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# Modeling and Multi-objective Optimization of Refinery Hydrogen Network*

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**Abstract** The demand of hydrogen in oil refinery is increasing as market forces and environmental legislation, so hydrogen network management is becoming increasingly important in refineries. Most studies focused on single-objective optimization problem for the hydrogen network, but few account for the multi-objective optimization problem. This paper presents a novel approach for modeling and multi-objective optimization for hydrogen network in refineries. An improved multi-objective optimization model is proposed based on the concept of superstructure. The optimization includes minimization of operating cost and minimization of investment cost of equipment. The proposed methodology for the multi-objective optimization of hydrogen network takes into account flow rate constraints, pressure constraints, purity constraints, impurity constraints, payback period, *etc*. The method considers all the feasible connections and subjects this to mixed-integer nonlinear programming (MINLP). A deterministic optimization method is applied to solve this multi-objective optimization problem. Finally, a real case study is introduced to illustrate the applicability of the approach.
**Keywords** refinery, multi-objective optimization, hydrogen network, mixed integer nonlinear programming

## 1 INTRODUCTION

Oil refinery consumes hydrogen in large amounts for removing sulfur and nitrogen compounds and producing lighter fuels. During the past decade, crude oil gets heavier and contains more sulfur and nitrogen. Hydrogen availability has become an important issue because refiners are facing challenges of stricter regulation and increasing demand for transportation fuel. Along with the legislation for environment protection, tougher gasoline and diesel quality specifications have been implemented to reduce pollutants from automotive exhausts. Thus the hydrogen supply in many refineries is becoming a critical problem. As the demand for hydrogen grows, the management and optimization of hydrogen system in refinery is becoming increasingly important to ensure optimum economics [1–6].

Many investigations focused on the optimization of hydrogen network in refinery. Graphical based methods were first used to optimize hydrogen network. Towler *et al*. [1] introduced a method to analyze hydrogen network using value composite curves. Alves and Towler [2] proposed hydrogen pinch analysis for targeting the minimum hydrogen consumption of the whole hydrogen system. Zhao *et al*. [3] employed a non-iterative graphical technique to achieve the utility target. Zhao *et al*. [4] developed an iterative targeting procedure for multiple impurities. Liao *et al*. [5, 6] obtained optimal conditions for pinch problems and proposed a rigorous targeting approach for hydrogen minimization. Further, mathematical programming methods were used to solve these problems. Hallale and Liu [7] developed an improved superstructure optimization method for hydrogen network accounting for the pressure constraints as well as compressors for retrofit scenarios. Liu and Zhang [8] provided a detailed model of purification units for selection of purification processes and their integration in hydrogen networks. Khajehpour *et al*. [9] proposed reduced superstructure based on heuristic rules to optimize a refinery in Iran and a 22.6% reduction in hydrogen production was achieved. Liao *et al*. [10] considered purification processes for refinery hydrogen management and demonstrated the application of superstructure based approach for retrofit design of an existing refinery. Kumar *et al*. [11] used mathematical modeling technique to optimize the hydrogen distribution network in refinery and analyzed the characteristics of linear programming (LP) model, nonlinear programming (NLP) model and mixed-integer nonlinear programming (MINLP) model. Ahmad *et al*. [12] developed a novel approach for the design of flexible hydrogen networks that can remain optimally operable under multiple periods of operation.

However, most studies employ single-objective optimization method to optimize the hydrogen network, few account for multi-objective optimization techniques. The optimization of hydrogen network aims at minimizing operating cost and investment cost

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simultaneously. The operating cost may decrease with the increase of some decision variables, while the investment cost increases. It is useful and necessary to find the compromise to balance the two objectives. Thus the optimization of hydrogen network requires multi-objective optimization.

In this paper, a novel approach is presented for modeling and multi-objective optimization of hydrogen network in refineries. An improved multi-objective optimization model for hydrogen network is proposed based on the concept of superstructure. Minimizing total operating cost and minimizing investment cost are the objective functions of the optimization. The tradeoff between the two costs is explored. The proposed methodology for multi-objective optimization of hydrogen networks takes into account flow rate constraints, pressure constraints, purity constraints, impurity constraints, exiting and new equipment, payback period, *etc*. The method is not limited to optimize the feed routes of hydrogen consumers, but also accounts for the optimization of feed routes of purifiers. To make the approach more suitable for real systems, two different off-gases from hydrogen consumers are considered. The flow rate and purity of hydrogen consumer are considered as variables, and the minimum pure hydrogen of hydrogen consumer is regarded as constant. Then the optimization model is converted into a MINLP. The final suitable optimization scheme is determined by an optimization procedure. Finally, a real case study is introduced to demonstrate the effectiveness of the presented approach.

## 2 REFINERY HYDROGEN NETWORK

In oil refinery, some processes consume hydrogen, such as hydrotreating, hydrocracking, isomerization and purification processes, and some produce hydrogen, such as the catalytic reforming process. These processes compose a hydrogen network.

