh(i) + mc(i)))^2 \geq 0 \qquad (12)$$

for i = 1,...., n

and

$$Ks . (\sum_{i=1}^{n} (mh(i) + mc(i)))^2 - P$$
$$+ Kc . (\sum_{i=1}^{n} (mh(i))^2 + Kc(i) . (mh(i))$$
$$+ Ks(i) . (mh(i) + mc(i))^2$$
$$+ Kr . (\sum_{i=1}^{n} (mh(i) + mc(i)))^2 \geq 0 \text{ for } i = 1,....,n$$

where Ks, Kh, Kh(i), Kc, Kc(i), Ks(i) and Kr are loss coefficients for different sections of the duct system.

Air mixing box equations,

$$[(k(i) . mc(i)^2) / dPc(i)]^{1/2}$$
$$+ [(k(i) . mh(i)^2) / dPh(i)]^{1/2} = 1 \qquad (13)$$

for i = 1,...,n

where

K(i) : flow resistance coefficient when damper is open.

Zone heat balance equations,

$$q(i) - mc(i) . (T(i) - Tc)$$
$$- mh(i) . (T(i) - Th) = 0 \qquad (14)$$

for i = 1,....,n

Heat removed through cold coil,

$$Qc - (\sum^{n} mc(i)) . (Tm - Tc) = 0 \qquad (15)$$
$$i=1$$

Heat added through hot coil,

$$Qh - (\sum_{i=1}^{n} mh(i)) . (Tm - Th) = 0 \qquad (16)$$

Return temperature calculation,

$$M * Tr - \sum_{i=1}^{4} (M(i) . T(i)) = 0 \qquad (17)$$

where

$$M(i) = mc(i) + mh(i)$$

Mixed temperature calculation,

$$M.Tm$$
$$- (Po.To.M + (1 - Po).Tr.M + Ef) = 0 \qquad (18)$$

where

Ef : energy consumed by fan.
= f (M)

Flow constraint,

$$M = Mdesign$$

$$\text{where } Mdesign = \sum_{i=1}^{n} m(i)design \qquad (19)$$

Optimization of Model II

Again the generalized reduced gradient method is used for the solution. The objective function that is minimized is:

$$Cf . Ef - Ch . Qh + Cc . Qc \qquad (20)$$

where

Cf = $ cost of 1 BTU/hr of electricity.
Ch = $ cost of 1 BTU/hr of heating.
Cc = $ cost of 1 BTU/hr of cooling.

Optimal settings for Th and Tc are determined using the optimizer.

This model can easily be extended to optimize a variable speed system in which case the fan speed is also prescribed. To achieve this, equation (10) and (19) have to be modified as follows:

$$P - K1 . (S / Sdesign - (M / K2)^2) = 0 \qquad (10a)$$

$$M / Mdesign = S / Sdesign \qquad (19a)$$

Optimization Techniques

Several non-linear programming techniques have been applied to the models described. Direct methods and penalty function methods have been experimented with. Generalized Reduced Gradient (GRG) method which is a direct method proved to be the most efficient for our purposes. The major advantages of the GRG method in our case can be summarized as follows:
(1) As most of the constraints are equalities, especially in Model I the size of the problem is smaller compared to other methods , therefore efficiency is better.
(2) In constrast to the penalty function method, at each step of the algorithm we are at a feasible point and the value of the objective function is continually improving. This means that even if the algorithm stops prematurely before reaching a global optima or solution time exceeds the specified period we can still use the results. This feature is extremely important when optimization is being done on-line.
The major disadvantage of the GRG method is that you either have to start from a feasible point or find a feasible point using some suitable method.

CONCLUSIONS

The discussions above show that the modelling of the systems is not difficult. We have used algebraic equations in representing system behavior, due to the small time lags in the building response relative to the calculation period. The larger time lags due to diurnal periodicity are taken into account in the predictive section of the models.

The difficulties in this type of application are the identification of the many cases of the mixed integer problem, and the pathological cases encountered in the search for the optimum. In other words one has to set up each feasible combination of equipment that can run together at one time and model it. Then a feasible starting point must be found for each one of these cases for the given conditions in the building before one can continue with the optimization. Not to mention the trivial but important problem of what to do when incoming data about the state of the systemis either erronous or missing would be a disservice to the reader. One tends to spend a considerable amount of time in solving these practical problems as well as the problems associated with non-convergence.

Overall this project has been rewarding both in terms of the savings achieved in energy use and the continuing challenge it posed at each step of the way in our work.

