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Abstract

This paper presents a mixed-integer nonlinear programming (MINLP) model for performing structural and parameter optimization of utility plants that satisfy given electrical, mechanical and heating demands of industrial processes. In this model a non-linear objective function that accounts for the cost of equipment and operation is minimized. The proposed approach allows for the simultaneous optimization of the configuration, and selection of flowrates, enthalpies and steam turbine efficiencies. All major conventional utility plant equipment are included in the superstructure for the MINLP model. The proposed approach is not only useful for synthesis, but also for analyzing different design alternatives. The model has been implemented in the computer package STEAM, and several applications are reported to illustrate the program capabilities, including a comparison with a simplified MILP model.

Introduction

Utility plants supply the required utility demands to industrial process plants, namely, electrical, mechanical and steam demands. Electrical demands come from external and internal electrical utility plant devices. Mechanical demands come from the power required to drive process units as compressors, pumps, blowers, etc. and from the power to drive utility pumps and air fans. Steam demands arise from the heat that is required from the heat exchange network and from the reaction system.

The equipment that can be typically used in a utility plant include different types of boilers and steam turbines, electric motors, electric generators driven by gas turbines or steam turbines, headers at different pressures to collect and distribute steam and condensate, and other auxiliary units such as deaerators, condensers, and utility pumps. A number of feasible arrangements of these units can provide the specified utility demands.

To address the problem of synthesis and design of utility plants several methods have been reported in the literature. These methods generally follow two basic approaches, those based on thermodynamic targets and heuristic rules, and those based on optimization techniques. Examples of the first group are the methods by Nishio et al. (1980), and Chou and Shih (1987). The main drawback of these methods is that even if the design with highest thermal efficiency is obtained, it may not be economically attractive because capital costs may be too high. The method by Nishio et al. (1980) relies on linear programming for the selection of drivers. The Chou and Shih (1987) design strategy allows for the inclusion of gas turbine cycles. This strategy gives preference to satisfying the heating over the power demands, and back-pressure turbines over condensing turbines. No rules are given to extend the method for the inclusion of electric motors.

The first papers using mathematical optimization approaches were based on LP models such as the ones in Nishio and Johnson (1979), and Petroulas and Reklaitis (1984). Papoulias and Grossmann (1983) introduced the MILP approach. This approach consists in formulating an MDLP model to select among all the alternative units included in a proposed utility plant superstructure by minimizing linear capital costs with fixed charges and operating costs. The MILP formulation is derived from the original MINLP formulation by fixing operating conditions such as pressures and temperatures. The MILP approach has been recently used for the multiperiod optimization of utility plants (Hui and Natori (1996), Iyer and Grossmann (1996)), and for multiobjective approaches for waste minimization in utility plants, Chang and Hwang (1996).

Colmenares and Seider (1989) presented a method for the design of a utility plant integrated with a chemical process using an NLP model to solve a superstructure of combined Rankine cycles. Due to the nature of the NLP model there is no option for chosing from among different steam turbine configurations, or for selecting electric motors for mechanical power demands. Existing methods based on MINLP models (Kalitventzeff (1991), Diaz and Bandoni (1996)) address the problem of optimal operation, and are not applicable to the synthesis of new utility plants.

In this paper a comprehensive MINLP model for utility plants is presented. This model allows for the synthesis and design of new utility plants, and also for analyzing different design alternatives, for given electrical, mechanical and heating demands. The optimal solution is selected from a superstructure containing conventional utility plant equipment that are specified by the designer for each demand. The electrical demands can be satisfied by an electric generator driven by a gas turbine or a steam turbine. Steam can be generated in different types of boilers included in the superstructure. The mechanical power demands can be satisfied by different types of steam turbines working with inlet and outlets at different steam pressures, and at a variable efficiency depending on the working conditions and the mechanical power generated. Also the option of using an electric motor for each power demand can be considered. The design analysis of specific alternatives in utility plants is addressed by fixing some of the options available in the model to match the equipment options considered. The final solution includes the flowrates and enthalpies for steam, water and gas, and also the steam turbine efficiencies for the optimal configuration using the selected operational parameters.

In the next section, the problem for the synthesis, design and optimization of utility plants is stated. It is followed by a description of the proposed MINLP model, including a presentation of the method employed to obtain the enthalpy, entropy, steam turbine efficiencies and cost functions. Next, STEAM, a user-friendly computer program implementing the proposed model is introduced. Finally, examples on synthesis, design and operation of utility plants are presented. Additional information on the data used in this study is included in an Appendix.

Problem Statement

Given a set of demands of electricity, mechanical power and steam at various pressure levels, the objective is to design a utility plant at minimum cost by determining the equipment configuration and its corresponding operating conditions.

The superstructure that will be considered for this model (see Figure 1) includes the main conventional utility plant equipment.

Steam can be generated in four different types of boilers:

1. Heat Recovery Steam Generator for recovering heat contained in gas turbine or furnace exhaust gases, and for generating superheated high pressure steam. Supplementary firing is allowed in these units.
2. High pressure boiler fired by fuel.
3. Medium pressure boiler fired by fuel.
4. Waste heat boiler working at medium pressure, recovering heat from process flue gases or from process units such as chemical reactors. This unit can raise saturated or superheated steam.

In all the boilers a necessary blowdown has to be considered. In this work the blowdown rate is treated as an operating parameter.

Steam is collected and distributed to steam consumers, steam turbines or to the next low pressure steam header through letdown valves. The model determines the optimal enthalpy and entropy in each steam header given its pressure as a fixed operating parameter. The pressure can be modified on a case-by-case basis as will be illustrated in the examples presented later.

Utility plants usually have three types of devices for satisfying external and internal power demands, i.e., gas turbines, steam turbines and electric motors. Gas turbines are generally used to drive electric generators and to recover the exhaust gas heat in a boiler to raise steam. This arrangement is commonly known as a cogeneration system. For this purpose, an open cycle gas turbine has been included in this model. Other options to drive electric generators are steam turbines or a combination of gas and steam turbines.

Steam turbines are used to generate electricity, and to satisfy mechanical power demands. Several types of steam turbines are possible. For high pressure turbines the following configurations are considered:

1. Back-pressure turbine exhausting to medium pressure
2. Back-pressure turbine exhausting to low pressure

3. Extraction back-pressure turbine exhausting to medium and low pressure.
4. Condensing turbine.
5. Condensing turbine with steam extraction to medium pressure.

For medium pressure turbines the configurations considered are:
6. Back-pressure turbine exhausting to low pressure.
7. Condensing turbine.
Steam turbine efficiencies are variable and depend on the inlet steam pressure, type of exhaust, i.e., condensing or noncondensing, and the mechanical power supplied. If a condensing turbine is selected a condenser and a vacuum header has to be selected.

Electric motors can also be used to meet the required power demands. The electric motor efficiency is given as an operating parameter for these units.

Steam can be returned as a condensate or not, depending on whether it is used for heating purposes or it is used in the process as a raw material, for example in steam cracking. The return of condensate is collected in a condensate header at a given pressure and saturated conditions.

A deaerator is included for steam stripping to remove dissolved gases from boiler feedwater. The operating parameters for this unit are the vent ratio and operating pressure. Demineralized water is added to compensate for plant losses. A boiler feedwater heater can be optionally included. Utility pumps are included for the supply of boiling feedwater, cooling water and for the return of vacuum condensate.

MINLP Model

Given the specified utility demands and superstructure, the optimal configuration and operating conditions will be determined using an MINLP model for the minimization of the capital and operating costs of the general form (Grossmann, 1996):

$$
\begin{aligned}
\min\ z &= c^T y + f(x) \\
s.t.\quad & Ay + h(x) = 0 \\
& By + g(x) \leq 0 \\
& Cy + Dx \leq d \\
& Ey \leq e \\
x \in X &= \{x \in R^n : x^L \leq x \leq x^U\} \\
y \in Y &= \{0,1\}^m
\end{aligned}
\qquad (1)
$$

In the above problem the objective function to minimize is a linear function of the 0-1 variables and nonlinear function in the continuous variables, that accounts for the capital and operating costs. The constraints are nonlinear or linear in continuous variables such

as flowrates, temperatures, enthalpies, entropies and steam turbine efficiencies, and linear in binary variables representing the potential presence of units.
In this section we will present the specific objective function and different types of constraints involved in problem (1).

The following indices will be used:
g : air or exhaust gas stream in the gas turbine.
n or m: unit number.
p : utility level for steam.
(e.g. High Pressure (HP), Medium Pressure (MP), Low Pressure (LP).
st : steam turbine unit number.
w : utility level for internal and external power demands.
we: utility level for external power demands only.
wi : utility level for internal power demands only.