In hydrogen networks, a source is a stream that makes hydrogen available to the network. Hydrogen sources are the products of hydrogen-producing processes, off-gases of hydrogen-consuming processes, or the imported hydrogen (or fresh hydrogen). A sink is a stream that takes hydrogen from the hydrogen network with fixed flow rate and purity requirements. Hydrogen sinks are the inlet streams of various hydrogen-consuming units such as hydrotreaters and hydrocrackers. In addition, hydrogen sources can be made more acceptable by using compressors and/or purifiers. Hydrogen is further supplied by hydrogen utilities, while the discharge of hydrogen sources is mixed and sent to the fuel system.

Figure 1 shows a diagram of a typical hydrogen consumer [13]. A liquid feed stream is mixed with a gas stream rich in hydrogen and fed into the hydrotreating or hydrocracking reactor. The reactor effluent is cooled and sent into a high pressure gas-liquid separator. Most of the gas from the separator is recycled to the reactor inlet after desulfurization. In order to keep the high purity recycle hydrogen and avoid the accumulation of hydrogen sulfide in the system, a part of these gases need to discharge outward. The liquid product from the bottom of high pressure gas-liquid separator is sent to a low-pressure separator. The low pressure hydrogen from the low-pressure separator may be used as hydrogen source directly or sent to purifiers after desulfurization. The liquid product from the bottom of low pressure separator is sent to a stripper. The dry gas from the top of stripper may be purified by purifiers after desulfurization or sent to the fuel gas system. The liquid product from the bottom of stripper separator is sent to a fractionator. The gas from the top of fractionator is sent to the fuel gas system. Here the mixture of the makeup hydrogen and the recycle hydrogen is defined as the sink, and the low pressure hydrogen, dry gas and the recycle hydrogen are defined as the source.

## 3 OPTIMIZATION CONSTRAINTS

To develop a multi-objective optimization problem, many constraints should be considered, such as hydrogen sink constraints, hydrogen source constraints,

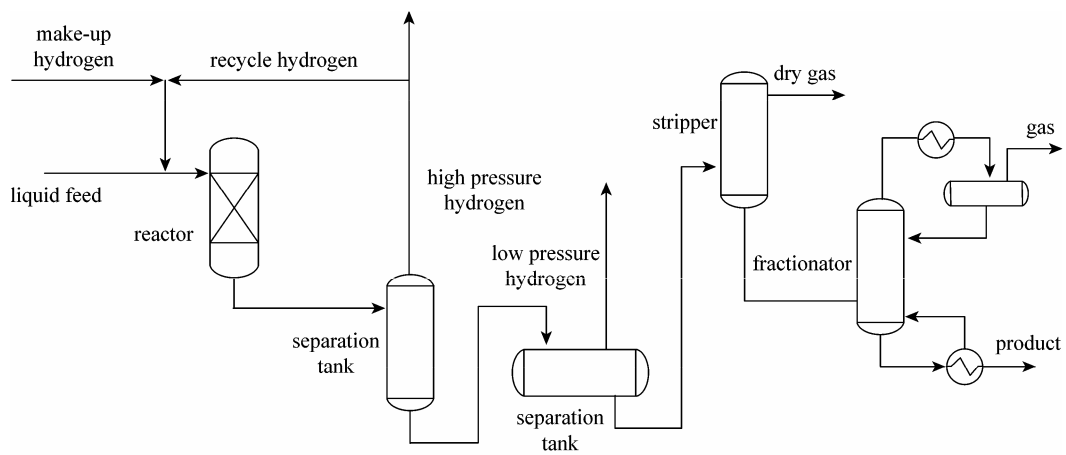


**Figure 1 A typical process of hydrogen consumption in a refinery**

impurity constraints, compressor constraints and purifier constraints. Integer variables are employed to indicate compressors, purification units and pipelines. All the possible connections from sources to sinks should be considered. In a word, hydrogen network is optimized to effectively use existing equipment, install additional equipment and restructure process stream for the minimum total annual cost and maximum hydrogen yield of purification system.

### 3.1 Hydrogen sink constraints

In establishing the connections between hydrogen sources and sinks, the constraints imposed by the sinks cannot be violated and the sources must provide enough hydrogen to each sink.

$$\sum_j F_{j,k} = F_k \quad \forall j \in J, k \in K \tag{1}$$

$$\sum_j F_{j,k} \cdot y_k = F_k \cdot y_k \quad \forall j \in J, k \in K \tag{2}$$

Every sink needs the minimum pure hydrogen to maintain its current production, and the hydrogen purity of every sink has to be greater than or equal to the minimum requirement purity.

$$F_k \cdot y_k \geqslant F_k^{\min} \quad \forall k \in K \tag{3}$$

$$y_k^{\min} \leqslant y_k < 1 \quad \forall k \in K \tag{4}$$

### 3.2 Hydrogen source constraints

The amount of gas available from each source must be greater than or equal to the total amount sent to the sinks.

$$\sum_k F_{j,k} \leqslant F_j \quad \forall j \in J, \quad k \in K \tag{5}$$

### 3.3 Logic constraints

With general binary variable $X_{j,k}$, the relationships between $X_{j,k}$ and $F_{j,k}$ are

$$X_{j,k} = 1 \Leftrightarrow F_{j,k} > 0 \quad \forall (j,k) \in O \tag{6}$$

$$X_{j,k} = 0 \Leftrightarrow F_{j,k} = 0 \quad \forall (j,k) \in O . \tag{7}$$

Based on the preceding binary variable $X_{j,k}$, the flow rate constraint is

$$F_{j,k} \leqslant X_{j,k} \cdot U_{j,k} \quad \forall (j,k) \in O \tag{8}$$

$$F_{j,k} \geqslant X_{j,k} \cdot u_{j,k} \quad \forall (j,k) \in O \tag{9}$$

where $U_{j,k}$ and $u_{j,k}$ are upper and lower bounds of $F_{j,k}$.

