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AN ENERGY RESOURCE ALLOCATION MODEL FOR THE UNIVERSITY OF CENTRAL FLORIDA CENTRAL ENERGY PLANT

BY

MOHAMMED A. CHAMMA
B.S., University of Central Florida, 1978

RESEARCH REPORT

Submitted in partial fulfillment of the requirements
for the Degree of Master of Science in Engineering
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ABSTRACT

The demand for energy increases every year, and it is important that we ensure that the energy consumed is used efficiently. This study examines a system which provides energy in multiple forms from multiple energy sources using multiple energy conversion equipment. Such a system is termed a Central Energy Plan (CEP). A linear programming model was formulated to provide a close approximation of a CEP operation. It was used to determine the optimal operating configuration, that is, which equipment should be on or off at a particular time of the day, to minimize the operating cost of the plant while at the same time meeting output requirements.

The CEP model was validated by using actual data provided by the physical plant personnel at the University of Central Florida (UCF). The feasibility of installation of a steam turbine driven electrical generator to improve the performance of the CEP was investigated as a test vehicle to prove the practicality of the model.

I wish to dedicate this report to my parents, who have always considered knowledge the most important entity, even above the physical necessities of life.

ACKNOWLEDGEMENT

I would like to express my sincere thanks to Dr. R. D. Doering, my advisor, for his guidance and encouragement in the preparation of this report. I would also like to express my gratitude to the Allison and Montero families to whom I am indebted for their continuous help and support.

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CHAPTER 1

INTRODUCTION

The 1974 curtailment of crude oil shipment to the consuming nations caused management to embark on immediate measures to reduce energy consumption. Still the cost of energy production continues to increase in parallel with the energy demands. It is important that energy plants allocate the available energy resources as efficiently as possible, since most of them are not renewable. Long term measures of energy conservation have been devoted to development of new techniques for energy management. These typically are computer based and control energy usage equipment via programmed algorithms which respond dynamically to environmental and process requirements. These techniques can be typified by Energy Management Systems (EMS) which have been applied to universities, shopping malls, and many large commercial and industrial buildings to control heating, ventilating and air conditioning (HVAC) systems. For example, the physical plant at the University of Central Florida (UCF) uses a Delta 2000 EMS system to automatically program the operation of the mechanical systems, such as air handlers, pumps, and compressors, to

reduce energy consumption during hours of low energy demands.

To ensure the perpetuation of our socio-economic order it is essential that we conserve energy, by making the most efficient use of it. Otherwise, at the rate energy resources are being depleted, future generations may not have enough to continue mankind's progress. These considerations urge that energy use be optimized.

In reality, the concept of energy optimization is not new. For many years, large plants have used waste energy to provide shaft work, and to generate electricity. For example, many of the oil refining plants used to generate about 40% of their electrical power requirements by using a gas turbine driven generator. The generated heat from the generator was recuperated and used to provide hot water for the plant. [Wilson 1966, p. 9] These cogeneration applications were limited in the days of so-called cheap and unlimited energy, because first cost economics and the requirement of more complex design considerations did not justify the long term economics. Today, however, with the continued upward spiraling fuel costs, energy conservation has become a vital activity.

Objective of the Study

This paper develops an EMS technique for a special type of energy system, one which provides energy in many forms from multiple energy supplies using multiple energy conversion equipment. This system has been termed a Central Energy Plant (CEP), and has become increasingly popular in recent years for applications in large building complexes where the energy loads are captive and the distribution lines are relatively short. The objective will be accomplished in two steps:

1) Development of a Linear Programming (LP) model which incorporates various parameters and constraints of a typical CEP so that it can be used to determine the minimum cost equipment operating configuration to satisfy the energy demand on the plant.
2) Use the LP model to study the economic feasibility of installing a steam driven electrical generator at the UCF CEP.

CHAPTER 2

DESCRIPTION OF U.C.F. CEP

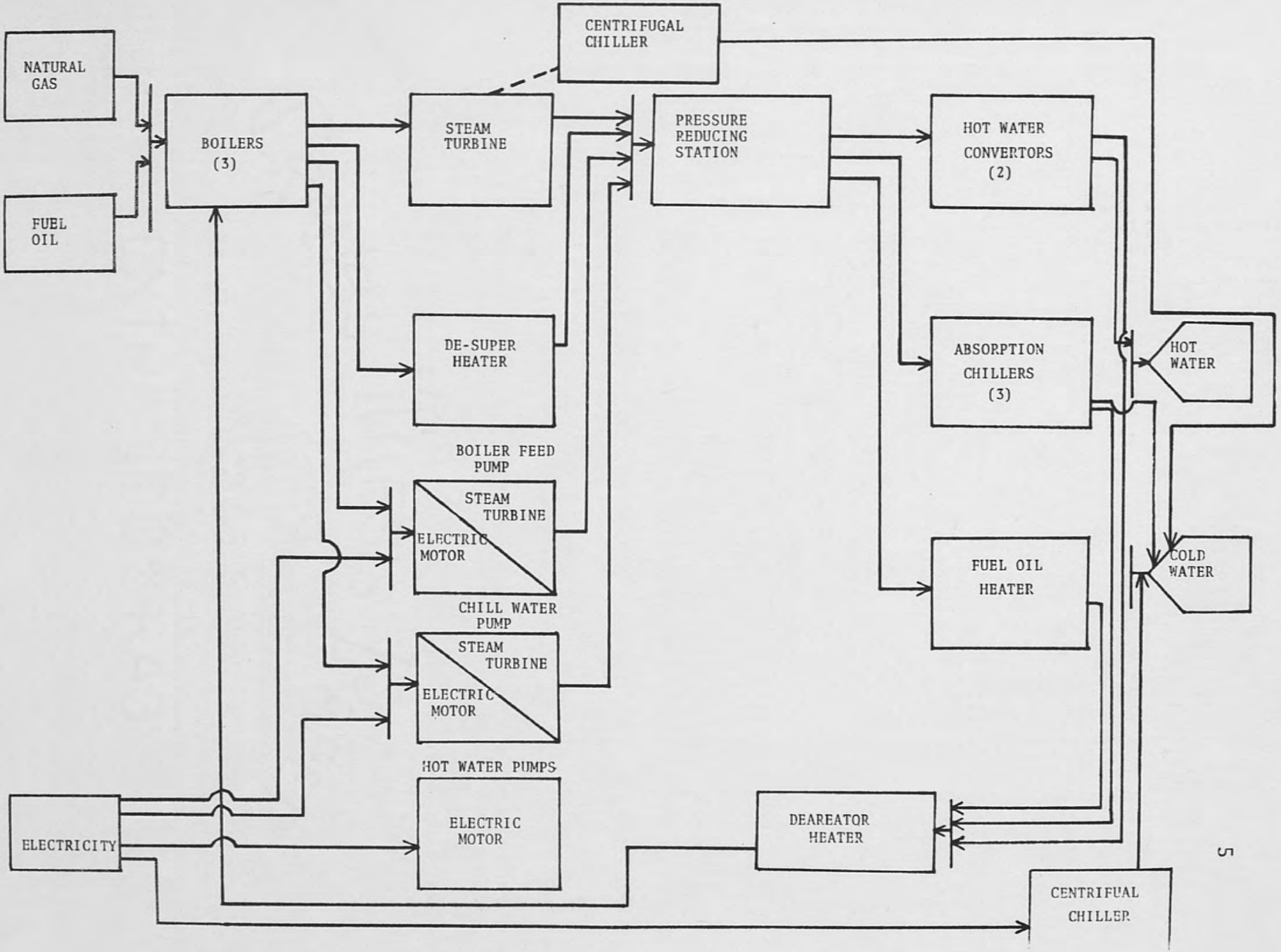
To better focus this research toward the practical applications an actual system was considered; operational characteristics were taken from the CEP which serves the UCF campus.

System Description

UCF currently spends about $1.5 million each year in fuel and purchased energy costs. With the continued energy shortage and escalating energy costs, it is appropriate to identify and explore operational methods which might reduce fuel consumptions and costs in operation of the CEP. The energy costs rob the other campus activities. Figure 1 is a block diagram of the physical system which identifies the major equipment and the basic steam cycle on which the plant was designed.

The system is designed to use three sources of energy: Electricity, natural gas, and fuel oil from which it produces and distributes two forms of energy, chilled water and hot water, as required, to meet the demand on campus. At the present time, electricity is not generated at this

Figure 1. Present Central Energy Plant


NATURAL GAS
FUEL OIL
BOILERS (3)
CENTRIFUGAL CHILLER
STEAM TURBINE
PRESSURE REDUCING STATION
HOT WATER CONVERTORS (2)
DE-SUPER HEATER
ABSORPTION CHILLERS (3)
HOT WATER
BOILER FEED PUMP
STEAM TURBINE
ELECTRIC MOTOR
FUEL OIL HEATER
COLD WATER
CHILL WATER PUMP
STEAM TURBINE
ELECTRIC MOTOR
HOT WATER PUMPS
ELECTRIC MOTOR
ELECTRICITY
DEAREATOR HEATER
CENTRIFUAL CHILLER

centrifugal chiller which requires approximately 15% of the electricity purchased by the University. The balance is consumed for lighting and operation of HVAC and other mechanical systems on campus.

Chilled water is distributed through a circulating loop at a supply temperature of 45°F to the building HVAC systems and returns at a temperature of 55°F. The water is generated by three absorption chillers fired by low pressure steam and two centrifugal chillers; one powered by a steam turbine and the other by electric motor. The total cooling capacity is 5600 tons of refrigeration per hour.

Hot water at 200°F is pumped through a circulation loop to each building campus through a closed loop circulating system from the CEP. The water is generated by two hot water convertors which use low pressure steam. The water is circulated by electrically powered pumps through the heating loop. Both hot and cold water are circulated through 7 miles of piping to the UCF campus before returning to CEP.

The Central Energy Plant (CEP) at UCF operates on a high and low pressure steam system using the basic steam cycle. High temperature steam at 235 psig and 500°F is generated in 3 boilers fired by gas and/or fuel oil. The steam is used in a desuper heater and the turbine driven equipment. The desuper heater cools the steam to 400°F,

and provides some of the high temperature water for the heating loop. The superheated steam is used to drive the steam turbine which powers the centrifugal chiller and pumps.