Sets:

I_n = [mjunit n has input flowrate from unit m}

O_n = {mjunit n has output flowrate to unit m}

$^\wedge{}_{we}^{s}$ = {rt|umt n supplies the external power demand we}

N_{wi}^{s} = {n|unit n supplies the internal power demand wi}

N_{wi}^{d} = {n|unit n is an internal power - consuming unit}

N_g^s = {n|unit n supplies electricity}

N_g^d = {n|unit n is an electricity - consuming unit}

WE = {vvejset of external power demands}

WI = |vw|set of internal power demands}

Parameters:

$h[$ = fuel enthalpy to unit n
hf = liquid saturation enthalpy at the outlet conditions of a steam turbine
h_g = steam saturation enthalpy at the outlet conditions of a steam turbine
Sf = liquid saturation entropy at the outlet conditions of a steam turbine
s_g = steam saturation entropy at the outlet conditions of a steam turbine
$T|_c$ = boiler efficiency
$T|_n$ = efficiency of unit n (eg, pumps, air fans)
p°_n = pressure at the outlet of unit n

P_n^I = pressure at the inlet of unit n

p_g = pressure in the gas turbine at the stream g

ρ_n = fluid density through unit n

DE = electricity demand

DQ^p = heating demand at level p

DW^{we} = mechanical power demand at level we

Cf = cost of fuel

CQW = cost of cooling water

CDW = cost of demineralized water

$\alpha_n, \beta_n, \gamma_n$ = cost coefficients for nonlinear cost functions

a_n, b_n, c_n = cost coefficients for linear cost functions

Continuous variables:

F_{mn}^x = flowrate from unit m to unit n

F_n^f = fuel flowrate to unit n

H_{mn}^x or $H_{mn}^x(p_m^o, T_m)$ or $H_{mn}^x(p_m^o, S_m)$ = enthalpy from unit m to unit n

Hs_{mn}^x = ideal enthalpy from unit m to unit n

S_n or $S_n(P_n^o, T_n)$ = entropy in unit n

S_n^I = entropy at the input of unit n

T_n = temperature at the outlet of unit n

Q_n^{wh} = waste heat duty to unit n

Q_{pn}^x = steam production of level p in unit n

W_n^{we} = external power demand produced in unit n at level we

W_n^* = internal power demand produced in unit n

$\bar{W}_n^d$ = electricity demanded by unit n

$\bar{W}_n^*$ = electricity produced by unit n

W_n^d = internal mechanical power demanded by unit n

Hgt_g = enthalpy of the stream g in the gas turbine

Sgt_g = entropy of the stream g in the gas turbine

Tgt_g = temperature of the stream g in the gas turbine

Binary variables represent selection of units:

y_n = units other than power generating devices

y_{aw} = HP steam turbine unit exhaust to MP satisfies the power demand w

y_{bw} = extraction turbine unit exhaust to MP and LP satisfies the power demand w
y_{cw} = extraction turbine unit exhaust to MP and vacuum satisfies the power demand w
y_{stw} = turbine unit st other than an extraction turbine satisfies power demand w

Using the given sets, parameters and variables the following equality and inequality constrains may be stated:

(I) Mass balances

$$\sum_{m\in I_n} F_m^n + F_n^f - \sum_{m\in O_n} F_n^m = 0 \qquad \text{Vn} \tag{2}$$

(II) Energy balances

$$\sum_{mel_n} F_m{}^H m' \quad \sum_{m\in O_n} \pm{}^F n \quad "n \quad {}^+Qn \quad +{}^F n \quad K \wedge c" \quad Qn \quad " \; {}^W n \quad {}^{,W} \bar{n} = 0 \qquad \text{Vn} \tag{3}$$

(III) Momentum balances neglecting the kinetic and potential energy terms:

$$\frac{p_n^o}{Pn} - \frac{p_n^i}{\text{P«}} - W_n^d \,\text{Tl}_n = 0 \qquad \text{n e } N^\wedge \tag{4}$$

(IV) Satisfaction of heating demands

$$\sum_n Q_n^p \geq DQ^p \qquad \text{Vp} \tag{5}$$

(V) Satisfaction of electricity demands

$$\sum_{n\in N_e^s} \hat{W}_n^5 - DE - \sum_{n\in N_e^d} \hat{W} \text{Jf} - 0 \tag{6}$$

(VI) Satisfaction of external and internal mechanical power demands

$$\sum_{n\in N_{we}^s} W_n^{we} - DW^{we} = 0 \qquad \text{Vwe}$$

(7)

$$\sum_{n\in N_{wi}^s} W_n^s - \sum_{n\in N_{wi}^d} W_n^d = 0 \qquad \text{Vwi}$$

(VII) Conditional constraints to ensure upper bounds in the selected units,

$$V_n \quad -Umax_n y_n \quad \leq \quad 0 \tag{8}$$

where Umax$_n$ is an upper bound for the continuous variable V, and y, represents the existence of the corresponding unit. To specify a lower bound for this same unit the necessary relation is,

$$-V_{rt} \quad + \quad Umin_n y_n \quad \leq \quad 0 \tag{9}$$

where Umin, denotes the minimum value allowed for the continuous variable when the unit is selected. Notice that the constraint in (8) will set to zero the variables when the unit is not selected.

(VIII) Constraints to select only one steam turbine for each demand

$$\begin{aligned} &\sum y_{awe} + y_{nwe} = 1 && \forall we \\ &\sum_{n \in N^s_{wi}} y_{awi} + y_{nwi} = 1 && \forall wi \end{aligned} \tag{10}$$

(IX) Constraints to select the turbine units for a high pressure extraction turbine

As shown in Figure 2, two possible extraction turbines can be considered (see point XI for further explanation). The following relations are needed in order to ensure the simultaneous presence of the two turbines units, the first one exhausting to MP and the second one exhausting to LP or vacuum, and also to avoid the presence of two extraction turbines for the same power demand:

$$\begin{aligned} &yb_w - ya_w \leq 0 \\ &yc_w - ya_w \leq 0 \qquad \forall w \\ &yb_w + yc_w \leq 1 \end{aligned} \tag{11}$$

(X) Constraints related to steam properties

For the operating pressure in each header, expected maximum and minimum temperatures are specified. Using these parameters the steam enthalpies and entropies are computed using second order polynomial correlations obtained from steam tables (ASME, 1992). The following correlations for steam properties are necessary to determine enthalpies, temperatures and entropies, and later to obtain steam turbine efficiencies:

$$H?(HP,T_n) = a, + a_2\ T_n + a_3\ T_n^2 \quad (12)$$

$$S_n(HP,T_n) = b_x + b2\ T_n + {*}3\ T_n^2 \quad (13)$$

$$H?(MP,T_n) = c, + c_2\ T_n + c_3\ 7J,^2 \quad (14)$$

$$S_H(MP.T_m) = </, + d_2\ 7n + <{*}3\ T_n^2 \quad (15)$$

$$HfiMPX) = e, + e_2\ S\wedge + e_3\ S\wedge^2 \quad (16)$$

$$H?(LP,T_n) = /, + /_2\ r_{fl} + /_3\ r_{fl}^2 \quad (17)$$

where all the coefficients are constants (see Appendix table Al for numerical values). Equations (12) and (13), and (14) and (IS) are used to calculate the enthalpy and entropy in the high pressure and medium pressure header respectively. Equation (16) is used to calculate the ideal enthalpy at the steam turbine outlets at medium pressure, as will be seen shortly. Finally, equation (17) is used to calculate the low pressure header enthalpy. The steam enthalpy at the outlet of a steam turbine to a steam header or to a condenser is calculated through:

$$H^n_{st} = Hi - r\backslash jHi - H\$\backslash \quad neO_{st};\ mel_{st} \quad (18)$$

where m in this case is the header at the inlet of the steam turbine exhausting to the header or condenser n. The ideal steam turbine outlet after a high pressure to medium pressure expansion for the range of temperatures selected in each header will be in a single phase region (see Table Al in the Appendix), so it can be calculated using the equation (16) introduced before, as follows:

$$Hs^n_{st}(MP.Si) = t| + e_2\ S^l_{st} + e_3\ s'J{*} \quad (19)$$

For a two phase ideal outlet, the ideal enthalpy is calculated by:

$$Hs^n_{st} = h_f + {*}\pounds\ (h_g - h_f) \qquad neO_{st} \quad (20)$$

The steam quality, x^n_{st}, for a given stream can be calculated in terms of entropies :

$$x^n_{st} = \frac{S_{st} \sim S_f}{S_g \sim S_f} \quad (21)$$

where S^i_{st} is the entropy at the turbine inlet.

(XI) Constraints related to the steam turbine efficiency

In this model steam turbine efficiencies are variables that depend on the inlet pressure, exhaust conditions (condensing or noncondensing turbine) and the shaft power. Steam turbine efficiencies are correlated from the literature (Peltier, 1995). For an inlet steam pressure lower than 6.9 MPa, the efficiency is given by,

$$\eta_{st} = c\left(\frac{a - W_{st}}{b + W_{st}}\right) \qquad (22)$$

and for an inlet steam pressure greater than 6.9 MPa, the efficiency is given by,

$$\eta_{st} = a + bW_{st} + cW_{st}^2 \qquad (23)$$

Coefficients for these functions are given in Table A3 and Table A4. To obtain these correlations it has been considered that correction factors for superheating and pressure ratio are small enough to be neglected at this point. Also, full load is assumed for each turbine.