### 3.4 Impurity constraints

Catalyst of hydrogenation has a high requirement for impurities. It is necessary to analyze the impurities of sources and their effect on the catalyst. In the optimization, the connections of some equipment should be limited. Impurity constraints are described as

$$X_{j,k} = 0 \quad \forall (j,k) \in O_{\text{forbidden}} . \tag{10}$$

### 3.5 Compressors constraints

Here both flow rates and purity in the compressors are considered as variables, and the constraints on the compressors can be described as follows.

The flow rate of gas entering the compressor must be equal to the exit flow rate. The balance for the flow rate is

$$\sum_j F_{j,\text{comp}} = \sum_k F_{\text{comp},k} \quad \forall j \in J, k \in K . \tag{11}$$

The amount of pure hydrogen entering the compressor must be equal to the leaving amount. The hydrogen balance is

$$\sum_j F_{j,\text{comp}} \cdot y_j = \sum_k F_{\text{comp},k} \cdot y_{\text{comp},k} \quad \forall j \in J, k \in K . \tag{12}$$

The amount of gas fed to one compressor never exceeds its maximum capacity. The capacity limit is

$$\sum_j F_{j,\text{comp}} \leqslant F_{\text{comp}}^{\max} \quad \forall j \in J . \tag{13}$$

### 3.6 Purifiers constraints

#### 3.6.1 *Mass balance constraints*

According to Hallale and Liu [7], purifiers such as pressure-swing adsorption (PSA) and membrane separation can be modeled as one sink (inlet stream) and two sources (the product stream and the residue stream). The flow rate balance and hydrogen balance for the purifiers are

$$F_{p,\text{f}} = F_p^{\text{P}} + F_p^{\text{R}} \quad \forall p \in N \tag{14}$$

$$F_{p,\text{f}} \cdot y_{\text{f}} \cdot R = F_p^{\text{P}} \cdot y_p^{\text{P}} \quad \forall p \in N \tag{15}$$

$$F_{p,\text{f}} \cdot y_{\text{f}} = F_p^{\text{P}} \cdot y_p^{\text{P}} + F_p^{\text{R}} \cdot y_p^{\text{R}} \quad \forall p \in N \tag{16}$$

$$\sum_i F_{i,p} = F_{p,\text{f}} \quad \forall i \in M, p \in N \tag{17}$$

$$\sum_i F_{i,p} \cdot y_i = F_{p,\text{f}} \cdot y_{\text{f}} \quad \forall i \in M, p \in N \tag{18}$$

where $F_{p,\text{f}}$ is the inlet flow rate of purifier $p$, and $F_{i,p}$ is the flow rate of feed stream from off-gas $i$ to purifier $p$.

The recovery ratio $R$ can be calculated by the following correlation:

$$R = f\left(F_{p,\text{f}}, y_{p,\text{f}} y_p^{\text{P}}\right) \tag{19}$$

The correlation can be obtained by theoretical derivation or experimental study. The experimental results are usually provided by the purifier manufacturer. In this paper, the correlation is obtained from experimental results from daily operation in refinery.

**3.6.2** *Hydrogen purity constraints*

The feed purity is between those of product and residue,

$$y_p^{\mathrm{R}} \leqslant y_{\mathrm{f}} \leqslant y_p^{\mathrm{P}}. \tag{20}$$

**3.6.3** *Capacity limits*

An existing purifier is designed for a specific flow rate and there will be a maximum flow rate constraint on each purifier.

$$\sum_i F_{i,p} \leqslant F_p^{\max} \quad \forall i \in M, p \in N \tag{21}$$

Every purifier has a minimum purity requirement for every feed stream.

$$y_i \geqslant y_p^{\min} \quad \forall i \in M, p \in N \tag{22}$$

**3.6.4** *Logic constraints*

Considering general binary variable $X_{i,p}$, the relationships between $X_{i,p}$ and $F_{i,p}$ are expressed as

$$X_{i,p} = 1 \Leftrightarrow F_{i,p} > 0 \quad \forall (i,p) \in O_p \tag{23}$$

$$X_{i,p} = 0 \Leftrightarrow F_{i,p} = 0 \quad \forall (i,p) \in O_p \tag{24}$$

Based on the preceding binary variable $X_{i,p}$, the flow rate constraints are

$$F_{i,p} \leqslant X_{i,p} \cdot U_{i,p} \quad \forall (i,p) \in O \tag{25}$$

$$F_{i,p} \geqslant X_{i,p} \cdot u_{i,p} \quad \forall (i,p) \in O \tag{26}$$

where $U_{i,p}$ and $u_{i,p}$ are upper and lower bounds of $F_{i,p}$.