The saturated steam at 235 psig is processed through a pressure reducing station where the pressure is reduced to 20 psig and becomes low pressure supply steam for low pressure operated equipment. Exhaust steam from the turbine driven equipment also goes into the low pressure steam supply.

When the steam has given up its heat of condensation, it becomes condensate, and is pumped to the deaerator heater where air is removed, and it becomes boiler feed water. Approximately 94% of the condensate is returned on each cycle, the rest is lost in steam leaks and boiler blow down. The control of operations of any equipment is primarily manual at this time.

CHAPTER 3

DEVELOPMENT OF CEP MODEL

INTRODUCTION

A model is the best way to analyze a complex interrelated system such as a Central Energy Plant (CEP) because it permits examination of different operational configurations without disturbing the operations. Modeling is developing a system or expression which faithfully duplicates the functions of a real system. It may take on a physical form or be a completely analytical expression; its precise characteristics are often unknown. When a problem can be defined in model terms, its solutions may be more easily found. Investigation of the performance of the actual system through an analogous model system is more easily accessible to the system analyst. A model, however, cannot be exactly identical to the real system in performance since many assumptions are typically necessary in order to simplify the complex real system into a model.

The benefits of modeling are numerous. It permits the study of the actual system without interfering or

making changes in it. It is also less costly working on a model than on a real system. Experiments can be repeated many times on the model, while repetition on the real system is not always feasible.

Modeling a Central Energy Plant

Traditionally, the operating decisions in a CEP are performed by a control room dispatcher on the basis of empirical data which has been gathered from the past years. This data base represents knowledge of equipment efficiencies, equipment limitations, and costs of energy. The decisions may resolve into simple economic choices, but, as the operation relationships between equipments become complex and the energy rates change, the information required to make good decisions surpass the capabilities of the dispatcher to relate all the parameters and their effects. Even in a simple system it is sometimes difficult to predict how it would respond to changes in its parameters. This difficulty can be eased by developing a model that can be used to describe the system, and then exercised to develop more information to predict how it will perform under given conditions of input and operating constraints. Specifically, the model can provide information to better define the interactions of the plant equipments so that more cost effective decisions can be made under varying plant load conditions.

The Central Energy Plant (CEP) can be approached in this manner using simulation or optimization techniques such as linear programming. Simulation involves the construction of a working mathematical model which presents the same properties and relationships of the actual system under study. The simulation model takes time to reach a steady state, and even then, it is difficult to know when a steady state is reached. Simulation provides a possible solution, but generally it is not the optimal one. Due to the characteristics of simulation real system behavior is predicted, but only within a probability distribution.

Linear Programming (LP) is easy to grasp and formulate and typically fits the CEP operating process of given constraints and requirements. It requires three basic kinds of data:

1) Coefficients for the objective function
2) Coefficients of substitution (technological coefficients)
3) Capacities of requirements

Linear Programming is more sensitive to a root analysis, because it deals with changes in data which directly affect changes in the optimal solution which is unique according to the situation under study.

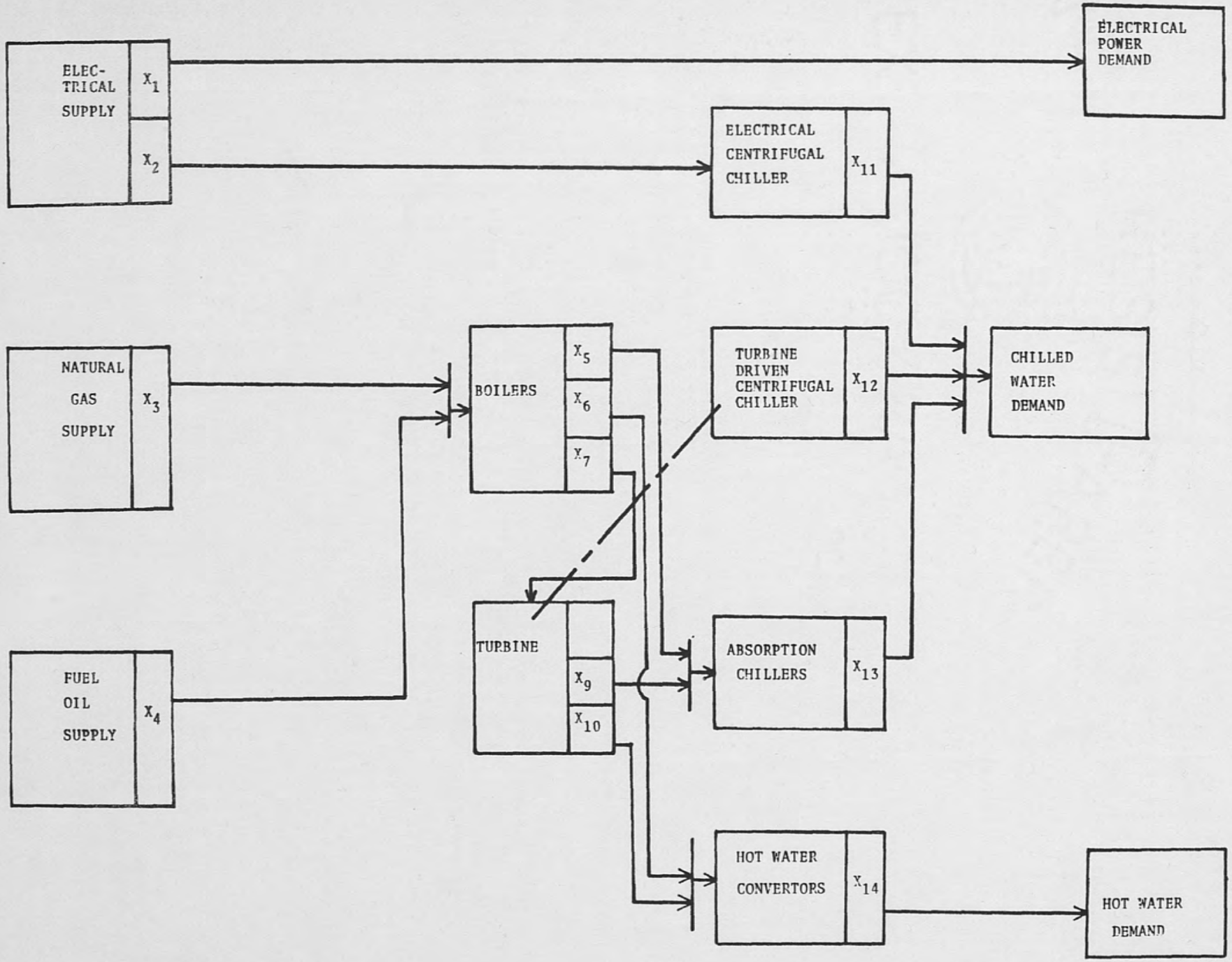
For the Central Energy Plant (CEP) at UCF it appears that an LP model would be the better approach because it better fits the characteristics of the plant itself, and would be less expensive to apply than simulation.

System Equations for U.C.F. CEP

The objective of this model is to minimize the operating cost via different equipment configurations. It should indicate which equipment should be "on" or "off" at a given period of the day while meeting the demands and system constraints. The simplified model shown in Figure 2 assumes constant temperature for the absorption chillers and the hot water convertors, in order to keep the efficiency of these equipment relatively constant. Also, the equipment should be operating at a load greater than 40% of the maximum. Maintenance and start up costs were not considered in this model.

The start ups of the different equipments are considered instantaneous, while in reality, it takes considerable time to switch from gas to fuel oil to fully operate a boiler or activate an absorption chiller. Additionally, start ups are limited by the characteristics of the equipment; for example, the large electrically driven centrifugal chiller is limited in the starts it can make per day, because of the motor size.

Figure 2. Proposed CEP Model


ELEC-
TRICAL
SUPPLY
X_1
X_2
ELECTRICAL
POWER
DEMAND
ELECTRICAL
CENTRIFUGAL
CHILLER
X_{11}
NATURAL
GAS
SUPPLY
X_3
BOILERS
X_5
X_6
X_7
TURBINE
DRIVEN
CENTRIFUGAL
CHILLER
X_{12}
CHILLED
WATER
DEMAND
FUEL
OIL
SUPPLY
X_4
TURBINE
X_9
X_{10}
ABSORPTION
CHILLERS
X_{13}
HOT WATER
CONVERTORS
X_{14}
HOT WATER
DEMAND

The conversion relationships relate the flow of energy from one state to another. The model indicates the rate at which electricity, natural gas and fuel oil are purchased, and the rates at which the conversion equipments are operating. The rates are expressed in Million British Thermal Units per hour (MBTU/HR).

The costs of the rates at which energy is purchased can be expressed in dollars per Million British Thermal Units ($/MBTU). Therefore, the objective function to minimize the cost of energy used per hour could be written.

Minimize $Z = C_1X_1 + C_1X_2 + C_2X_4$ where,

C_1 = is the cost of purchased electricity ($/MBTU)

C_2 = is the cost of natural gas ($/MBTU)

C_3 = is the cost of fuel oil #6 ($/MBTU)

X_1 = is the rate at which electricity is purchased to meet the electrical power demand (MBTU/HR)

X_2 = is the rate at which electricity is purchased to operate the electrical centrifugal chiller (MBTU/HR)

X_3 = is the rate at which natural gas is purchased to operate the boilers (MBTU/HR)

X_4 = is the rate at which fuel oil is purchased to operate the boilers (MBTU/HR)

Each piece of equipment (boilers, steam driven turbine, electrical centrifugal chiller, turbine driven centrifugal chiller, absorption chillers, and hot water convertors) operates between a realistic maximum and minimum output

capacity for a given efficiency. For example, the equations:

$a_1X_3 + a_2X_4 \geq b_1 (X_{15} + X_{16} + X_{17})$ This relationship ensures the energy converted by one operating boiler is greater or equal to b_1 which is the minimum capacity of one boiler. The coefficients a_1 and d_2 are energy conversion factors for natural gas (X_3) and fuel oil (X_4) respectively. The variables X_{15}, X_{16} and X_{17} represent boiler number 1, 2 and 3.