An extraction steam turbine with no condensate in the extraction steam can be decomposed in turbine units (Chou and Shih, 1987). Figure 2 shows *how the high pressure turbine arrangement has been treated to account for the following options:
- expansion to medium pressure.
- expansion to medium and low pressure.
- expansion to medium pressure and vacuum.

Note that the number of options available is limited for the minimum inlet pressure. Common pressures found in low pressures steam headers are not high enough to supply steam to a turbine unit. Other configurations for a high pressure turbine, as is shown in the superstructure (Figure 1), include a single outlet to low pressure or to vacuum.

Steam quality has to be kept as high as possible, otherwise the steam turbine efficiency decreases. Therefore, at the outlet of back-pressure turbines only a single phase is considered. For the same reason, steam quality at the outlet of condensing turbines is restricted to be higher than 0.85.

(XII) Constraints related to air and exhaust gas turbine properties

Air and exhaust gas enthalpies in the gas turbine are calculated using the correlations of Backcock and Wilcox Co (1992):

$$\begin{aligned} Hgt_g &= aTgt_g^2 + bTgt_g - c \\ Sgt_g &= d\ln Tgt_g + eTgt_g - f - i_g \ln p_g \end{aligned} \qquad (24)$$

Functions to obtain the entropy in each gas turbine stream are derived from this data considering a pressure and temperature of reference of 0.1013 MPa and 298 K, respectively, and assuming ideal gas behavior (coefficients are given in Appendix Table AS). In these correlations the coefficients depend on the air/gas temperature and for mixtures of gases are determined also by the mixture composition. The compositions of air, natural gas and exhaust gas are presented in Table A6. Ambient air is assumed to be standard wet air, with a content of 0.013 kg water/kg of dry air, which corresponds approximately to 60% relative humidity at 27 °C. The exhaust gas composition is obtained using a mass ratio of 0.017 kg fuel/kg air, and assuming complete combustion. The effect of the supplementary firing on the gas composition is considered small enough to be neglected, so the gas exhausting from the heat recovery boiler is assumed to have the same composition as the exhaust gas at the gas turbine. Notice that the air inlet properties are parameters due to the fact that the gas turbine inlet conditions are fixed.

(XIII) Objective function

The objective function includes the capital and operating cost of the utility plant.

$$\min \ Z = C_F \sum_n F_n^f + C_{CW} F_{CW} + C_{DW} F_{DW} + \sum_{n \in N_{wi}^d} \left(\alpha_n G_n^{\beta_n} + \gamma_n y_n \right) + \sum_{n \in N_{wi}^d} \left(a_n y_n + b_n G_n + c_n G_n^2 \right) \qquad (25)$$

The capital or investment cost functions are calculated using the graphical data in Garret (1989) and Ulrich (1984) and presented in the Appendix Table A7 along with linearized expressions for these functions used later in example 2. The prices are updated using the Chemical Engineering index (CE index=382), and annualized using a capital recovery factor of 0.15. Operating costs include the price of all the utilities consumed: Fuel, demineralized water and cooling water. See Table 1 for these costs and additional information data on utilities. Electricity is generated in the utility plant, thus it is not included in the utilities cost.

The MINLP model consist of minimizing the nonlinear objective function (25) subject to the constraints (2) to (24). Note that all the constraints are linear except equations (3), (4), (12M19)and(22M24).

Description of STEAM

The MINLP model presented in the previous section has been implemented in the user friendly computer program STEAM, that automatically generates the model and interfaces with GAMS (Brooke et al., 1992). The program STEAM is available in IBM/ADC operating system and will be briefly presented in this section. A flowchart of

this program is presented in Figure 3. The way it works is through the use of different menus. The main menu is structured as follows:

1. **Input data.**
2. **Edit data.**
3. **View of the superstructure.**
4. **MINLP model equations and parameters.**
5. **Run design optimization.**
6. **Run design analysis.**
7. **Output MINLP.**
8. **Summary of results.**
9. **Exit**

The input data can be entered as an existing data file or introduced interactively. These data and the internal operating parameters can be modified using the main menu and other following submenus. Given the data of the problem, the program is asked to perform a new design or a design analysis of a given plant configuration. Next, STEAM creates a GAMS file containing the corresponding model equations and optimizes the problem using DICOFT++ (Viswanathan and Grossmann, 1990). MINOS was used as the NLP solver, and OSL as the MILP for the master problems. The output includes all the information concerning the optimal configuration and the operating conditions selected. Also model statistics are available.

Examples

In this section some examples are used to illustrate some capabilities of the proposed MINLP model and its implementation in STEAM. See Table 2 for a summary of the operating parameters and Table A2 in the Appendix for the specified range of temperatures in each steam header used in these examples. A summary of computational results is shown in Table 3. Note that except for example 4, the NLP relaxation was very close to the MINLP optimum solution. In fact, in example 3 there is a zero relaxation gap. Also, note that the CPU times were reasonable despite the fact that the problems are not small (especially example 2). Since nonconvexities are involved in the MINLP model, the global optimum can not be guaranted. Figure 4 to Figure 8, show the optimal configuration and the main operating parameters for each of the following examples. In these figures the following abbreviations and units are used:

F : flowrate (Ton/h)
H : enthalpy (kWh/Ton)
T : temperature (°C)
P : pressure (MPa)
Ef : steam turbine efficiency

Example 1

Consider the synthesis of a utility plant to supply three external mechanical power demands, electricity, steam at medium and low pressure, and that also meets the internal utility plant power demands. The data for the demands is given in Table 4. All the units included in the superstructure can be selected to supply these utilities. The results for this example are shown in Figure 4. The electric generator is driven by a noncondensing back-pressure steam turbine. This is due to the fact that the electric demands in this case are low compared to the large amount of steam required to satisfy the heating demands, so this option is found more attractive than the gas turbine option or a combination of both devices. A conventional boiler is chosen to raise high pressure steam. Steam turbines are selected to supply the external mechanical power demands, except for the power demand no. 3. The total cost for this optimal design of the utility plant is $11,748,000 /yr (Table 3). It should be noted that if a gas turbine for driving the electric generator is forced to be included in the final design, the cost increases to $11,914,000/yr.

Assume that the heating demands are instead 16,000 kW for medium pressure and 30,000 kW for low pressure. In this case, the electrical demands still remain low compared to the heating demands. As we can see in Figure 5, a steam turbine is still selected to drive the electric generator. Since the heating demands are lower than in the original case, the steam available to generate mechanical power is lower too, and therefore less steam is required for steam consumers. Thus, in the optimal solution a condensing steam turbine is now selected to satisfy one of the external mechanical demands. Notice that the change of type of steam turbine for the power demand no. 2, produces a slight change in temperature in the medium and low pressure steam headers. In this example we can see the ability of the proposed model to chose the best option for electrical generation and the optimal configuration of power generating devices, and also their influence on the operating conditions.

Example 2

In this example a larger synthesis and optimization problem will be addressed. In this case, eight external power demands plus the necessary internal demands have to be met, along with steam at two levels of pressure, and electricity. The data for this example are given in Table 5. Consider that 52,000 kW of process heat is available for the generation of superheated steam at 1.7 MPa. The optimal configuration and operating conditions for this example are presented in Figure 6. The cost of this design is $18,630,000/yr. As can be seen, in this case a gas turbine is selected to drive the electric generator. Mechanical demands are satisfied with a combination of different types of back-pressure steam turbines, and electric motors. High pressure steam turbines exhaust mainly to the low pressure header due to the fact that this header has the highest steam demand. The heat contained in the exhaust gas at the gas turbine is not enough to generate the required high pressure steam, and therefore supplementary firing is necessary in the heat recovery boiler. Notice also that low pressure steam is supplied to steam consumers very close to saturated conditions. Steam is clearly superheated in the steam headers at higher pressures.

This same problem was solved using a simplified MILP model derived from the original MINLP model. Nonlinear functions are linearized using the method that was proposed by Papouiias and Grossmann (1983). See the Appendix for the linearized investment costs functions that were used (Table A7). In order to test the results for this example using both approaches, the operating conditions in both cases have to be as close as possible. Therefore for the MILP problem the steam headers were chosen at the optimal operating conditions obtained using the MINLP model presented in this paper. For the linear model steam turbine efficiencies were assigned a fixed value of 0.65. The rest of operating parameters are common for both models and are given in Table 2. As is shown in Table 6, the mechanical power assignment by using the simplified MILP model, is completely different. This clearly shows the great influence on the optimal solution of some operating parameters, that are kept fixed in the MILP model, such as temperatures in steam headers and at the steam turbine outlets, or steam turbine efficiencies at different working conditions.

Example 3

This example illustrates the application of the proposed model to evaluate design alternatives in a utility plant. It is assumed that some of the steam turbines are fixed, while the rest have the option of being replaced by electric motors. To handle this type of problems STEAM generates a set of new equations fixing the integer variables that define the fixed choices in the configuration of the given plant.