**3.6.5** *Special constraints*

For some purification processes, due to the special requirements for purification technology or process convenience, some feed streams must be purified in some purifiers, while some feed streams can not be purified in some purifiers.

$$F_{i,p} = F_i \quad \forall i \in M, p \in N \tag{27}$$

$$X_{i,p} = 0 \quad \forall i \in M, p \in N \tag{28}$$

### 3.7 Adding new equipments to the system

In order to retrofit the refinery hydrogen network to the utmost extent, new equipment such as compressors, purifiers and pipelines may be added. Incorporation of these new facilities can be represented by binary variables. Therefore, the capital cost has to be calculated by means of a set of binary variables.

The capital cost of a new compressor is related to its power consumption and many data are available in literature [7]. The relationship is a linear one:

$$C_{\mathrm{comp}} = \left(a_{\mathrm{comp}} \cdot X_{j,k} + b_{\mathrm{comp}} \cdot \mathrm{Power}_{j,k}\right) \tag{29}$$

where $C_{\mathrm{comp}}$ is the investment cost of new compressors, and $a_{\mathrm{comp}}$ and $b_{\mathrm{comp}}$ are the cost coefficients for compressors.

The cost of new pipes in a hydrogen network can be calculated as follows [7]

$$C_{\mathrm{pipe}} = \left(a_{\mathrm{pipe}} \cdot X_{j,k} + b_{\mathrm{pipe}} \cdot D^2\right) \cdot L \tag{30}$$

where $C_{\mathrm{pipe}}$ is the investment cost of new pipes, and $a_{\mathrm{pipe}}$ and $b_{\mathrm{pipe}}$ are the cost coefficients for pipes.

The most common purifiers in refinery are pressure-swing adsorption (PSA) unit and membrane separation unit. Their investment costs can be expressed as [1]

$$C_{p,\mathrm{PSA}} = a_{\mathrm{PSA}} \cdot A_{i,p} + b_{\mathrm{PSA}} \cdot F_{p,\mathrm{f}} \tag{31}$$

$$C_{p,\mathrm{mem}} = \left(a_{\mathrm{mem}} + \frac{b_{\mathrm{mem}}}{z_{\mathrm{mem}}}\right) \cdot F_{p,\mathrm{f}} \tag{32}$$

where $C_{p,\mathrm{PSA}}$ and $C_{p,\mathrm{mem}}$ are the capital costs of PSA unit and membrane separation unit, respectively, $a_{\mathrm{PSA}}$ and $b_{\mathrm{PSA}}$ are the cost coefficients for PSA unit, and $a_{\mathrm{mem}}$, $b_{\mathrm{mem}}$, and $z_{\mathrm{mem}}$ are the cost coefficients for membrane separation unit.

## 4 FORMULATION OF THE OPTIMIZATION PROBLEM AND SOLUTION STRATEGY

Minimizing operating cost and minimizing investment cost are the objective functions of the multi-objective optimization problem in this paper. The first objective function for the optimization of hydrogen network is the operating cost

$$C_1 = C_{\mathrm{H_2}} + C_{\mathrm{power}} - C_{\mathrm{fuel}} \tag{33}$$

where $C_{\mathrm{H_2}}$, $C_{\mathrm{power}}$ and $C_{\mathrm{fuel}}$ are the cost of hydrogen, power and fuel per hour, respectively.

The cost of a hydrogen utility is assumed proportional to its flow rate, and is calculated by

$$C_{\mathrm{H_2}} = \sum_j \left(\sum_k F_{j,k} \cdot C_j \cdot t_j\right) \quad \forall j \in J, k \in K \tag{34}$$

where $C_j$ is the price of hydrogen source $j$, and $t_j$ is the operating hours for hydrogen sink $j$.

The compressor power cost is expressed as

$$C_{\mathrm{power}} = C_{\mathrm{e}} \cdot \sum_j \sum_k \left(\mathrm{Power}_{j,k} \cdot t_{j,k}\right) \quad \forall j \in J, k \in K \tag{35}$$

where $\mathrm{Power}_{j,k}$ is the compressor power, $C_{\mathrm{e}}$ is the price of electricity, and $t_{j,k}$ is the operating hours of compressors.

The compressor power can be represented as [7]

$$\mathrm{Power}_{j,k} = \frac{C_p \cdot T}{\eta}\left[\left(\frac{P_{\mathrm{o}}}{P_{\mathrm{i}}}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] \cdot \frac{\rho_{\mathrm{o}}}{\rho} \cdot F_{j,k} \tag{36}$$

where $C_p$ is the heat capacity of the stream at constant pressure, $T$ is the inlet temperature, $\eta$ is the efficiency,

$\gamma$ is the ratio of specific heat of gas at constant pressure to specific heat of gas at constant volume, $P_o$ is the final delivery pressure, $P_i$ is the intake pressure, $\rho$ is the density of the gas under the design condition, $\rho_o$ is the density under standard conditions, and $F_{j,k}$ is the mass flow rate of compressor.