$a_1X_3 + a_2X_4 \leq b_2 (X_{15} + X_{16} + X_{17})$ This equation ensures that the maximum energy converted by one boiler can not exceed b_2 which is the maximum output capacity.

$a_1X_3 + a_2X_4 = X_5 + X_6 + X_7$ This relationship ensures that the continuous flow of energy input converted by one to three boilers is equal to the total energy output, $X_5 + X_6 + X_7$

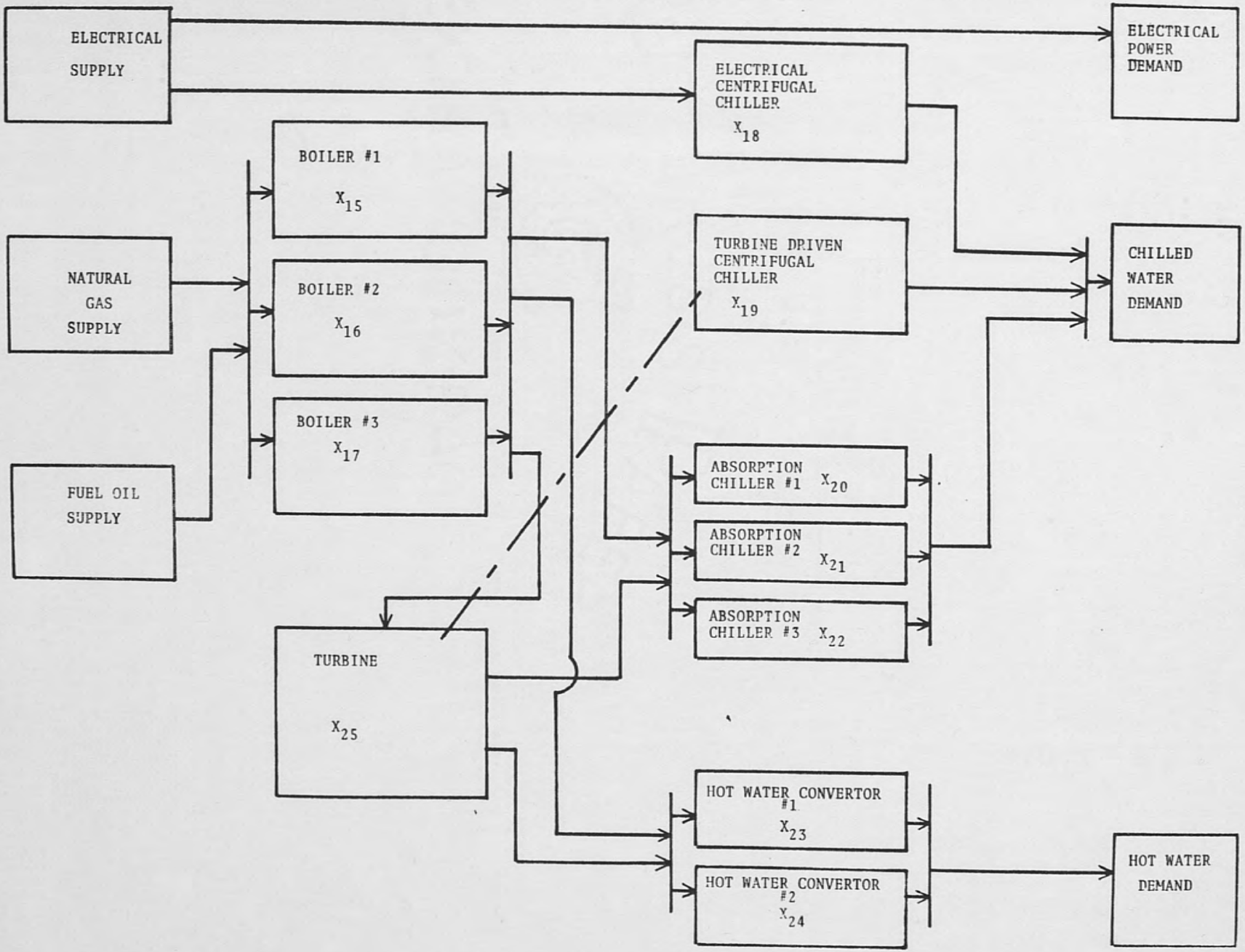
where,

X_5 = is the rate at which the absorption chillers are using steam (MBTU/HR)

X_6 = is the rate at which hot water convertors are using steam (MBTU/HR)

X_7 = is the rate at which the turbine is using steam (MBTU/HR)

Figure 3. Detail of the Proposed Model


ELECTRICAL SUPPLY
ELECTRICAL POWER DEMAND
ELECTRICAL CENTRIFUGAL CHILLER
X_{18}
BOILER #1
X_{15}
NATURAL GAS SUPPLY
BOILER #2
X_{16}
TURBINE DRIVEN CENTRIFUGAL CHILLER
X_{19}
CHILLED WATER DEMAND
BOILER #3
X_{17}
FUEL OIL SUPPLY
ABSORPTION CHILLER #1 X_{20}
ABSORPTION CHILLER #2 X_{21}
ABSORPTION CHILLER #3 X_{22}
TURBINE
X_{25}
HOT WATER CONVERTOR #1
X_{23}
HOT WATER CONVERTOR #2
X_{24}
HOT WATER DEMAND

The block diagram in Figure 3 shows the variables and the flow of energy among all equipments. The constraint equations for the remainder of the equipment comprising the CEP are based on the same reasoning as the ones for the boilers.

$$a_3X_7 \geq b_3 (X_{25})$$
$$a_3X_7 \leq b_4 (X_{25})$$
$$a_3X_7 = X_9 + X_{10}$$

Turbine Exhaust

$$a_4X_2 \geq b_5 (X_{18})$$
$$a_4X_2 \leq b_6 (X_{18})$$
$$a_4X_2 = X_{11}$$

Electrical Centrifugal Chiller

$$a_5X_7 \geq b_7 (X_{19})$$
$$a_5X_7 \leq b_8 (X_{19})$$
$$a_5X_7 = X_{12}$$

Turbine Driven Centrifugal Chiller

$$a_6X_5 + a_7 X_9 \geq b_9 (X_{20} + X_{21} + X_{22})$$
$$a_6X_5 + a_7 X_9 \leq b_{10}(X_{20} + X_{21} + X_{22})$$
$$a_6X_5 + a_7 X_9 = X_{13}$$

Absorption Chillers

$$a_8X_6 + a_9 X_{10} \geq b_{11}(X_{23} + X_{24})$$
$$a_8X_6 + a_9 X_{10} \leq b_{12}(X_{23} + X_{24})$$
$$a_8X_6 + a_9 X_{10} = X_{14}$$

Hot Water Convertors

where,

a_3 = The efficiency of the turbine to convert high pressure steam to low pressure steam.

b_3 = Minimum low pressure steam exhaust of the turbine (MBTU/HR).

b_4 = Maximum low pressure steam exhaust of the turbine (MBTU/HR).

X_9 = The rate at which low pressure steam is used to operate the absorption chillers (MBTU/HR).

X_{10}= The rate at which low pressure steam is used to operate the hot water convertors (MBTU/HR).

a_4 = The efficiency of the electrical centrifugal chiller to convert power to cold water.

b_5 = Minimum output of the electrical centrifugal chiller of cold water (MBTU/HR).

b_6 = Maximum output of the electrical centrifugal chiller of cold water (MBTU/HR).

X_{11}= The rate at which the cold water is produced by the electrical centrifugal chiller (MBTU/HR).

a_5 = The efficiency of the turbine driven centrifugal chiller to convert high pressure steam to cold water.

b_7 = Minimum output of the turbine driven centrifugal chiller in cold water (MBTU/HR).

b_8 = Maximum output of the turbine driven centrifugal chiller in cold water (MBTU/HR).

X_{12}= The rate at which cold water is produced by the centrifugal chiller (turbine driven) (MBTU/HR).

a_6 = The efficiency of the absorption chillers using superheated steam to produce cold water.

a_7 = The efficiency of the absorption chillers using low pressure steam to produce cold water.

b_9 = Minimum output of one absorption chiller in cold water (MBTU/HR).

b_{10}= Maximum output of one absorption chiller in cold water (MBTU/HR).

X_{13}= The rate at which cold water is produced by the absorption chillers (MBTU/HR).

a_8 = The efficiency of hot water convertors using high pressure steam to produce hot water.

a_9 = The efficiency of hot water convertors using low pressure steam to produce hot water.

b_{11}= Minimum output of one hot water convertor of hot water (MBTU/HR).

b_{12}= Maximum output of one hot water convertor of hot water (MBTU/HR).

X_{14}= The rate at which hot water is produced by the hot water convertors (MBTU/HR).

X_{18} = The electrical centrifugal chiller.

X_{19} = The steam driven centrifugal chiller.

X_{20} = The absorption chiller #1

X_{21} = The absorption chiller #2

X_{22} = The absorption chiller #3

X_{23} = Hot water convertor #1

X_{24} = Hot water convertor #2

X_{25} = The steam driven turbine.

The three absorption chillers are identical. Also, the two hot water convertors have the same capacity.

The efficiencies are the percentage of energy input which is converted to the corresponding energy output for a designated piece of equipment.

For a given energy demand the following relationships indicate which machine is on or off for a given period of the time of the day;

$$X_5 + X_6 + X_7 = b_2 (X_{15} + X_{16} + X_{17})$$

This relationship indicates which boiler should be on, and which boiler should be off for a given energy demand.