Consider a given plant working under the operating parameters given in Table 2, and covering the utility demands presented in Table 7 in which fixed units are assigned to each mechanical power demand. The total cost of this plant with fixed configuration is $20,838,000/yr. The problem consists in determining for each power demand a possible reassignment to electric motors. For this case, the power demand no. 6 and the gas turbine assignments are considered fixed, given the characteristics of these demands. The result for this example is shown in Figure 7. As shown in the figure, in the optimal solution an electric motor is selected for the power demand no. 4, while for the rest of the demands the original structure is kept. The total cost for the new plant is $20,336,000/yr which is 2.4% lower than the optimized initial plant with fixed configuration.

Example 4

This example is adapted from the methanol utility plant requirements presented in Kovac and Glavic (1995). This data was obtained by simulation of an existing methanol plant. For this case the given data have been scaled to fit the requirements of a larger production plant.

The required utility plant has some features that depart from the more conventional cases as the ones presented so far. Process waste heat covers almost all the need of heat duty to generate steam. High pressure steam is generated using waste heat from the exhaust flue gas of the steam reformer. Process waste heat generated in the chemical reactor is used to generate saturated medium pressure steam. The steam header pressures are 10.4 MPa, 4.0 MPa and 0.45 MPa for high, medium and low pressure, respectively. The maximum and minimum temperatures in these headers are given in Table A2. Medium pressure steam is consumed for reaction in the steam reformer, so it is not returned as condensate. Low pressure steam is used for heating in the distillation process plant section. For a detailed description of the demands and the waste heat available see Table 8.

The optimal configuration and operating conditions shown in Figure 8. In this configuration, which has a cost of $2,925,000/yr, the high pressure steam is used to generate the required electricity and to drive the synthesis gas compressor. Steam exhausting from the steam turbine for the synthesis gas compressor and steam from the reactor waste heat boiler is used to drive other steam turbines, and to satisfy the required steam demands. Notice that in this case a steam turbine is selected to drive the high pressure boiling feed water pump.

Conclusions

An MINLP model has been proposed for the synthesis, design and analysis of utility plants for given utility demands and operating parameters. The model predicts the optimal unit configuration and the optimal operating conditions, such as, flowrates, enthalpies and steam turbine efficiencies. Several correlations have been used to account for steam and air/gas properties, and also steam turbine efficiencies depending on the turbine operating conditions.

Several examples were presented to show the capabilities of the model implemented in the program STEAM. These examples have illustrated the capability of the model to select between steam and/or gas cycles, and the best arrangement of different kinds of steam turbines and electric motors for a power demand. The model allows also for the analysis of design alternatives in which some of the equipment is fixed, while the rest can be replaced by other units as was illustrated in example 3. In example 2 the results were compared with those obtained with a simplified MILP model, showing the great influence in the final solution of some variables such as temperatures and steam turbine efficiencies, which are treated as fixed parameters in the MILP models. Table 3 shows that even the larger examples are solved with modest computational effort. These results were obtained with DICOPT++ as MINLP solver, using the option of termination when there is no further improvement on NLP subproblems, and running in a IBM RS6000 workstation.

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APPENDIX

Table Al. Coefficients for steam properties functions

(Units: Enthalpy (kJ/kg), Entropy (kJ/kg °Q, Temperature *CO)*

Pressure (Mpa)	Function
10.4	***H^HP.T,)*** = 1411.39+53140 T_n -2.7918c-3 7_{rt}^2
	S_n(HP,T_n) = 3.3147+95143c-3r_n-65759c-6r_n^2
4.5	5S5 } *m* 1734.95+5.0183 T_n- 33290c- 3 T^2
	= 3.8927+0.0106 T_n - 8.955 lc - 6 T_{rt}^2
4.0	***H_n^m(MP,T_n)*** = 1714.85+53757 T_n -4.0789c -3 T_n^2
	S_n(MP,T_n) = 3.8450+0.01116 T_n - 1.0828c-5 7_n^2
	[illegible] = 3639.72-788.476 5^ + 107.156 S_n^{i2}
1.7	***H?(MP,T_n)*** = 2152.85 + 3.5888 7*,,-2.1697c-3 T^2
	S_n{MPJ$_n$) = 4.9354 + 8.8145c - 3 T_n - 8.0227c - 6 $7''_n{}^2$
	H_n^m(MP,S_n^i)i = 4436.67 -982.815 S_n^l +113306 S_n^{i2}
0.45	***H?(LP,T_n)*** » 2387.24 + 2.5597 T_{rt} - 1.0346c - 3 T^2

Table A2. Steam header operating parameters used in the examples

Pressure (MPa)	Minimum Temperature CO	Maximum Temperature *CO*	Min. Entropy **(kJ/kg"C)**	Max. Entropy **(kJ/kg°C)**
10.4	376	530	6.069	6.673
4.5	325	430	6.409	6.812
4.0	250.3'	400	6.068'	6.773
1.7	204.3*	300	6.396*	6.855
0.45	147.9*	250	6.855'	7.323

• saturated values

Table A3. Coefficients for the steam turbine efficiency function. Noncondensing steam turbine.

	Steam inlet pressure (MPa)			
	10.4	4.5	4.0	1.7
a	0.5658	-427.0992	-378.0419	-181.9821
b	**3.4434e-5**	**865.5034**	**758.8181**	**381.1312**
c	**-1.4713e-9**	**-0.8217**	**-0.8223**	**-0.8150**

Table A4. Coefficients for the steam turbine efficiency function. Condensing steam turbine*

	Steam inlet pressure (MPa)			
	10.4	**4.5**	**4.0**	1.7
a	0.6636	-313.3561	**-244.8585**	-142.4190
b	**9.381 le-6**	**648.2201**	**528.1410**	323.1106
c	**-2.37054e-10**	**-0.7714**	**-0.7769**	-0.7700

Table A5. Functions for Enthalpy and Entropy in the Gas Turbine.

Hgt_g **a** $a\ Tgtg^2 + b\ Tgt_g - c$

$Sgt_g = d\ inTgtg + e\ Tgt_g - f - g\ \backslash np_g$

(Hgt_e in kJ/kg, Sgt_e in kJ/kg K, Tgt_e in **K,** p_P in MPa)

	Compressor Inlet	Compressor Outlet	Turbine Inlet	Turbine Outlet
a	6.47238e-5	1.14274e-4	7.43569e-5	1.26596e-4
b	0.977148	0.929784	1.06576	0.9531
c	297.01	285.84	354.81	294.08.
d	0.977148	0.929784	1.06576	0.9531
e	1.29447e-4	2.28548e-4	1.970774e-5	2.53192e-4
f	6.26332	6.02301	6.73545	6.16319
g	0.287	0.287	0.287	0.287

Table A6. Air/gas **composition** (% **wt**)

Standard wet air		Natural Gas		Turbine Exhaust Gas	
0,	22.84 %	CH_4	72.89 %	CO,	4.62 %
N_2	75.87%	C,H_6	25.89%	H,0	4.78%
H,0	1.28%	N_2	1.22 %	N,	74.62 %
				0,	15.98 %

Table A7. Investment Cost **Data (includes linearized** costs used **in example** 2).

Unit	Type of Cost Function	Investment Cost ($/ycar)
Held erected boiler[1] F: steam flowrate (Ton/h) P: pressure (MPa)	Nonlinear	22970 F^fp, fp,=0.6939+0.1214 P-3.7984e-3 P^2
Large package boiler F: steam flowrate (Ton/h) P: pressure (MPa)	Nonlinear	4954 F^fp, fp^l.3794-0.5438 P+0.1879 P^2
	Linear (4.5 MPa)	101840+3441F
	Linear (1.7 MPa)	37237+1258 F
Heat Recovery Boiler	Nonlinear	941Ffg0.75
Ffg: flue gas flowrate (Ton/h)	Linear	6996+211.5 Ffg
Steam Turbine Wst: power (kW)	Nonlinear Linear	2237 Wst^(MI 81594+18.052 Wst
Electric Motor Wei: power (kW)	Nonlinear Linear	79 Wei""* 1601+27.28 Wei
Gas Turbine Wgt: power (kW)	Nonlinear Linear	952 Wgf^7' 321350+67.618 Wgt
Electric Generator Weg: power (kW)	Nonlinear Linear	176 Weg^04* 8141+0.6495 Weg
Deaerator	Nonlinear	904 *F:^M*
(F_B= BFW Flowrate Ton/h)	Linear	7271+79.25 F.
Condenser Q: heat dissipated (kW) Fc: Cooling water flowrate (Ton/h)	Nonlinear Linear	43 CT 3977+1.84 Fc
Centrifugal Pump Pw: Power in kW fpw=l until 1.03 MPa, fpw=1.62 1.03-3.45 MPa, fpw=2.12 >3.45MPa	Nonlinear Linear	(475.3+34.95 Pw • 0.0301 Pw^2)fpw (633+27.24 Pw)fpw
Centrifugal Fan (Fg=Flowrate Ton/h)	Nonlinear Linear	1174+283 Fg+0.1553 Fg^2 350.9 Fg

[1] Used for the cost of 10.4 MPa HP boilers.