The value created by fuel is obtained through heat value calculation [7]

$$C_{\text{fuel}} = F_{\text{fuel}}\left[y \cdot \Delta H^{\Theta}_{\text{c,H}_2} + (1-y) \cdot \Delta H^{\Theta}_{\text{c,CH}_4}\right] \cdot C_{\text{heat}} \quad (37)$$

where $\Delta H^{\Theta}_{\text{c}}$ is the standard heat of combustion, $F_{\text{fuel}}$ is the flow rate of fuel, $y$ is the hydrogen purity of fuel, and $C_{\text{heat}}$ is the price of fuel.

The second objective function is the annualized investment cost,

$$C_2 = f_{\text{A}} \cdot \left(\sum_{\text{comp}} C_{\text{comp}} + \sum_{p} C_p + \sum_{\text{pipe}} C_{\text{pipe}}\right) \quad (38)$$

where $f_{\text{A}}$ is the annualizing factor, and $C_p$ is the investment cost of new purifiers.

The variables that affect the hydrogen network optimization process are the flow rates from hydrogen sources to hydrogen sinks ($F_{j,k}$, $F_{i,p}$), the flow rates of compressor ($F_{j,\text{comp}}$, $F_{\text{comp},k}$), the flow rates of purifiers ($F_p^{\text{P}}$), the purities of hydrogen sinks ($y_k$), the hydrogen product purities of purifiers ($y_p^{\text{P}}$), the outlet purities of compressors ($y_{\text{com},k}$), and binary variables ($X_{j,k}$ $X_{i,p}$) indicating the hydrogen stream, piping, compressors and purifiers. According to characteristics of model and the requirement of hydrogen management in refinery, the flow rates from hydrogen sources to hydrogen sinks ($F_{j,k}$, $F_{i,p}$) and binary variables ($X_{j,k}$ $X_{i,p}$) are selected as the main decision variables for optimization in this study.

Among process variables selected using mechanism analysis, the sensitivity analysis on each variable is performed using the optimization model presented in Section 3 and Section 4 to obtain its relation with the operating cost and the investment cost. It is shown that the appropriate set point value of one variable for minimizing the operating cost may not be suitable for minimizing the investment cost. Therefore, appropriate tradeoff solutions for the two optimal objectives should be considered.

Thus, the two objectives, minimization of the operating cost and minimization of the investment cost, are formulated as follows

min $C_1$ ($F_{j,k}$, $y_k$, $F_{i,p}$, $F_p^{\text{P}}$, $y_p^{\text{P}}$, $F_p^{\text{R}}$, $y_p^{\text{R}}$)

min $C_2$ ($F_{j,k}$, $F_{i,p}$, $X_{j,k}$, $X_{i,p}$).

It is suitable for traditional multi-objective evolutionary algorithms to solve the models with a few variables. However, in this work, the optimization model involves lots of continuous variables and binary variables, so it is difficult to solve this multi-objective optimization problem using those evolutionary algorithms such as the niched Pareto genetic algorithm (NPGA) [14], the non-dominated sorting genetic algorithm II (NSGA II) [15], and the neighborhood and archived genetic algorithm (NAGA) [16]. In this study, an evaluation function method is employed [17].

To normalize the objective functions [18], the function is transformed to $f_1$,

$$f_1 = \frac{C_1(x) - C_1^{\min}}{C_1^{\max} - C_1^{\min}}. \quad (39)$$

Similarly, another function $f_2$ may be transformed to

$$f_2 = \frac{C_2(x) - C_2^{\min}}{C_2^{\max} - C_2^{\min}} \quad (40)$$

where $C_1^{\max}$ and $C_1^{\min}$ are the maximum and minimum operating cost, $C_2^{\max}$ and $C_2^{\min}$ are the maximum and minimum investment cost, respectively. In this paper, the maximum operating cost is the one before optimization, and the minimum operating cost is the solution of optimization model under the present constraints. The maximum investment cost is the solution of optimization model under the present constraints, and the minimum of the investment cost, which is also the investment cost under the present circumstances, is zero.

The new objective function is

$$\min f = \omega_1 \cdot f_1 + \omega_2 \cdot f_2 \quad (41)$$

where coefficients $\omega_1$ and $\omega_2$ in the objective function are the weight coefficients for the operating cost and investment cost respectively, with $\omega_1 + \omega_2 = 1$.

The new normalized objective function is more sensitive to the weight coefficients $\omega_1$ and $\omega_2$, and the influence from the relative size of two original objective function values becomes smaller. Consequently, the optimization results are more reasonable and reliable. Based on the proposed multi-objective optimization strategy, different values of $\omega_1$ and $\omega_2$ will be selected to compromise the operating and investment costs, and the Pareto curve for the optimization model will be obtained.