The equations,

$$X_{11} = b_6 (X_{18})$$

$$X_{12} = b_8 (X_{19})$$

$$X_{13} = b_{10}(X_{20} + X_{21} + X_{22}),$$

ensure that the cold water demand is satisfied by operating the electrical centrifugal chiller, or the turbine driven centrifugal chiller, or the 3 absorption chillers, or all of them working at the same time;

$$X_{14} = b_{12} (X_{23} + X_{24})$$

This equation ensures that the hot water demand is satisfied by 1 or 2 hot water convertors operating at the same time. The 3 energy demands of electrical, hot and cold water are stated by:

$$X_1 \geq EPD$$

$$X_{11} + X_{12} + X_{13} \geq CWD$$

$$X_{14} \geq HWD$$

where,

EPD = Electrical power demand (MBTU/HR)

CWD = Chilled water demand (MBTU/HR)

HWD = Hot water demand (MBTU/HR)

The following relationships,

$X_i \leq 1, \; i = 15, \text{---}, 25$

$X_i \geq 0, \; i = 1, \text{---}, 25$

guarantee that the operating equipment of CEP model is operating between 0 and 1 where "0" indicates that the equipment is idle and the "1" indicates that the equipment is operating at a maximum load of 100%

Together, the objective function, the constraints for each configuration, the constraints indicating which machine should be on, the energy demand requirements, and the constraint that all X_1 through X_{25} be non-negative can be combined to yield the Linear Programming (LP) model. The system equations which represent the CEP model then can be written,

Minimize $Z = C_1X_1 + C_1X_2 + C_2X_3 + C_3X_4$

subject to:

$a_1X_3 + a_2X_4 \text{ -- } b_1 (X_{15} + X_{16} + X_{17}) \geq 0$

$a_1X_3 + a_2X_4 \text{ — } b_2 (X_{15} + X_{16} + X_{17}) \leq 0$

$a_1X_3 + a_2X_4 \text{ — } (X_5 + X_6 + X_7) = 0$

$$a_3X_7 - b_3 (X_{25}) \geq 0$$

$$a_3X_7 - b_4 (X_{25}) \leq 0$$

$$a_3X_7 - (X_9 + X_{10}) = 0$$

$$a_4X_2 - b_5 (X_{18}) \geq 0$$

$$a_4X_2 - b_6 (X_{18}) \leq 0$$

$$a_4X_2 - X_{11} = 0$$

$$a_5X_7 - b_7 (X_{19}) \geq 0$$

$$a_5X_7 - b_8 (X_{19}) \leq 0$$

$$a_5X_7 - X_{12} = 0$$

$$a_6X_5 + a_7X_9 - b_9 (X_{20} + X_{21} + X_{22}) \geq 0$$

$$a_6X_5 + a_7X_9 - b_{10} (X_{20} + X_{21} + X_{22}) \leq 0$$

$$a_6X_5 + a_7X_9 - X_{13} = 0$$

$$a_8X_6 + a_9X_{10} - b_{11} (X_{23} + X_{24}) \geq 0$$

$$a_8X_6 + a_9X_{10} - b_{12} (X_{23} + X_{24}) \leq 0$$

$$a_8X_6 + a_9X_{10} - X_{14} = 0$$

$$X_5 + X_6 + X_7 - b_2 (X_{15} + X_{16} + X_{17}) = 0$$

$$X_{11} - b_6X_{18} = 0$$

$$X_{13} - b_{10} (X_{20} + X_{21} + X_{22}) = 0$$

$$X_{12} - b_8X_{19} = 0$$

$$X_{14} - b_{12} (X_{23} + X_{24}) = 0$$

$X_i \leq 1, \; i = 15, \text{---}, 25$

$X_1 \geq \text{EPD}$

$X_{11} + X_{12} + X_{13} \geq \text{CWD}$

$X_{14} \geq \text{HWD}$

$X_i \geq 0, \; i = 1, \text{---}, 25$

This system forces the equipment to operate at least at the minimum rate to achieve the optimal solution.

CHAPTER 4

CASE STUDY

System Definition

The CEP uses as raw material three sources of energy: electricity purchased from a power company, natural gas, and fuel oil #6. It generates two forms of energy: chilled water and hot water. Chilled water is circulated to the campus buildings at a rate of 4800 GPM. The electric motor driven centrifugal chiller produces 2000 tons of refrigeration, and the three absorption chillers contribute 800 tons of refrigeration each. The turbine driven centrifugal chiller generates 1200 tons of refrigeration. Total plant chilled water capacity is 2,760 tons of refrigeration.

The two hot water convertors produce 17,000,000 BTU of hot water each, and the resulting hot water circulates continuously at a rate of 850 GPM. Each boiler has a capacity of 45,000 lbs/hr of superheated steam at 235 psig and 500^{o}F for a total capacity of 120.3 MBTU/HR.

The energy consumption of the equipment is reported in the form of energy per unit time (power) and the model uses MBTU/HR. Accordingly, all equipment capacities and

power demands in kilowatts were converted to the single unit of MBTU/HR.

Likewise, fuel oil and natural gas have recognized heat values in units of BTU per gallon, and BTU per cubic feet, respectively. The boilers can be fired with natural gas or fuel oil. Tests have shown that energy conversion coefficient of performance (COP) for boilers using fuel oil is 70% and when fired by natural gas, the COP is approximately 73%.

The absorption chillers have a COP of 62% while the electrically driven centrifugal chiller has a COP of 4.0, and the turbine driven centrifugal chiller unit, 2.6. The hot water convertors have an efficiency of 75%. [Hutchinson 1976, p. 27] The performance efficiencies are summarized in Table 1.

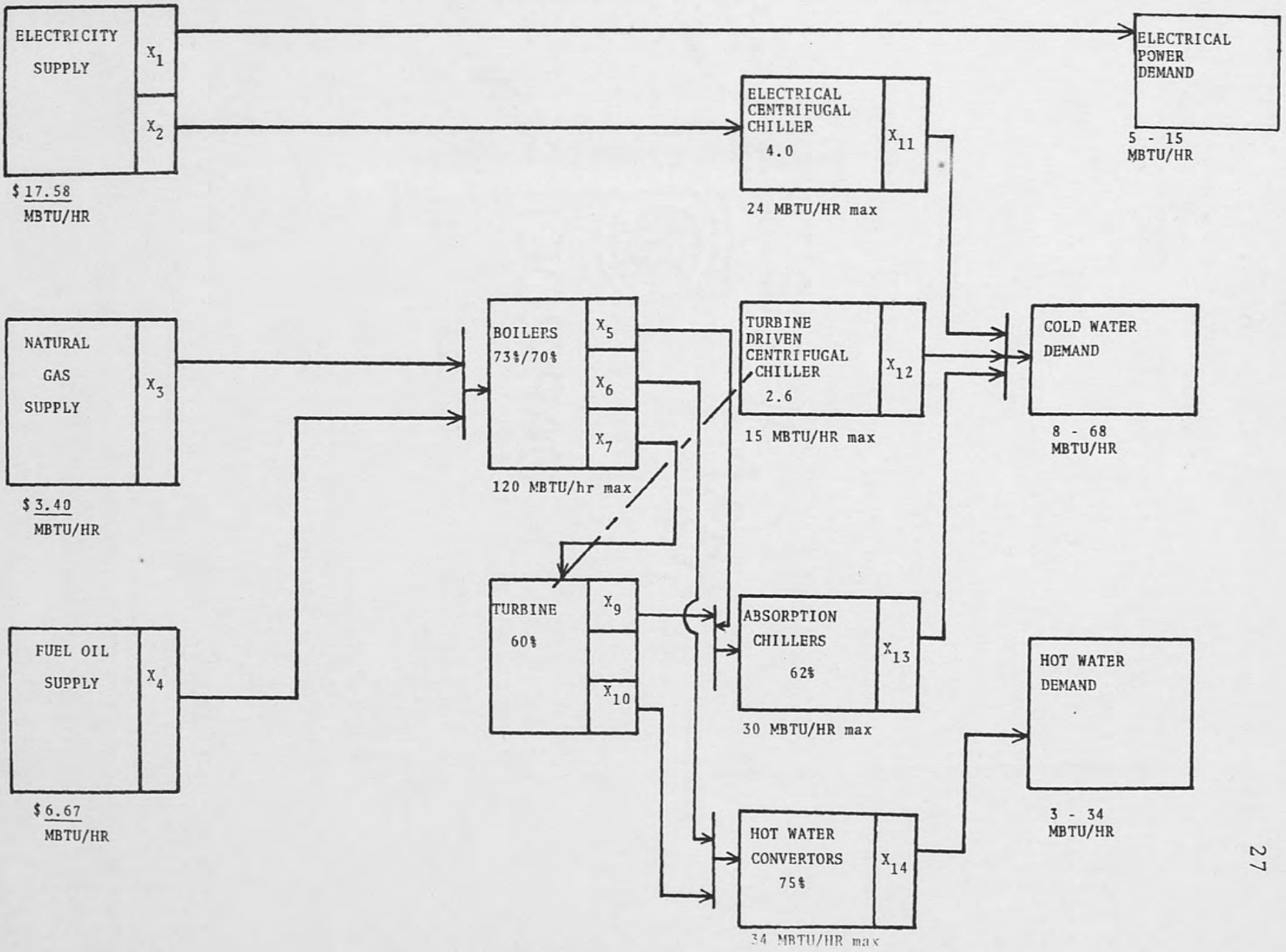
All efficiency values were considered to remain relatively constant within their normal operational load. In Figure 4 a typical system operating configuration involving the absorption chillers, centrifugal chillers, boilers and hot water convertors is shown. There are operating interactions between these equipments, and the demand requirements can be satisfied by different combinations of equipments. Accordingly, trade-off decisions are required based on operating constraints, input energy limits, and maximum output energy requirements by type. For example, the CEP at UCF consumes over 90% of natural

TABLE 1

CAPACITIES AND EFFICIENCIES

TYPE OF EQUIPMENT	COEFFICIENT OF PERFORMANCE (COP) %	MAXIMUM OUTPUT (MBTU/HR)
Boilers	73% fired with gas 73% fired with fuel oil	120
Turbine	60%	25
Electric Motor Driven Centrifugal Chiller	4.0	24
Steam Driven Centrifugal Chiller	2.6	15
Absorption Chillers	62%	30
Hot Water Convertors	75%	34

Figure 4. Proposed CEP Model


ELECTRICITY SUPPLY
X_1
X_2
$17.58 MBTU/HR
ELECTRICAL POWER DEMAND
5 - 15 MBTU/HR
ELECTRICAL CENTRIFUGAL CHILLER 4.0
X_{11}
24 MBTU/HR max
NATURAL GAS SUPPLY
X_3
$3.40 MBTU/HR
BOILERS 73%/70%
X_5
X_6
X_7
120 MBTU/hr max
TURBINE DRIVEN CENTRIFUGAL CHILLER 2.6
X_{12}
15 MBTU/HR max
COLD WATER DEMAND
8 - 68 MBTU/HR
FUEL OIL SUPPLY
X_4
$6.67 MBTU/HR
TURBINE 60%
X_9
X_{10}
ABSORPTION CHILLERS 62%
X_{13}
30 MBTU/HR max
HOT WATER DEMAND
3 - 34 MBTU/HR
HOT WATER CONVERTORS 75%
X_{14}
34 MBTU/HR max

gas and approximately 15% of electricity used on campus just to provide heating and cooling. The CEP by its nature is critical to the campus operation; thus any method used to study the plant must not disrupt its functioning.