TABLES

Table 1. Utilities Data.

Demincralizcd Water	Cooling Water	Fuel
Pressure: 0.14 MPa	Tout-Tin • 20 C	Natural Gas
Temperature: 27 C	Pout-Pin • 0.69 MPa	LHV: 13856 kWh/Ton
Cost: 0.24 $/Ton	Cost: 0.0185 $/Ton	Cost: 223 $/Ton

Table 2. Summary of operating parameters

Unit	Operating Parameters
Condenser Header	Pressure: 0.143 MPa Temperature: HOC
Vacuum Header	Pressure: 0.02 Map Temperature: 60 C
Deaerator	Pressure: 0.14 MPa Vent Ratio: 0.0015
Gas Turbine	Inlet Temperature: 27 C Inlet Pressure: 0.101 MPa Compressor Pressure Ratio: 19.8 Compressor Efficiency: 0.83 Turbine Outlet Pressure: 0.103 MPa Turbine Pressure Ratio: 18.9 Turbine Efficiency: 0.85 Mechanic Efficiency: 0.985 Combustion Chamber Efficiency: 0.99
Boilers	Blowdown Rate: 3% Excess Combustion Air: 15% Efficiency: 90%
Combustion Air Fans	Differential Pressure: 0.012 MPa Efficiency: 0.70
Electric motors	Efficiency: 0.90
Pumps	Efficiency: 0.65

Table 3. Summary of results and statistics for the presented examples.

	Example 1	Example 2	Example 3	Example 4
No. of 0-1 var.	56	101	83	70
No. of continuous **variables**	263	473	389	326
No. of constraints	338	599	541	446
Relaxed NLP, in k$/year	11610	18622	20336	2483
MINLP Optimum, in k$/year	11748	18630	20336	2925
No. of major iterations	3	3	3	4
CPU Time, in s (%NLP,%MBLP)	23.28 (77,23)	51.31 (85,15)	25.86 (83,17)	83.22 (87,13)

Table 4, **External utility** demands for **example** 1.

High Pressure Heating	OkW
Medium Pressure Heating	20000 kW
Low Pressure Heating	55000 kW
Electricity	4500 kW
Mechanical Power no. 1	1200 kW
Mechanical Power no. 2	1500 kW
Mechanical Power no. 3	700 kW

Table 5. **External utility** demands **for example** 2.

High Pressure Heating	OkW
Medium Pressure Heating	31500 kW
Low Pressure Heating	85500 kW
Electricity	33000 kW
Mechanical Power no. 1	3120 kW
Mechanical Power no. 2	1800 kW
Mechanical Power no. 3	550 kW
Mechanical Power no. 4	818 kW
Mechanical Power no. 5	2600 kW
Mechanical Power no. 6	1265kW
Mechanical Power no. 7	1940 kW
Mechanical Power no. 8	650 kW

Table 6. Results for example 2 (MILP model)

Power assignment:	
Mechanical Power:	Unit
no. 1	Extraction noncondensing HP steam turbine
no. 2	Noncondensing MP steam turbine
no. 3	Electric motor
no. 4	Electric motor
no. 5	Electric motor
no. 6	Noncondensing MP steam turbine
no. 7	Electric motor
no. 8	Electric motor
Heat Recovery Boiler BFW pump	Electric motor
Waste Heat Boiler BFW pump	Electric motor
Other results:	
Total electricity demand	40508 kW
Medium pressure steam	38.4 Ton/h (31500 kW)
Low pressure steam	112 Ton/h (85500 kW)
Total Cost	19876 k$/year

Table 7. External utility demands for example 3

High Pressure Heating	0 kW	
Medium Pressure Heating	15000 kW	
Low Pressure Heating	40000 kW	
Electricity	35500 kW	
Mechanical demands		Unit
Mechanical Power no. 1	2200 kW	Noncondensing HP extraction turbine
Mechanical Power no. 2	1600 kW	HP turbine exhausting to low pressure
Mechanical Power no. 3	1200 kW	HP turbine exhausting to medium pressure
Mechanical Power no. 4	1100 kW	MP steam turbine
Mechanical Power no. 5	700 kW	MP steam turbine
Mechanical Power no. 6	4000 kW	Condensing HP steam turbine

Table 8. Waste heat available and external demands in example 4

Waste heat available	
Furnace duty	65406 kW
Reactor duty	22450 kW
BFW heater duty	22562 kW
Mechanical demands:	
no. 1 (Gas synthesis compressor)	12684 kW
no. 2 (Recycle compressor)	1428 kW
no. 3 (Air coolers)	1055 kW
Steam demands:	
Medium pressure (Steam reformer)	66374 kW
Low pressure (Distillation)	18496 kW
Electrical demands	3000 kW