## 5 CASE STUDY

The case study is from a refinery in China. The refinery processes both high-sulfur crude and low-sulfur crude and produces a full range of fuel products. Fig. 2 shows the original hydrogen network in the refinery. Hydrogen sources include two continuous catalytic reforming units (CCR1 and CCR2). The recycle hydrogen is all recycled to the reactor inlet. The low pressure hydrogen and dry gas of hydrogen consumers (off-gases) which could also be treated as hydrogen sources is released as fuel gas. In addition, there are four hydrogen utilities: three hydrogen plants and a fertilizer plant (FER). Two PSA plants are used to purify the hydrogen product of CCR1 and CCR2 in the refinery. There are ten hydrogen consumers which

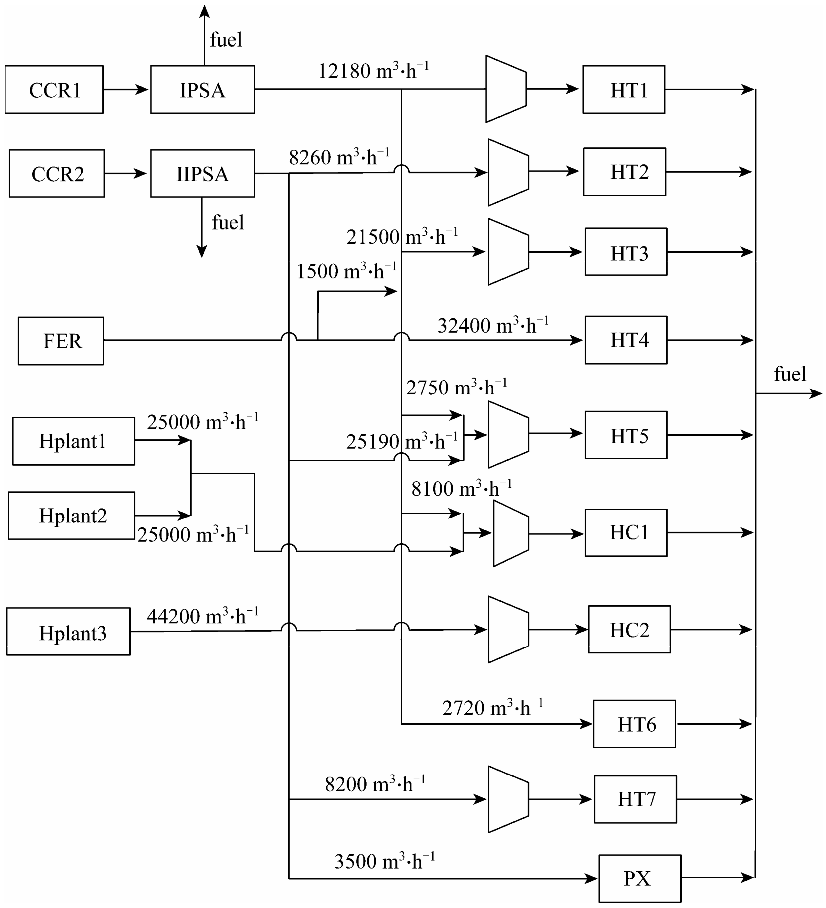


**Figure 2 The original hydrogen network in the case study**

are coking diesel hydrotreater (HT1), straight-run diesel hydrotreater (HT2), straight-run diesel hydrotreater (HT3), diesel hydrotreater (HT4), wax oil hydrotreater (HT5), two other hydrotreating units(HT6 and HT7), two hydrocracking units (HC1 and HC2) and *p*-xylene isomerization (PX). Tables 1−4 give the data of hydrogen sources, sinks, utilities and purifiers. The electricity costs and fuel costs are 0.6 CNY·(kW·h)$^{-1}$ and 0.03 CNY MJ$^{-1}$ respectively. The payback period is two years, with 5% interest rate per year. Considering the low purity of low pressure hydrogen of off-gases and PSA residual, a membrane separation unit is used as the candidate purifier.

The multi-objective problem and corresponding solution strategy is applied in the case study. The LINGO [19] (linear interactive general optimizer) system provides the access to MINLP solvers. The algorithm and features of solvers can be found at http://www.lindo.com. This MINLP model involves 296 constraints, 205 continuous variables and 97 binary variables.

The optimal solutions of the optimization problem yields an efficient frontier denoted as the Pareto curve, as shown in Fig. 3. The conflict between the effects of the decision variables on the two objective functions results in that the optimum is a Pareto set rather than a unique solution. The Pareto set has following property:

**Table 1 Hydrogen sources in the case study**

| Hydrogen sources | Flow rate/m$^3$·h$^{-1}$ | Purity/% | Pressure/MPa |
|---|---|---|---|
| CCR1 | 54060 | 92 | 1.2 |
| CCR2 | 52180 | 92 | 1.2 |
| HT1 off-gas1 | 1125 | 85 | 1.5 |
| HT1 off-gas2 | 983 | 43 | 0.58 |
| HT2 off-gas1 | 1050 | 68 | 1.4 |
| HT2 off-gas2 | 750 | 45 | 0.4 |
| HT3 off-gas1 | 1980 | 77 | 1.5 |
| HT3 off-gas2 | 1536 | 45 | 0.5 |
| HT4 off-gas1 | 3400 | 75 | 1.40 |
| HT4 off-gas2 | 2857 | 47 | 0.55 |
| HT5 off-gas1 | 2325 | 76 | 1.40 |
| HT5 off-gas2 | 1865 | 50 | 0.55 |
| HT6 off-gas1 | 258 | 78 | 1.32 |
| HT6off-gas2 | 180 | 45 | 0.52 |
| HT7 off-gas1 | 1032 | 79 | 1.23 |
| HT7 off-gas2 | 745 | 45 | 0.47 |
| HC1 off-gas | 8300 | 64 | 1.55 |
| HC2 off-gas | 5500 | 66 | 1.77 |
| PX off-gas | 350 | 75 | 1.35 |
| IPSA off-gas | 4000 | 53 | 0.77 |
| IIPSA off-gas | 5500 | 52 | 0.77 |