Application of LP Model

To validate the CEP model the LP output of equipment required on-line was compared on a one to one basis, with the real plant equipment operating configuration. [Harley 1976, p. 23]. The CEP model was not verified because of lack of available data from the UCF CEP.

To verify the model assuming data was available from the CEP. The following procedure would be followed.

1) Run the model for specific set of energy demands for an 8-hour period to determine cost and operation configuration.
2) For the same 8-hour period, check the UCF CEP to determine which equipment is on or off and the attendant operating costs.
3) Make an analysis comparing how faithful the CEP model is to the real system in cost and operating configuration terms.

The 24-hour load requirements were divided into

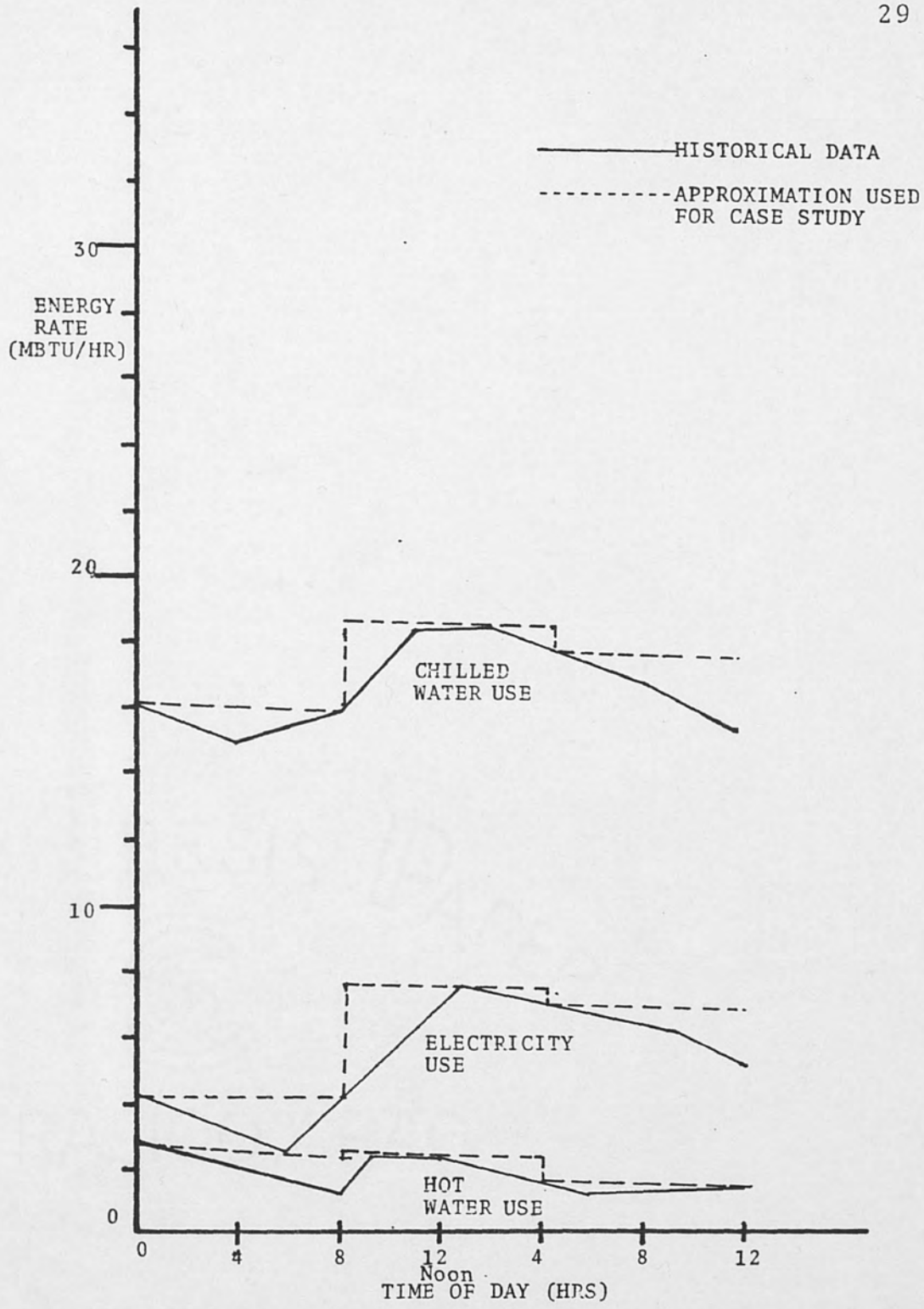


Figure 5. Typical Summer Day Energy Demands on CEP

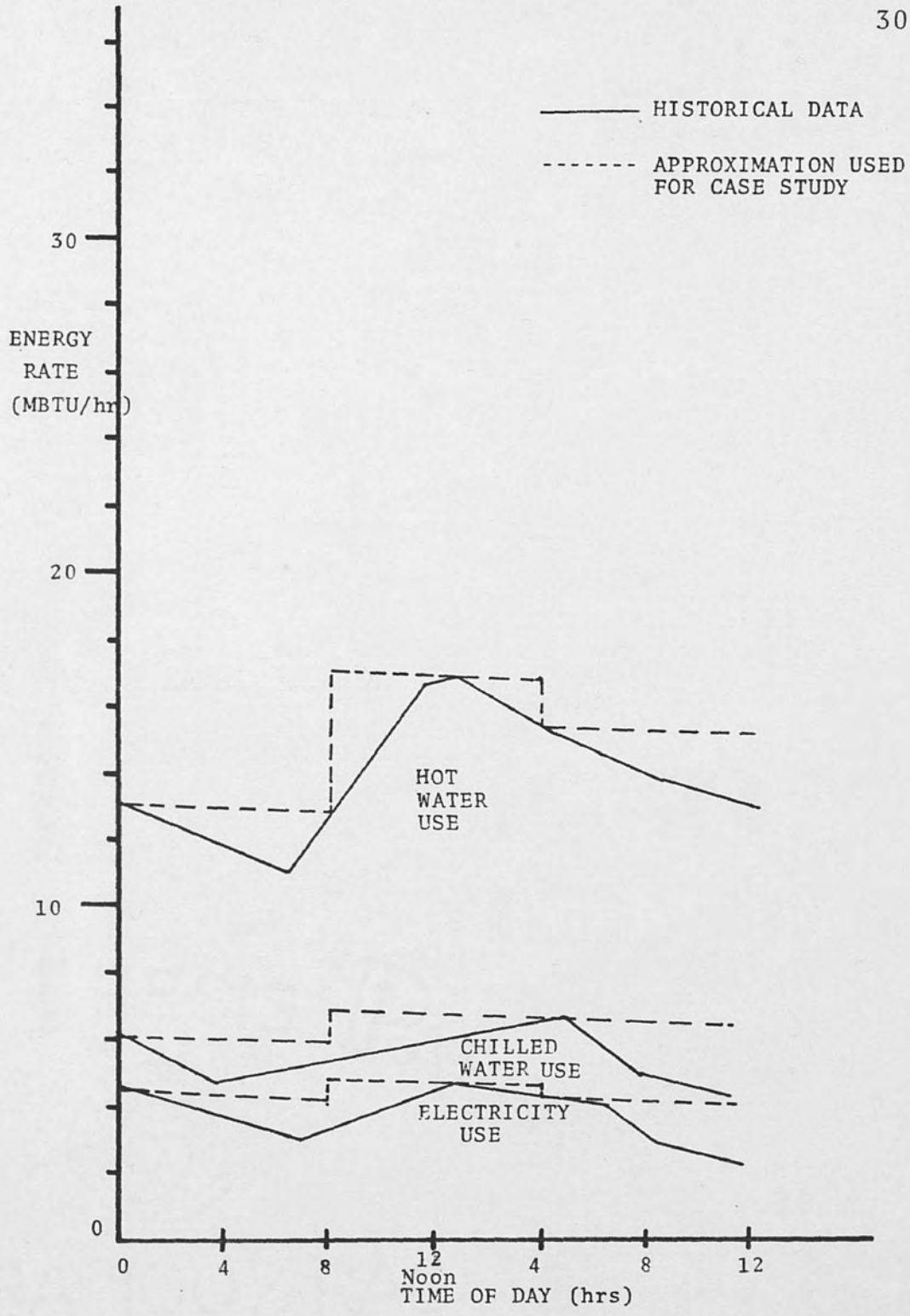


Figure 6. Typical Winter Day Energy Demands on CEP

three watches: midnight to 8 AM; 8 AM to 4 PM, and 4 PM to midnight. This approach paralleled the equipment operating constraints, and the demands were reasonably constant during these time periods. Figures 5 and 6 show typical energy curve demands for a typical summer and winter days. These curves were translated to approximate period demands for computer runs as shown in Table 2 by energy type over the three 8-hour watches. These values were used to validate the model. For each 8-hour watch a computer run is made. Each run uses the maximum demand during that period for each type of energy, i.e., electricity, chilled water, and hot water to satisfy the energy demands. (See dashed lines in Figures 5 and 6). Computer runs also are made for each 8-hour period using the average energy demands shown in Table 7. Using maximum energy demands, Table 4 summarizes 6 computer runs for every 8-hour period of a summer and a winter day and Table 8 summarizes 6 computer runs for the average energy demands. The different prices of energy are shown in Table 3.

The operating cost for the average demands were lower than for the maximum as might be expected, the difference was $44, or about 23% lower. The run data however showed it made no difference in the operating equipment profile.

TABLE 2

APPROXIMATE ENERGY DEMANDS
FOR SUMMER AND WINTER DAYS
(ALL UNITS IN MBTU/Hr.)