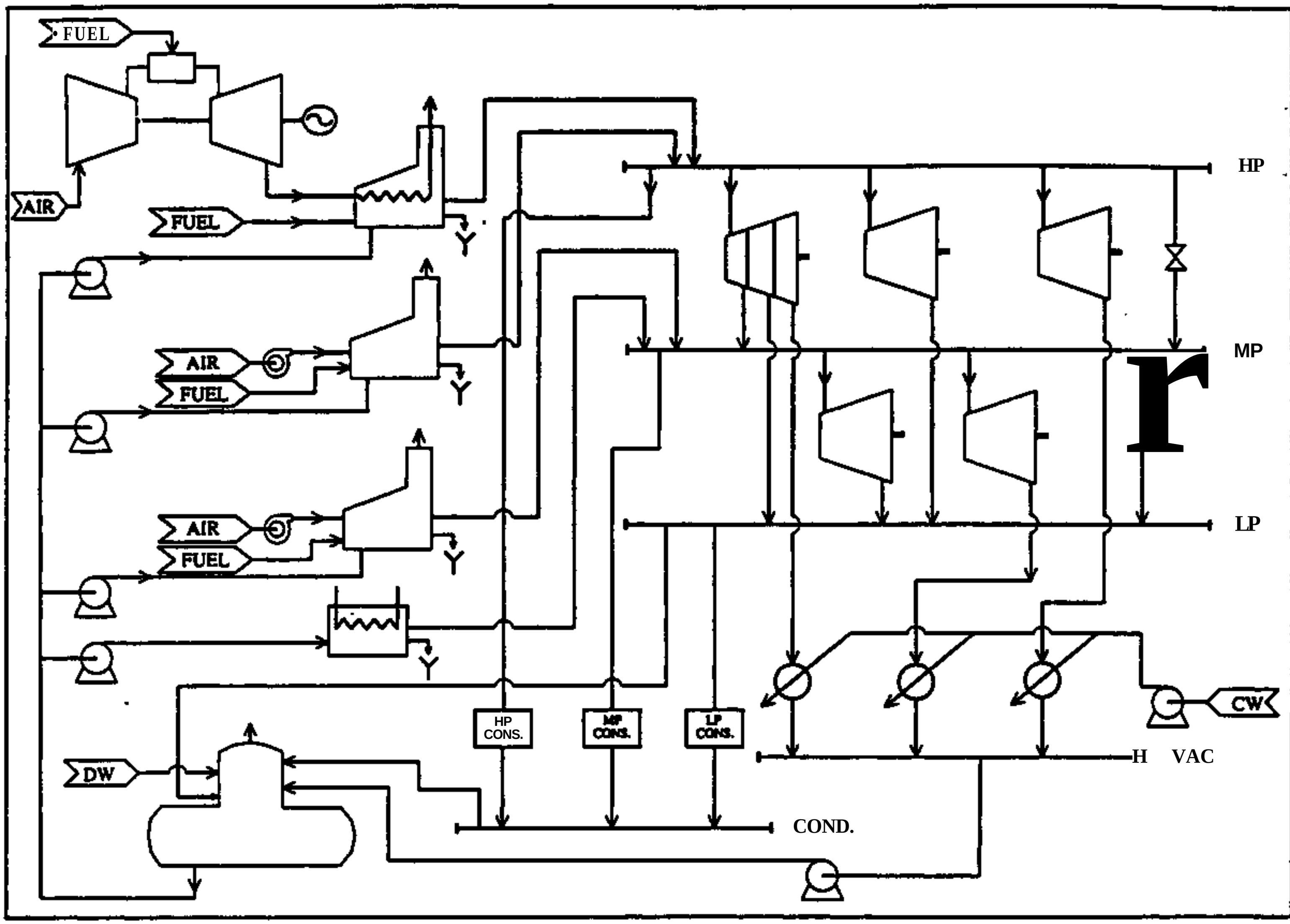

Figure 1. Superstructure of the utility plant

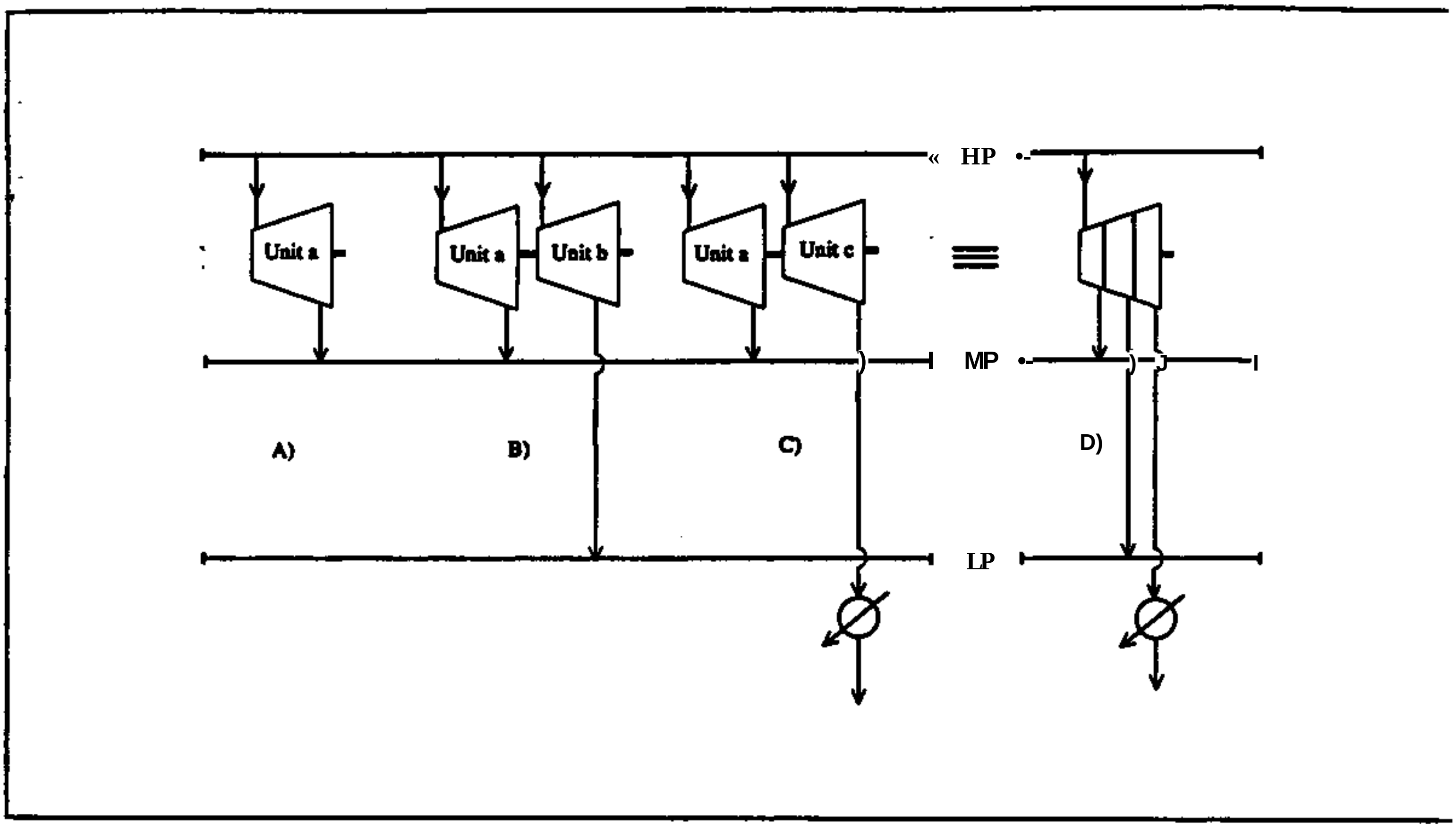

Figure 2. Decomposition of the high pressure extraction steam turbine

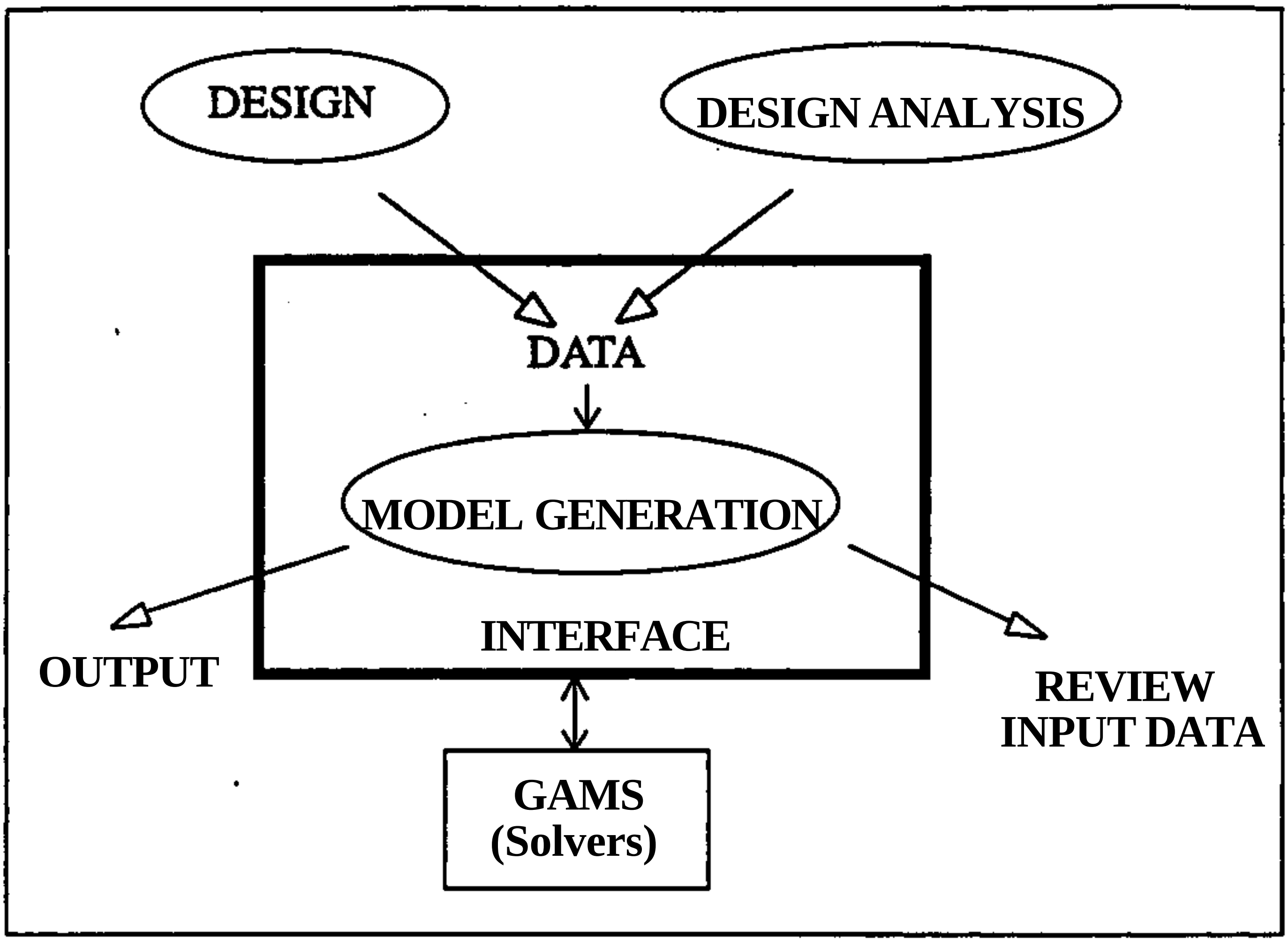

Figure 3. Flowchart of STEAM