**Table 2** Hydrogen sinks in the case study

| Hydrogen sinks | Flow rate /$m^3 \cdot h^{-1}$ | Minimum purity/% | Pressure /MPa |
|---|---|---|---|
| HT1 | 12180 | 92 | 7 |
| HT2 | 8260 | 92 | 5 |
| HT3 | 21740 | 92 | 7 |
| HT4 | 32380 | 96 | 7 |
| HT5 | 27940 | 96 | 10 |
| HT6 | 2720 | 96 | 1.2 |
| HT7 | 8200 | 96 | 3 |
| HC1 | 58110 | 97 | 20 |
| HC2 | 44180 | 97 | 20 |
| PX | 3500 | 96 | 2.3 |

**Table 3** Hydrogen utilities in the case study

| Hydrogen utilities | Maximum supply/$m^3 \cdot h^{-1}$ | Purity /% | Pressure /MPa | Price /$CNY \cdot m^{-3}$ |
|---|---|---|---|---|
| Hplant1 | 25000 | 96 | 1.2 | 0.55 |
| Hplant2 | 25000 | 96 | 1.2 | 0.55 |
| Hplant3 | 45000 | 97 | 2.3 | 0.55 |
| FER | 76000 | 96.5 | 7 | 0.45 |

**Table 4** Purifiers in the case study

| Purifiers | Purity/% | Recovery ratio | Maximum throughput /$m^3 \cdot h^{-1}$ |
|---|---|---|---|
| I PSA | 98 | 0.9 | 70000 |
| II PSA | 98 | 0.9 | 70000 |