	SUMMER DAY			WINTER DAY		
DEMAND	Midnight to 8 AM	8 AM to 4 PM	4 PM to Midnight	Midnight to 8 AM	8 AM to 4 PM	4 PM to Midnight
ELECTRICITY	5.7	9.8	9.0	6.5	6.5	5.7
CHILLED WATER	16.3	21.6	20.2	8.3	8.5	6.8
HOT WATER	3.4	3.6	3.2	17.1	20.6	15.6

TABLE 3

ENERGY COSTS

ENERGY FORM	PRICE ($/M^{2}BTU)
ELECTRICAL POWER	17.58
NATURAL GAS	3.40
FUEL OIL	6.67

Note: Prices are based on the following:

1) Electrical Power = $0.06/KWH

Natural Gas = $0.34/THERM

Fuel Oil #6 = $1.00/Gallon

2) 1 KWH = 0.03413 THERMS

1 THERM = 100,000 BTU's

1 Gallon #5 & 6 Fuel Oil = 1.50 THERMS

1 Gallon of LP = 0.916 THERMS

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1) Physical Plant, University of Central Florida, Orlando, Florida, interview with accounting department, September 1981.

2) Anderson 1966, p. 26.

Replacing the generalized values in the model with actual values yields the following:

Minimize $Z = 17.58\ X_1 + 17.58\ X_2 + 3.40\ X_3 + 6.67\ X_4$

subject to:

$0.73\ X_3 + 0.70\ X_4 - 10\ (X_{15} + X_{16} + X_{17}) \geq 0$

$0.73\ X_3 + 0.70\ X_4 - 40\ (X_{15} + X_{16} + X_{17}) \leq 0$

$0.73\ X_3 + 0.70\ X_4 - X_5 - X_6 - X_7 = 0$

$0.40\ X_7 - 2\ (X_{25}) \geq 0$

$0.40\ X_7 - 18\ (X_{25}) \leq 0$

$0.40\ X_7 - X_9 - X_{10} = 0$

$4.0\ X_2 - 10\ (X_{18}) \geq 0$

$4.0\ X_2 - 24\ (X_{18}) \leq 0$

$4.0\ X_2 - X_{11} = 0$

$2.6\ X_7 - 7\ (X_{19}) \geq 0$

$2.6\ X_7 - 15\ (X_{19}) \leq 0$

$2.6\ X_7 - X_{12} = 0$

$0.55\ X_5 + 0.62\ X_9 - 5\ (X_{20} + X_{21} + X_{22}) \geq 0$

$0.55\ X_5 + 0.62\ X_9 - 10\ (X_{20} + X_{21} + X_{22}) \leq 0$

$0.55\ X_5 + 0.62\ X_9 - X_{13} = 0$

$0.67\ X_6 + 0.75\ X_{10} - 4\ (X_{23} + X_{24}) \geq 0$

$0.67\ X_6 + 0.75\ X_{10} - 17\ (X_{23} + X_{24}) \leq 0$

$0.67\ X_6 + 0.75\ X_{10} - X_{14} = 0$

$X_{11} - 24\ X_{18} = 0$

$X_{12} - 15\ X_{19} = 0$

$X_{13} - 10\ (X_{20} + X_{21} + X_{22}) = 0$

$$X_{14} - 17\,(X_{23} + X_{24}) = 0$$

$$X_i \leq 1,\ i = 15, \text{---}, 25$$

$$X_1 \geq \text{EPD}^1$$

$$X_{11} + X_{12} + X_{13} \geq \text{CWD}^2$$

$$X_{14} \geq \text{HWD}^3$$

$$X_i \geq 0,\ i = 1, \text{---}, 25$$

1) $5 \leq \text{EPD} \leq 15$

2) $8 \leq \text{CWD} \leq 68$

3) $3 \leq \text{HWD} \leq 34$

Model Input and Output

The output of the CEP model would be a set of values that represent the consumption of energy sources and the schedule on which the various energy conversion equipment should be operated to satisfy the energy demands and operational constraints requirements. The CEP model would have as input the three major energy demands:

1) electrical power demand (EPD)
2) chilled water demand (CWD)
3) hot water demand (HWD)

The objective function would provide the minimum cost of an operational path that would involve the following forms of energy to run the plant:

1) amount of electricity purchased for demand (X_1)
2) amount of electricity purchased to run the electrical centrifugal chiller (X_2)
3) amount of gas purchased to run the boilers (X_3)
4) amount of oil #6 purchased to run the boilers (X_4)

The energy production of the different configurations with the energy input are shown in Table 4.

The results from the model for the typical summer and winter days indicate that only natural gas and electric power should be used as energy sources. This was due to the relatively low unit cost of gas compared to fuel oil. The "LP" model indicates which machine is "on" or "off" and so the operational energy path is identified.

If an equipment is on, it will be represented by "1" and if off, by "0." The results of the model do not yield exactly "0" and "1." Therefore, the fractional results indicate at what load of the maximum a certain equipment is working. In order to keep the COP of equipments constant, a 40% or greater load is required. Therefore, if the equipment is working at a load lower

TABLE 4

CASE STUDY RESULTS
(ALL UNITS MBTU/hr)

	SUMMER DAY			WINTER DAY		
COST	Midnight to 8 AM	8 AM to 4 PM	4 PM to Midnight	Midnight to 8 AM	8 AM to 4 PM	4 PM to Midnight
Electricity purchased						
Electric Use	6	10	9	7	7	6
Electrical Chiller	----	----	----	----	----	----
Energy consumed by boilers						
Gas	25.37	27.55	25.37	55.82	62.34	51.47
Fuel Oil #6	----	----	----	----	----	----
Chilled Water Generated by Electrical Chiller	----	----	----	----	----	----
Turbine Driven Chiller	15	15	15	0	0	0
Absorption Chillers	7	7	7	9	9	8
Hot Water Generated by Hot Water Convertors	4	5	4	18	21	16

TABLE 5

SUMMARY OF RESULTS FOR SUMMER DAY
(COST IN $/hr)

EQUIPMENT TYPE	VARIABLE	Midnight to 8 AM	8 AM to 4 PM	4 PM to Midnight
Objective Function Value	2	$191.77	$269.48	$244.45
Boilers	X_{15}	1	1	1
	X_{16}	0	1	1
	X_{17}	0	0	0
Electrical Chiller	X_{18}	0	0	0
Turbine Driven Chiller	X_{19}	1	1	1
Absorption Chillers	X_{20}	0	0	0
	X_{21}	0	1	0
	X_{22}	1	1	1
Hot water Convertors	X_{23}	0	0	0
	X_{24}	1	1	1

TABLE 6

SUMMARY OF RESULTS FOR WINTER DAY
(COST IN $/hr)

EQUIPMENT TYPE	VARIABLE	Midnight to 8 AM	8 AM to 8 AM	4 PM to Midnight
Objective Function Value	Z	$312.85	$335.50	$280.48
Boilers	X_{15}	1	1	1
	X_{16}	1	1	1
	X_{17}	0	0	0
Electrical Chiller	X_{18}	0	0	0
Turbine Driven Chiller	X_{19}	0	0	0
Absorption Chillers	X_{20}	1	1	1
	X_{21}	1	1	0
	X_{22}	0	0	0
Hot Water Convertors	X_{23}	1	1	0
	X_{24}	1	1	1

TABLE 7

AVERAGE ENERGY DEMANDS
FOR SUMMER AND WINTER DAYS
(ALL UNITS IN MBTU/HR)

	SUMMER DAY			WINTER DAY		
DEMAND	Midnight to 8 AM	8 AM to 4 PM	4 PM to Midnight	Midnight to 8 AM	8 AM to 4 PM	4 PM to Midnight
Electri-city	3.5	6	6	4	5	4
Chilled Water	15	17	16	5	6.5	5.5
Hot Water	2	2.5	2	12	15	13.5

TABLE 8

SUMMARY OF COSTS OF CEP
MAXIMUM ENERGY DEMANDS Vs. AVERAGE ENERGY DEMANDS
(ALL COSTS IN $/MBTU/HR)

	SUMMER DAY			WINTER DAY		
	Midnight to 8 AM	8 AM to 4 PM	4 PM to Midnight	Midnight to 8 AM	8 AM to 4 PM	4 PM to Midnight
Maximum Operating costs of CEP Using Maximum Energy Demands	191.77	269.48	244.45	312.85	335.80	280.48
Average Operating Costs of CEP Using Average Energy Demands	147.82	191.77	181.77	215.75	255.51	226.84

than 40% it would be rounded off to 0, and if it is working at a load greater than 40%, the result would be rounded off to 1. This process changes the value of the objective function. To eliminate this difficulty, the word integer is added to one constraint which is,

$$X_i \leq 1,\ i = 15, \text{----}, 25, \text{ integer}$$

Therefore, the computer runs yield directly "0" for off state and "1" for on state. The results are indicated in Tables 5 and 6. Also, in order to eliminate the rounding off process when solving an LP model, there is a method called the "Branch and Bound Method," which yields directly "0" and"1" for off and on states. (Zoutendijk 1976, p. 211)

The results of the computer runs however could provide the dispatcher with an insight as to which equipment should be on-line, and what amounts of power should be purchased from the outside utility company to meet the total electrical power demand. Take, for example, the midnight to 8 AM period of a summer day. This requires 6 MBTU/HR of electricity to meet the electrical power demand. 25.37 MBTU/HR of steam are necessary to generate 15 MBTU/HR of cold water produced by the steam driven centrifugal chiller, and 7 MBTU/HR of cold water produced by one absorption chiller to meet the cold water demand. 4 MBTU/HR of hot water are produced by one hot water convertor to meet the hot water demand. Therefore,

a steam driven centrifugal chiller, a boiler, an absorption chiller, and one hot water convertor are on line which results in operating costs of $191.77/HR.

The dispatcher's job then could be stated as switching on whichever equipment the model selects of those that must be on line at any given time to meet the mix of energy requirements, while at the same time minimizing the total operating costs. For example, as the demand for chilled water increases, he may start another absorption chiller, if the need is indicated by the solution of the model. In order to do so, it would require additional high temperature hot water (steam) which in turn will require more boiler firing. By the same token he may turn on the centrifugal chiller.