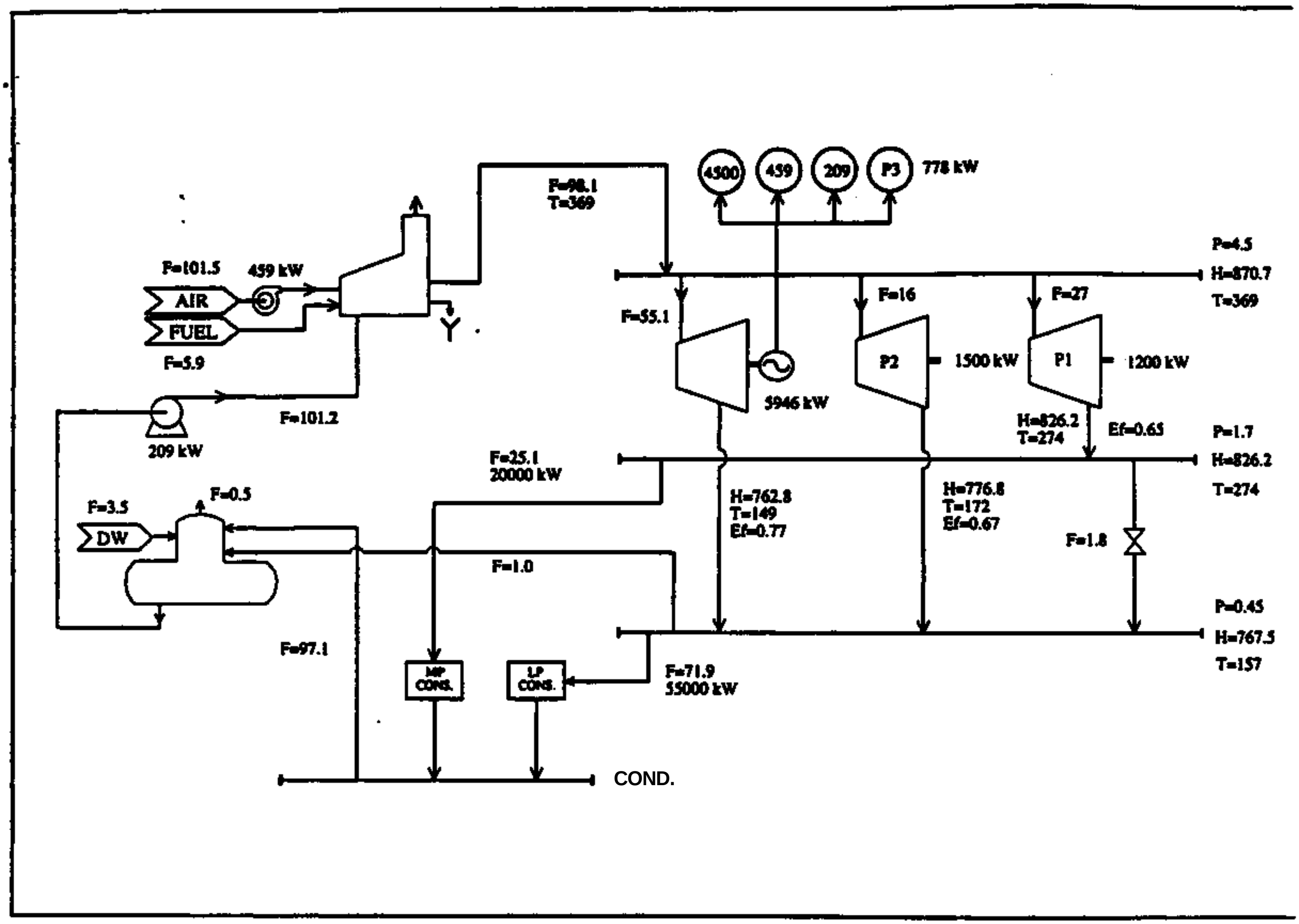

Figure 4. Optimal utility plant for example 1

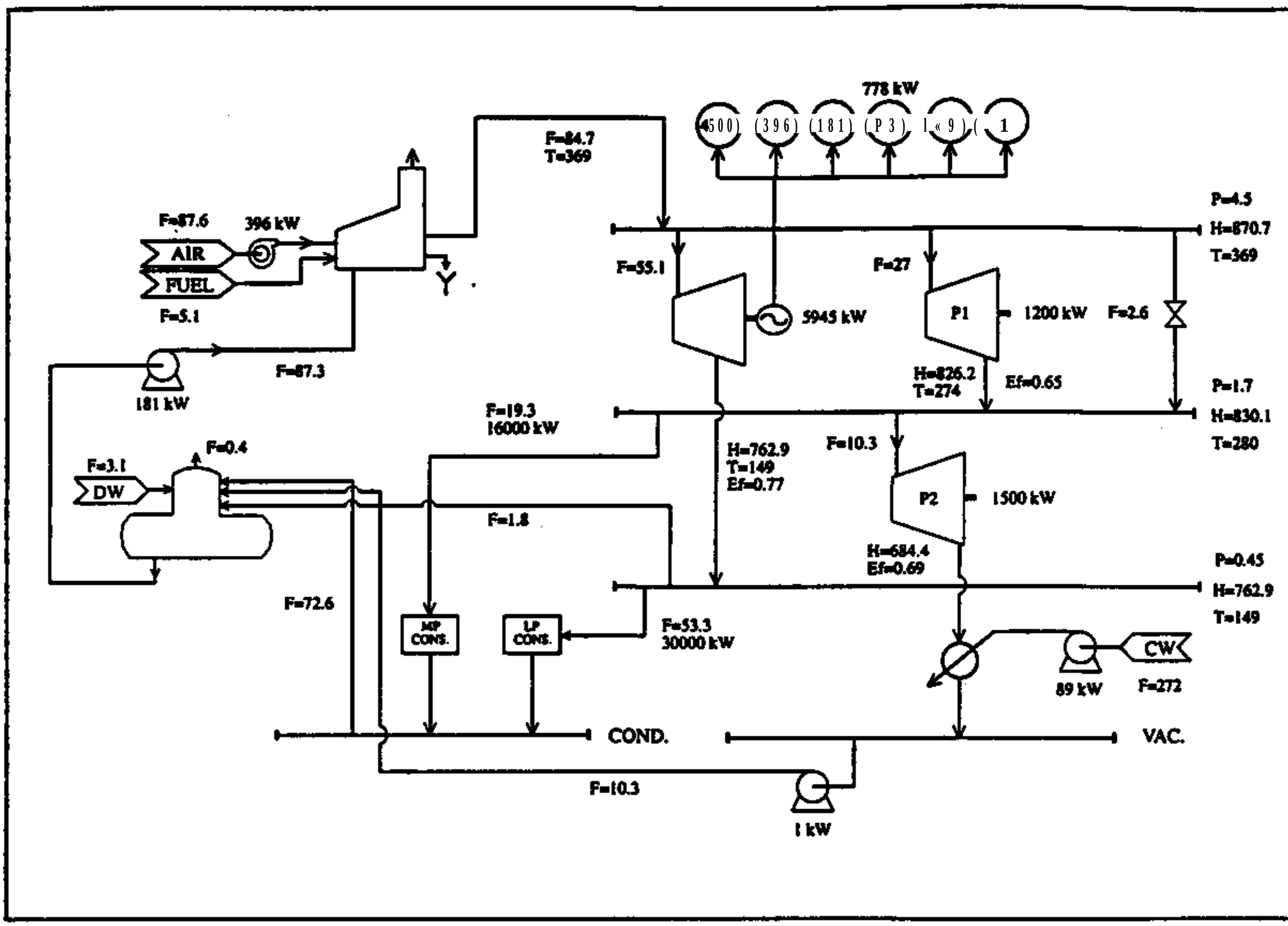

Figure 5. Optimal utility plant for example 1 with lower heating demands.

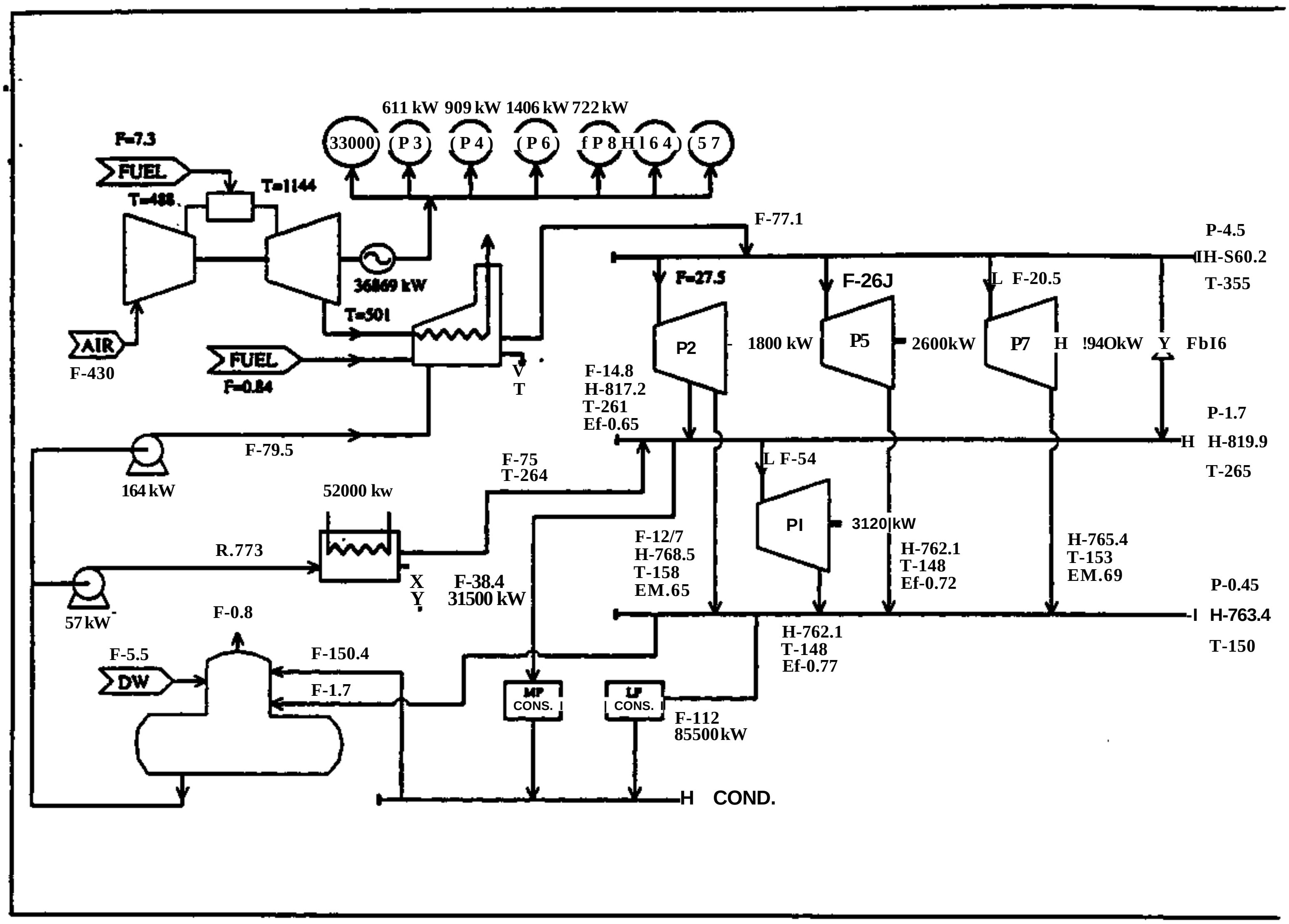

Figure *6.* Optimal utility plant for example 2.