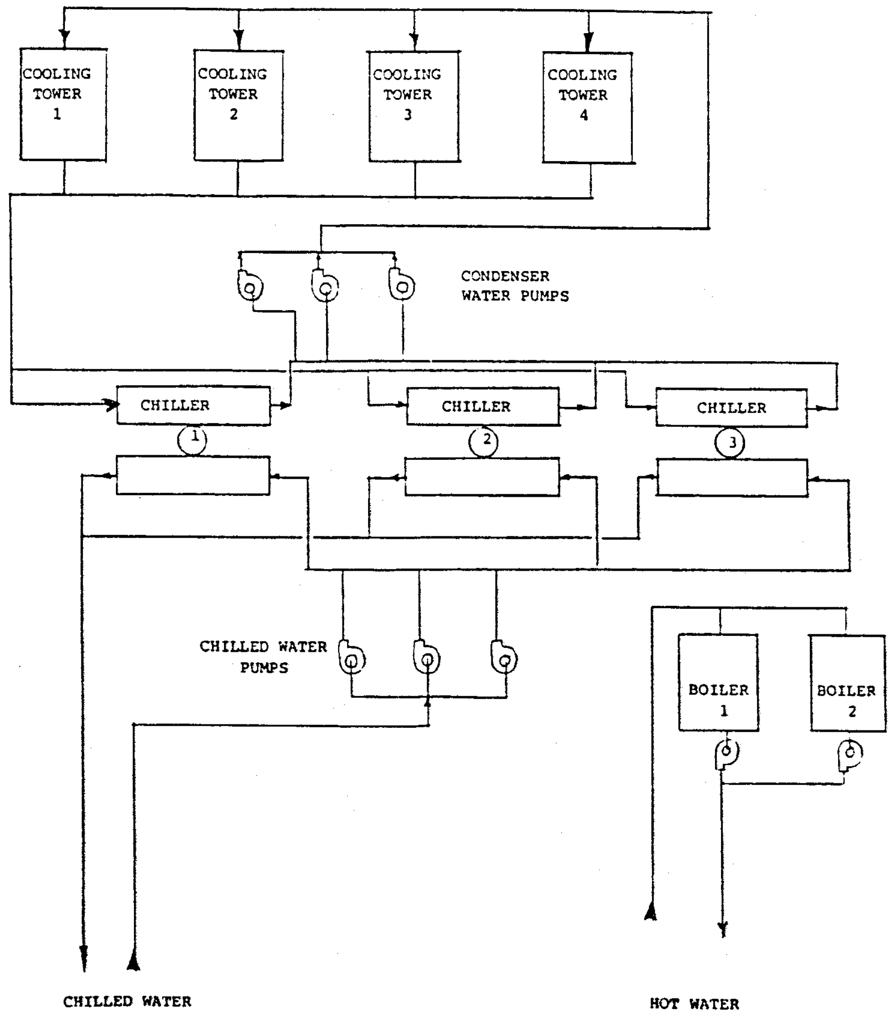

Figure 1: Central Plant Diagram.

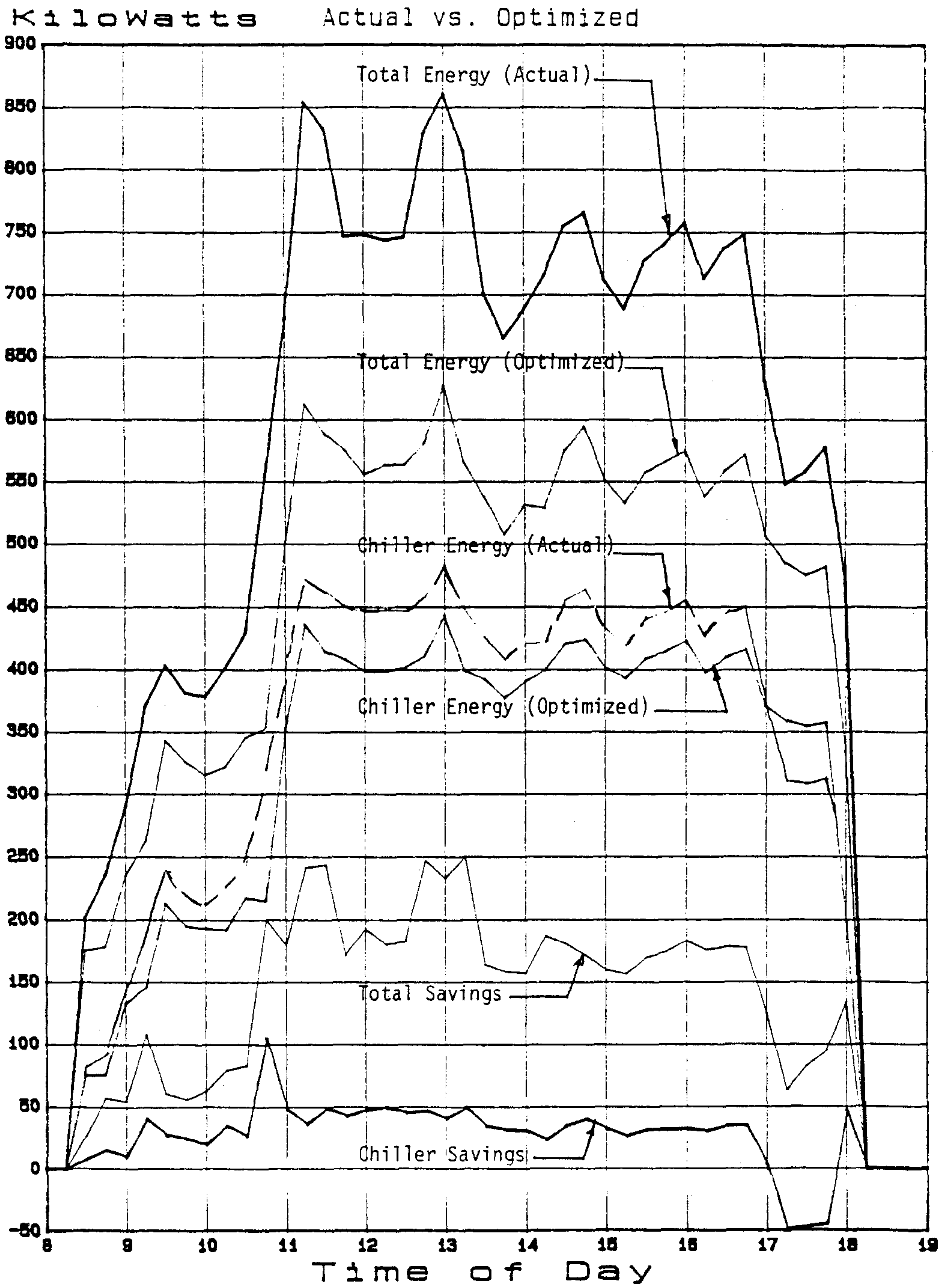

Figure 2: Typical Summer Day Dperation.

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