Based on this analysis, the following recommendations could be derived as an operational guide for the plant:

1) On a summer day, load up the turbine generator.
2) Use the total amount of cold water produced by turbine driven centrifugal chillers to meet the demand.
3) Use the rest of the steam generated by the boiler for the absorption chiller to complete the cold water demand.
4) Generate the hot water demand by one hot water convertor.

On a winter day the system operations would be similar, except that typically the hot water demands are higher and less steam would be available to operate the turbine driven centrifugal chiller. However, less chilled water would typically be required.

CHAPTER 5

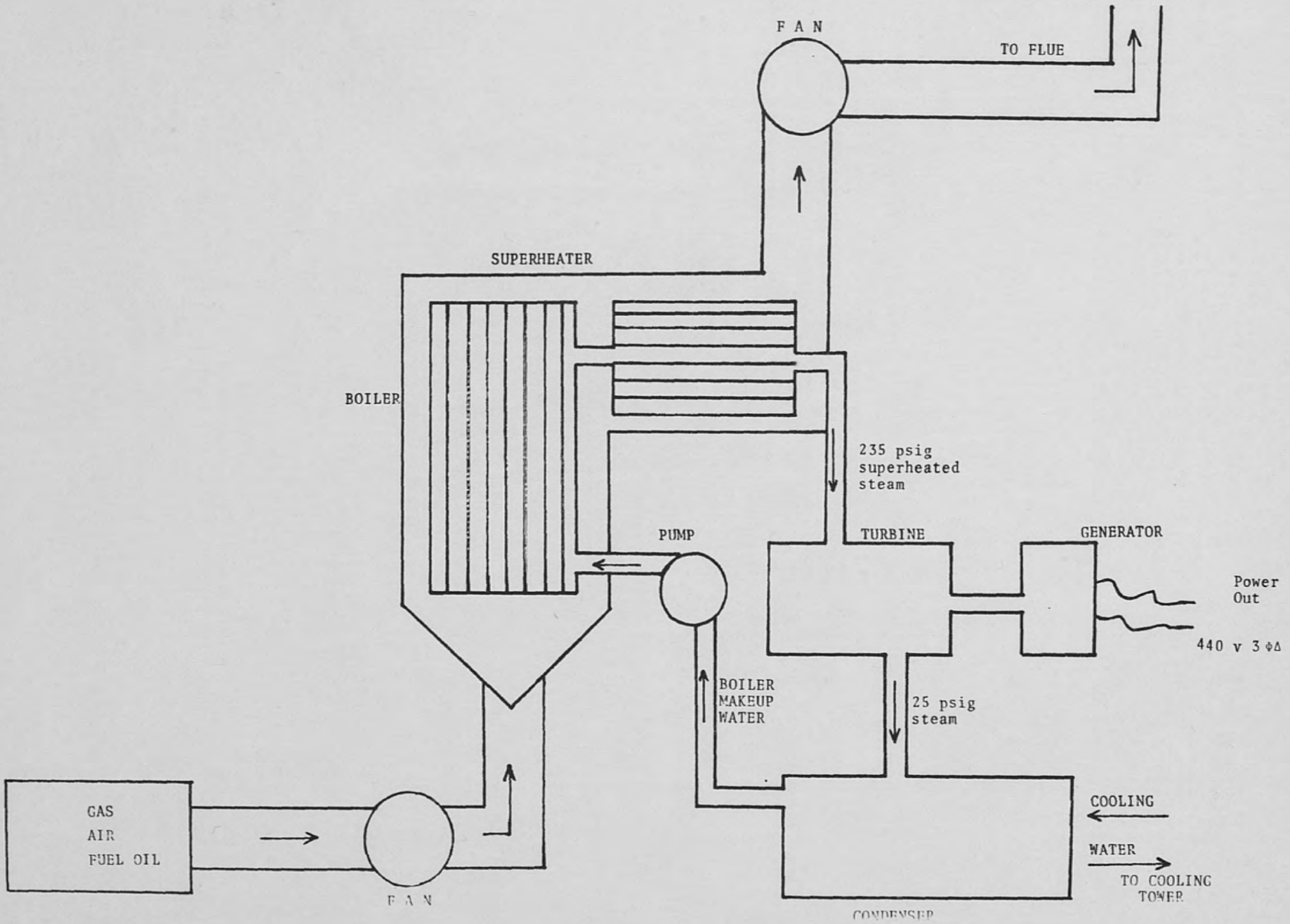
INSTALLATION OF A STEAM DRIVEN ELECTRICAL GENERATOR

For each CEP there are generally a number of technological ways to improve energy efficiency. [APS Studies on the Technical Aspects of the More Efficient Use of Energy, New York American Institute of Physics 1975, p. 25]. For example, at the UCF plant, a good start would be to investigate the steam usage since the plant is based on the steam cascade cycle. It is noted that steam usage varies widely over the year. In summer, a lot of steam is generated to operate the centrifugal chiller, which contributes to the total production of cold water, and in turn provides much low pressure steam for heating hot water. In winter, the centrifugal chiller is idle, and the absorption chillers by themselves are able to satisfy the chilled water demand. The steam that is used in summer to drive the centrifugal chiller and produce low pressure steam for the hot water convertors must now be generated by passing the high pressure steam through a pressure reducing station. This is a waste of energy since the energy of

the throttled steam is lost. The installation of a steam driven electrical generator could use this waste energy to generate electrical power. Accordingly, an investigation of such a generator system was conducted to prove the practicality of the model, and hopefully improve the energy efficiency performance of the CEP.

In operation the electrical generator would be coupled to a new steam driven turbine as shown in Figure 7. The steam driven turbine generator would be rated at 950 kw output and would cost in the order of $125,000. The overall efficiency would be 28% which is shown in Figure 8. [Diamant 1970, p. 45] Since electricity has the highest cost per MBTU/HR of the three forms of purchased energy used by CEP, any amount of electrical power produced in house would reduce the total operating cost of the plant. The rest of the equipment of the plant would perform as previously stated. A complete block diagram in Figure 9 shows the modifications made in the CEP model when the electrical generator is integrated in the system. To state the electrical power production, the following equations would be added to the LP model previously discussed.

Figure 7. Generator Couple With Turbine


F A N
TO FLUE
SUPERHEATER
BOILER
235 psig
superheated
steam
PUMP
TURBINE
GENERATOR
Power
Out
440 v 3 ϕΔ
BOILER
MAKEUP
WATER
25 psig
steam
COOLING
WATER
TO COOLING
TOWER
GAS
AIR
FUEL OIL
F A N
CONDENSER

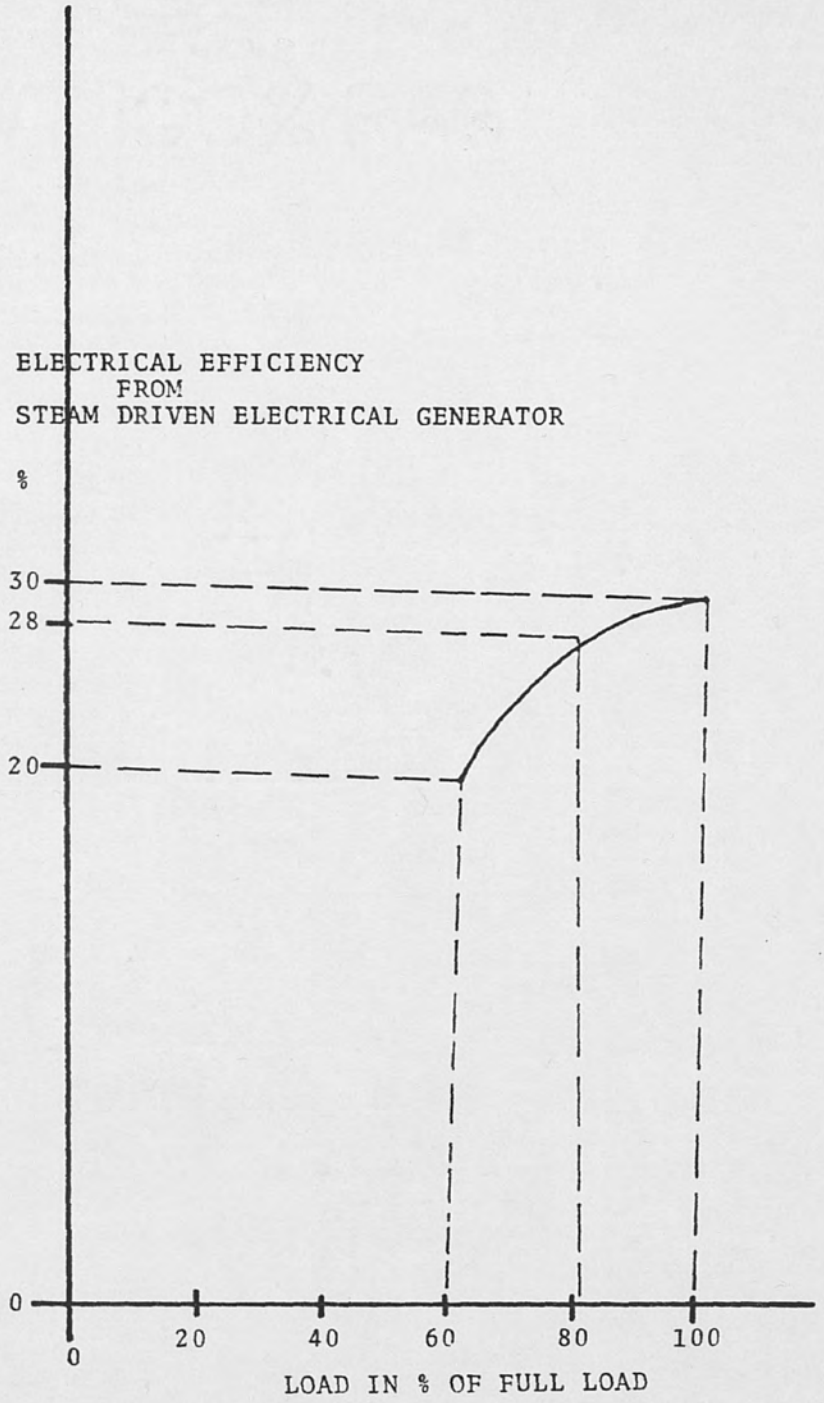


Figure 8. Coefficient of Performance (COP) of a Steam Driven Electrical Generator

$$a_{10}X_7 \geq b_{13}\ (X_{26})$$
$$a_{10}X_7 \leq b_{14}\ (X_{26})$$
$$a_{10}X_7 = X_8$$
$$X_{26} \leq 1, \text{ integer}$$

where,

a_{10} = is the efficiency of genrator to convert steam to electrical power (=28%)

b_{13} = is the minimum output capacity of the electrical generator (=1.3 MBTU/HR)

b_{14} = is the maximum output capacity of the electrical generator (=3.3 MBTU/HR)

X_8 = is the rate at which electrical power is produced by the generator (MBTU/HR)

X_{26} = is the turbine driven generator

To exercise the modified CEP model, a computer run was made for each 8-hour period using the same energy demands of the case "without an electrical generator". According to the computer results, the electrical generator provides a signficant amount of electricity to meet the electrical power demand and the CEP can operate at a lower cost.