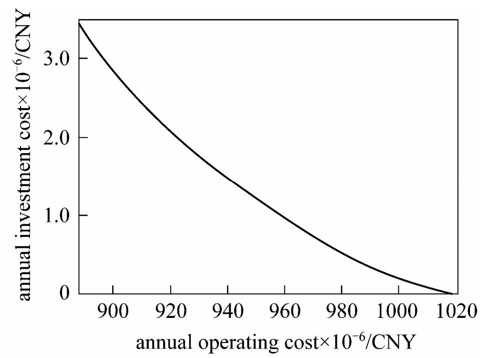


**Figure 3** Pareto curve for the optimization model

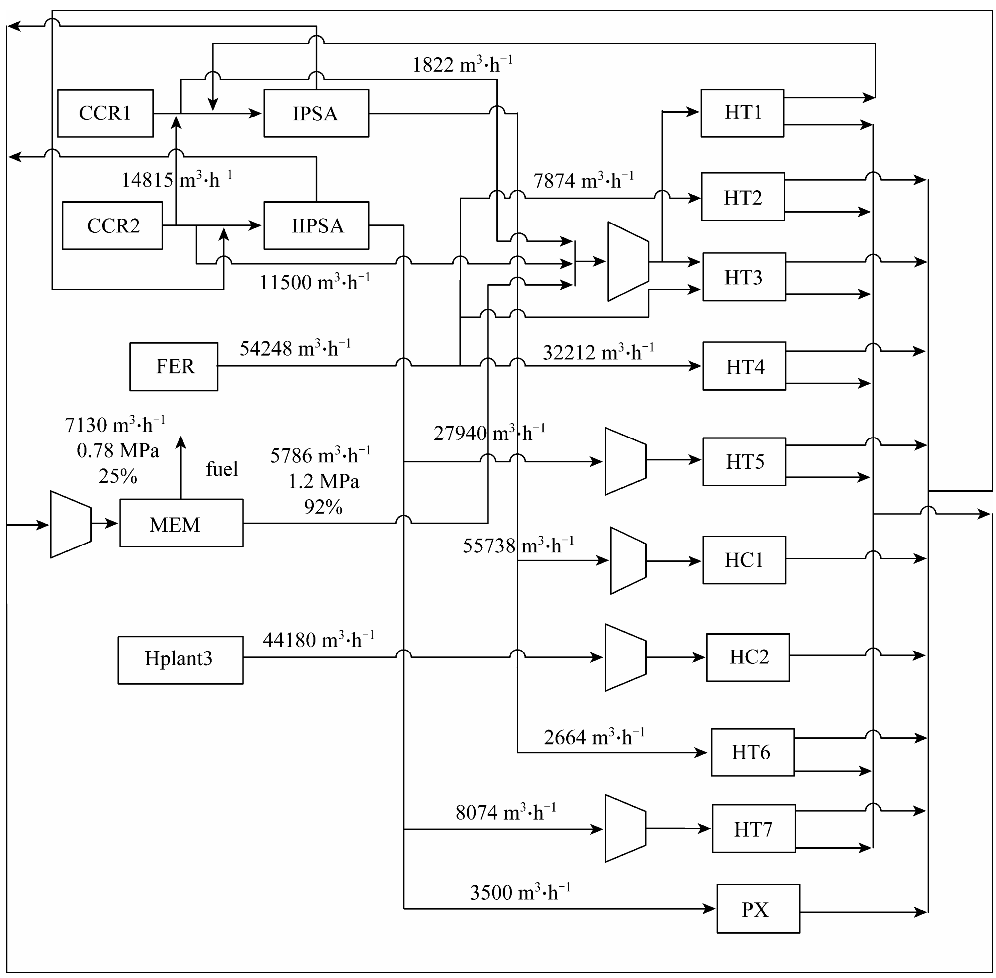


**Figure 4** Optimized hydrogen network

**Table 5 Optimization result** (annual cost in the unit of million CNY)

| | Operating cost | Hydrogen | Electricity | Fuel | Investment cost | PSA | Membrane | Compressor | Piping |
|---|---|---|---|---|---|---|---|---|---|
| new network | 887.75 | 793.2 | 106.6 | −12.05 | 3.44 | — | 1.68 | 1.76 | 0.19 |
| original network | 1019 | 911.3 | 132.8 | −25.1 | — | — | — | — | — |

when one point on the set is moved to another, one objective function is improved, while another function becomes worse. Hence, within the Pareto set, neither solution dominates. Both give the optimal solution for the two objective functions. The decision makers have to use additional information, such as the market quotation, the financial situation, and the corresponding decision variable values, to select an operating point (preferred solution) from the entire Pareto set for operation [20, 21].

With the above multi-objective optimization strategy, one of the optimization results is shown in Fig. 4. Comparing Fig. 4 with Fig. 2, we have following points.

(1) Because of higher pressure and higher purity, the amount of hydrogen imported from the FER plant increases, so two compressors are shut down, greatly reducing the power cost of compressors.

(2) A new membrane separation unit is added. The low pressure hydrogen of off-gases and PSA residual are purified by membrane separation unit. Its product is mixed with those from other hydrogen sources and sent to the hydrogen consumers, while the residue flow is sent to the fuel system.

(3) A part of hydrogen from reforming units is supplied to the hydrogen consumers, which will reduce operating costs of PSA units and make PSA units have ability to purify the high pressure hydrogen of off-gases. Therefore, it is suitable for PSA units to purify the high pressure hydrogen of off-gases and the hydrogen from reforming units. Since the feed purity of PSA decreases, the recovery ratio has to increase so as to maintain the product purity. To make good use of hydrogen from the FER and all of the off-gases, two of the hydrogen plants as well as two compressors are shut down.

Table 5 gives the optimization result. A 14.5% reduction in the total annual cost is achieved, saving 129.43 million yuan per year.

## 6 CONCLUSIONS

The present study addresses the challenge of managing the hydrogen network in refineries. An improved and validated model for hydrogen network is established to solve the multi-objective optimization problem: minimization of the operating cost and minimization of the investment cost. With the optimization based on the evaluation function method, an efficient frontier denoted as the Pareto curve is obtained. The relation between operating cost and investment cost is explored and used for selecting appropriate solution from the Pareto curve. This multi-objective optimization strategy will reduce the plant operation cost, save the investment cost, and thereby increase the profit. Moreover, this multi-objective optimization strategy may be applied to other similar industrial processes.

## NOMENCLATURE

| | |
|---|---|
| $a$, $b$ | capital cost coefficient |
| $C$ | cost, CNY |
| $C_p$ | heat capacity at constant pressure, $J\cdot kg^{-1}\cdot K^{-1}$ |
| $D$ | pipe diameter, m |
| $F$ | stream flow rate under standard condition, $m^3\cdot h^{-1}$ |
| $f_A$ | annualizing factor |
| $\Delta H_c^\Theta$ | heat of combustion under standard condition, $J\cdot m^{-3}$ |
| $J$ | set of hydrogen sources |
| $K$ | set of hydrogen sinks |
| $L$ | pipe length, m |
| $M$ | set of off-gases |
| $N$ | set of purifiers |
| $O$ | set of all possible matches between sources and sinks |
| $P$ | pressure, MPa |
| Power | power consumption, kW |
| $T$ | temperature, K |
| $t$ | annual operating hours, h |
| $U$ | upper bounds of flow rate under standard condition, $m^3\cdot h^{-1}$ |
| $u$ | lower bounds of flow rate under standard condition, $m^3\cdot h^{-1}$ |
| $X$ | binary variable for a flow between sources and sinks |
| $y$ | hydrogen purity, % |
| $z$ | capital cost coefficient |
| $\gamma$ | ratio of heat capacity at constant pressure to that at constant volume |
| $\eta$ | compressor efficiency |
| $\rho$ | density of gas, $kg\cdot m^{-3}$ |
| $\rho_0$ | density of gas under standard conditions, $kg\cdot m^{-3}$ |

### Superscripts

| | |
|---|---|
| max | maximum |
| min | minimum |
| P | product |
| R | residual |

### Subscripts

| | |
|---|---|
| comp | compressor |
| f | feed streams of purifiers |
| fuel | fuel system |
| $i$ | stream of off-gas |
| $j$ | source |
| $k$ | sink |
| mem | membrane |
| $p$ | purifier |
| pipe | pipeline |
| power | compressor power |

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