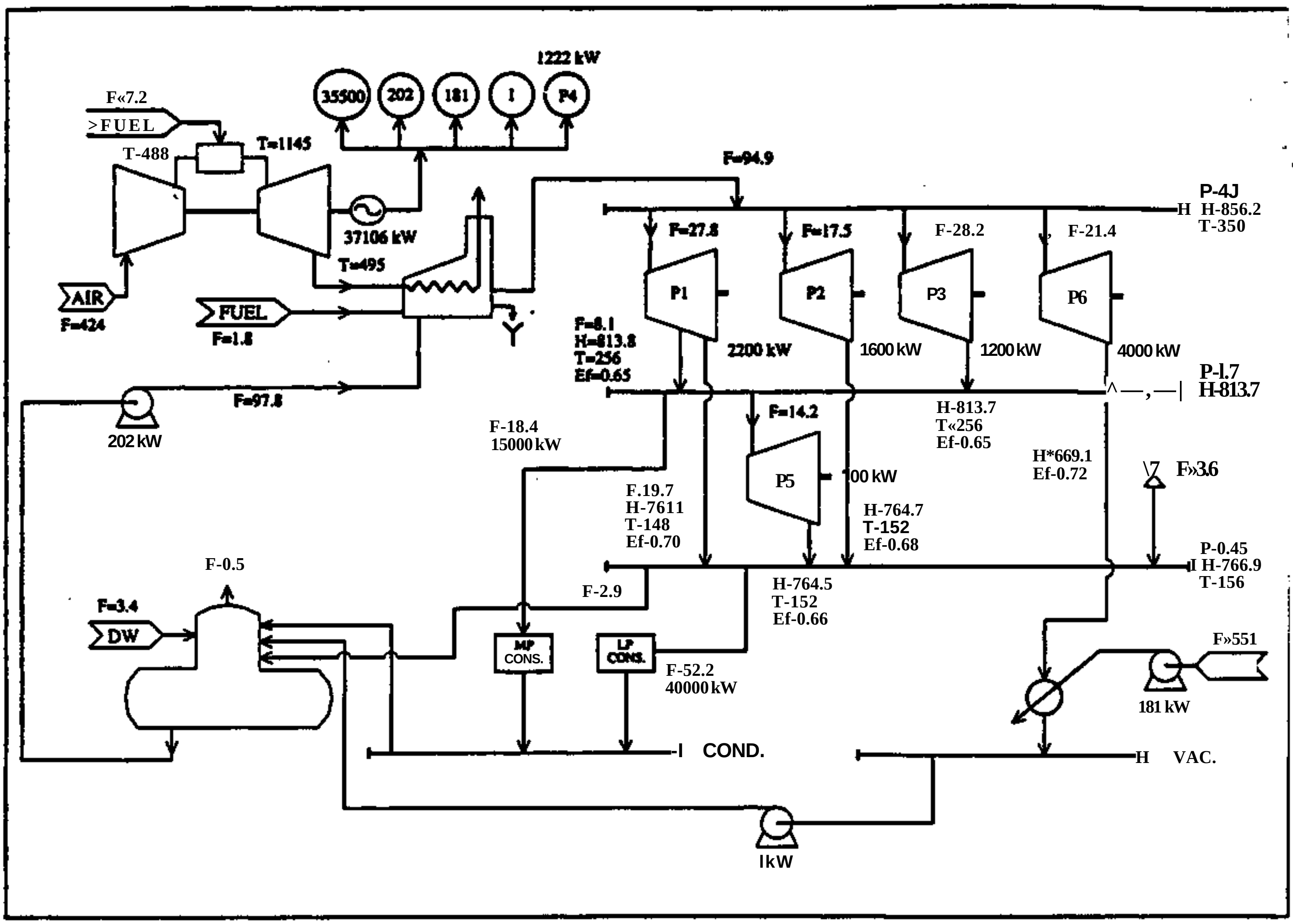

Figure 7. Optimal utility plant for example 3

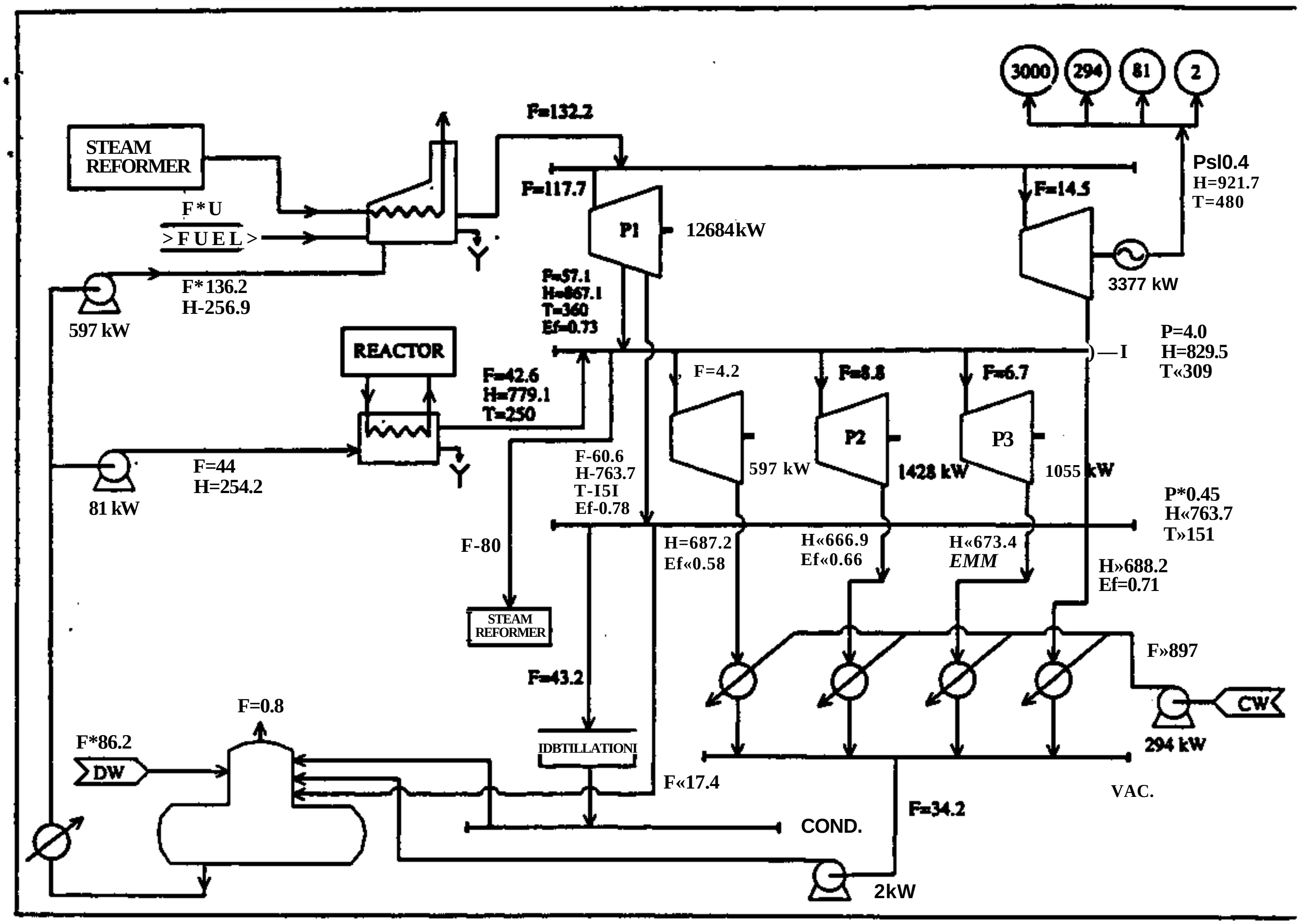

Figure 8. Optimal utility plant for example 4