Figure 9. Proposed CEP Model With a Steam Driven Electrical Generator.

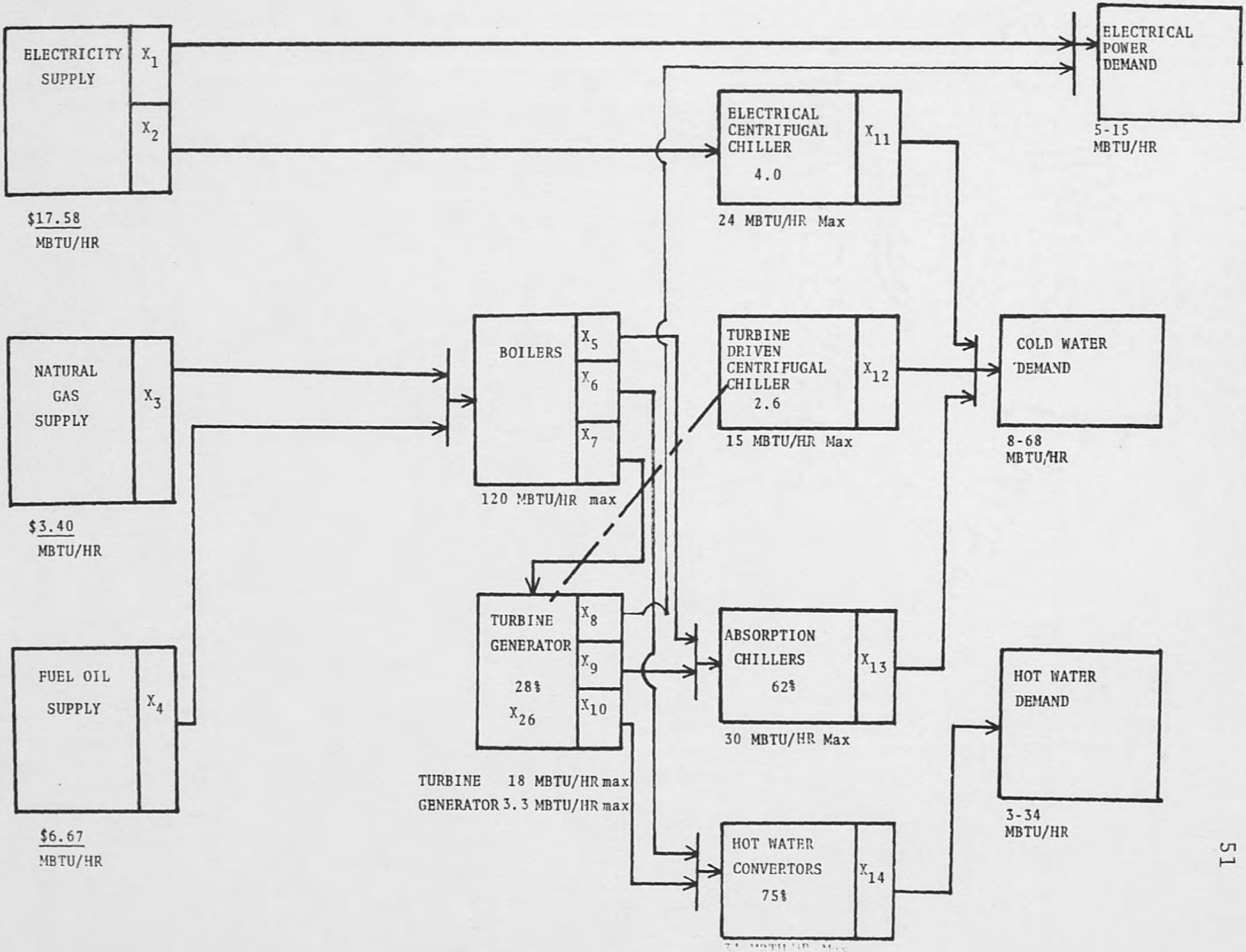

ELECTRICITY SUPPLY
X_1
X_2
$17.58
MBTU/HR
ELECTRICAL POWER DEMAND
5-15
MBTU/HR
ELECTRICAL CENTRIFUGAL CHILLER
4.0
X_{11}
24 MBTU/HR Max
NATURAL GAS SUPPLY
X_3
$3.40
MBTU/HR
BOILERS
X_5
X_6
X_7
120 MBTU/HR max
TURBINE DRIVEN CENTRIFUGAL CHILLER
2.6
X_{12}
15 MBTU/HR Max
COLD WATER DEMAND
8-68
MBTU/HR
FUEL OIL SUPPLY
X_4
$6.67
MBTU/HR
TURBINE GENERATOR
28%
X_{26}
X_8
X_9
X_{10}
TURBINE 18 MBTU/HR max
GENERATOR 3.3 MBTU/HR max
ABSORPTION CHILLERS
62%
X_{13}
30 MBTU/HR Max
HOT WATER DEMAND
3-34
MBTU/HR
HOT WATER CONVERTORS
75%
X_{14}

Table 9 lists the cost of operaton for each period of a summer day and winter day. In the summer the value of the objective function from midnight to 8 AM is $147.82 which would yield a total of $1,182.56 for the eight hour period. With a generator installed, the cost of the same period with the same energy demands would be $119.42/HR(8) = $955.36/HR. This improvement in the operating cost is due to the generation of electricity in the plant. The generator then has a payback period of six months which proves that it is a good investment.

TABLE 9

SUMMARY OF COSTS OF CEP
WITH Vs WITHOUT GENERATOR
(ALL COSTS $/MBTU/8HR)

	SUMMER DAY			WINTER DAY		
	Midnight to 8 AM	8 AM to 4 PM	4 PM to Midnight	Midnight to 8 AM	8 AM to 4 PM	4 PM to Midnight
Average Operating Cost of CEP (without generator)	$1,182.56	$1,534.16	$1,454.16	$1,726.00	$2,044.08	$1,814.72
Operating Cost of CEP (with generator)	955.36	1,306.96	1,306.96	1,498.80	1,816.88	1,587.52
Electri-city produced by genera-tor(MBTU/HR)	1.62	1.51	1.73	1.55	1.65	1.53

CHAPTER 6

OBSERVATIONS, CONCLUSIONS AND RECOMMENDATIONS

The Linear Programming (LP) model presented in this paper describes a complex Central Energy Plant system operating problem and presents a method for investigating and determining the optimum (lowest cost) equipment operating configurations. The system of equations developed in the model can be expanded or reduced to accomodate a variety of system combinations. This was illustrated by the evaluation of the addition of the steam driven turbine electrical generator alternative. The LP model is a simplified version of the actual UCF plant, since it was not possible to obtain data on all the operational constraints of the actual system. The CEP model satisfies the main objectives stated previously. It is cautioned, however, that the model could not run the plant since it must, of necessity, be simplified and would not incorporate all the operational constraints of the actual system. For example, the absorption chillers generally cost less to maintain than their centrifugal counterparts, but require more time to bring on line. On

the other hand, the centrifugal units are generally limited in the number of starts that they can make in a day due to the size of the drive motors. They must operate a minimum of 4 hours if put on line. Although these considerations might be incorporated into the model, it would be difficult, and the model would be cumbersome to the extent that such decisions are better handled by the operator.

The CEP model could be used as many times as necessary by updating the electrical, hot and cold water demands for a given period of the day. The management could preplan an equipment operating schedule to minimize operating costs. The maintenance hours could be set, because not all the equipments are on or off at the same time. The management could use the model for planning future operational growth scenarios. By elaborating the scenarios for future operations, it would minimize the unexpected mishappenings.

It must be recognized, however, that the model as presented has some inherent weaknesses and more work will be required to make it acceptable to an experienced plant operator. The three 8-hour periods for measuring energy demand should be expanded to better recognize the requirements of the particular facility over a smaller time frame. Clearly, the closer the model can follow

or anticipate the energy demand curves, the better it can predict plant equipment operating requirements for cost effective performance.

The model does need to be modified to include the maintenance and operational requirements of the equipment. For example, the absorption chillers generally cost less to maintain than their centrifugal counterparts, but they require more time to bring on line. On the other hand, the centrifugal units may be limited in the number of starts per day due to the size of the drive motors. The experienced operator knows these trade offs and will be reluctant to accept output from a model which does not recognize them.

A further consideration which should be introduced in the model is the variation in peak power demand cost which would be experienced in the real world as the electrical energy requirement is shifted between plant generated and purchased power. As more power is purchased, an additional surcharge should be concluded on the unit cost of electricity. This is a very real operational cost problem and one which would directly impact the decision to generate or purchase additional power.

It would be interesting also to investigate the CEP model using "branch and bound method" as further research, and to develop a dynamic programming model that could be used to analyze heat storage to satisfy the peak energy demand periods.

APPENDIX

APPENDIX A

A Linear Programming (LP) model was used to analyze the CEP model.

LP Model Modifications

The LP model computer program was developed by Harris. This can handle up to 25 constraints and 60 variables (slack and surplus included). LP model uses the two phase, full tableau form of the simplex method. It requires all right hand values to be nonnegative. The inequities must be converted to equalities by inserting slack and surplus variables.

The LP model used to exercise the CEP model was augmented up to 100 constraints, and 100 variables (slack and surplus variables included) to accomodate the size of the model.

The LP model is less expensive to operate because it uses less computer core storage and less computer time.

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