Simultaneous Designing of a Heat Exchangers Network with least Cost and Emissions

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Energy conservation and clean environment are important topics for search. Heat Exchangers Network (HEN) is an effective way of achieving energy recovery and minimizing operation cost for chemical plants. Reduction of greenhouse gasses (GHG) emission is a direct result of energy integration while gathering it with clean fuel switching minimizes emissions. In this work, we formulated a simultaneous methodology with a multiobjective function of minimizing cost and maximizing emission reduction through designing a [HEN] constrained by fuel type and minimum temperature difference approach (Tmin). Application of this methodology with a mathematical solver (GAMS) on an existing naphtha treating unit resulted excellent results. Energy recovery technique through HENs at several values of (Tmin) reduced energy consumption from 27% to 18% and reduced emissions of gasses from 21% to 12% comparing to actual data of the treating unit. While the application of fuel switching technique; increased emission reduction percentage to 34%. Combination of both techniques improved results; where HEN at optimum (Tmin=18C) with natural gas switching achieved reduction of energy and GHG by 24% and 44% respectively, so it is the candidate design for the unit revamping. Another revamping technique was fuel switching to coke, where adding Post Combustion Carbon Capture (PCC) is an emission reduction solution by 85%.

keywords: *Heat Exchangers Network; Simultaneous designing; Minimum utilities; Gases Emission; Fuel switching.*

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NOMENCLATURE

A. Indices:

i hot stream or hot utility

j cold stream or cold utility

cu cold utility

hu hot utility

in input

out output

s Stage index 1, ..., NOS and temperature location $1, \ldots, NOS + 1$

B. Sets:

HP $\{i|i$ is a hot process stream $\}$

CP $\{j|j$ is a cold process stream $\}$

HU hot utility

CU cold utility

ST $\{s|s$ is a stage in the superstructure, s = 1, . , NOS$\}$

C. Parameters:

$T_{i,in}$, $T_{i,out}$ input and output temperature of hot stream

$T_{j,in}, T_{j,out}$ input and output temperature of cold stream

Fcp heat capacity flow rate

$U_{i,j}, U_{i,cu}, U_{hu,j}$ overall heat transfer coefficients

NOS Stages Number

$\Omega_{i,j}$ The upper bound of heat exchanger load

$\Gamma_{i,j}$ The upper bound of temperature difference; which is estimated according to input and output temperatures of the superstructure

$\Delta T_{\min}$ minimum temperature difference of the exchanger (EMAT).

$unitcost$ heat exchanger fixed cost

$qcost$ Area-dependent cost coefficient for exchangers matching

$qccost$ Area-dependent cost coefficient for cold stream – hot utility matching

$qhcost$ Area-dependent cost coefficient for hot stream-cold utility matching

$hucost$ Hot utility cost

$cucost$ Cold utility cost

$C_{fuel_{switching}}$ Deviation in cost due to fuel switching

QH_{actual} Actual hot utility of the existing unit

$BaseFuel$ Original fuel of the existing unit before switching

$OtherFuel$ New fuel used after switching

D. Variables:

$dt_{i,j,s}$ temperature difference for match (i, j) in stage s

$dtcu_i$ temperature difference between hot stream i and cold utility

$dthu_j$ temperature difference between cold stream j and hot utility

$q_{i,j,s}$ heat exchanged between hot stream i and cold stream j in stage s

qcu_i heat exchanged between hot stream i and cold utility cu

qhu_j heat exchanged between hot utility hu and cold stream j

$t_{i,s}$ temperature of hot stream i at hot end of stage s

$t_{j,s}$ temperature of cold stream j at hot end of stage s

$z_{i,j,s}$ variable to detect the presence of (i,j) matching in stage s

zcu_i variable to detect the presence of matching between cold utility and hot stream i

zhu_j variable to detect the presence of matching between hot utility and cold stream j

E. List of Abbreviation:

HEN Heat Exchanger Network

HENS Heat Exchanger Network Synthesis

MILP Mixed Integer Linear Programming

MINLP Mixed Integer Nonlinear Programming

MO-MINLP Multi-objective Mixed Integer Nonlinear Programming

GAMS General Algebraic Modeling System.

GHG Greenhouse Gas Emissions

PCC Post-combustion carbon capture

EOR Enhanced Oil Recovery

MT Metric Ton

1. INTRODUCTION

Heat Exchangers Network (HEN) is the most effective way to achieve energy recovery and minimizing utilities for chemical plants. Reduction of gas emissions is a direct result of fuel combustion reduction. There are two important schools in this search field; firstly, Pinch Technology Method (PTM) [1–5] And secondly, Mathematical Formulation approaches [6–8].

Where detection of the best solutions after many trials of sequential application with the help of pinch technology principles can be realized. Application of the pinch design method [9], transportation formulation [10], and the transshipment model [11] decomposed HEN designing into two steps; firstly, estimation of minimum hot and cold utilities to minimize operating cost and secondly, minimization of HEN units to minimize capital cost [12].

Simultaneously handling the problem includes an objective function for achieving maximum heat integration. Equality and inequality constraints, which obey thermodynamics principles, represent the required methodology. Where, according to the process streams conditions (flowrates, temperatures specific heat, and heat transfer coefficient) location of pinch points can be represented and there is no need for temperature intervals in using their definition. Simultaneously handling saves time where fewer trials are required for reaching optimum condition [13,14]. Simultaneous optimization approach can achieve considerable economic savings as an objective function, because it allows the economic balance between capital structural cost and external utilities' cost [15]. Dong et al. [16] has modified a simultaneous optimization technique for integration of both water-allocation and HEN synthesis. The simultaneous optimization for distillation systems gathering with heat integration realized a better design than a sequential technique, as modified by Chen et al. and Luo et al. [17,18]

The MILP-MINLP methodology by Yee and Grossmann [6] was the base model for MO-MINLP simultaneous flexibility and operability technique for designing HEN which recovers utility considerably with any deviation of the streams' conditions [19–21].

As technology progress, population, and energy demand increase and so on this phenomenon generates more greenhouse gases emissions (GHG) which leads to environmental pollution and climate disturbance [22]. As energy management causes flue gas emissions decrease. Many techniques have been modified to control and reduce the greenhouse gas emissions, such as carbon capturing, fuel switching, CO2 storage approach, and process integration. Coupling between techniques achieved excellent results for emissions control [23–25].

Petroleum refineries consume a high percentage of fuels compared to the industrial sector. Many processes in any refinery as the reformer depend on the catalytic reaction which are very sensitive for sulfur and metal contaminants of petroleum products. Hydrotreating is the common unit in today's refineries [26]. Hydro-treater unit removes sulfur, nitrogen, and metal contaminants, but it consumed about 19% of refinery energy consumption. More energy management for this unit is an attractive target for reducing both cost and gases emission [27,28].

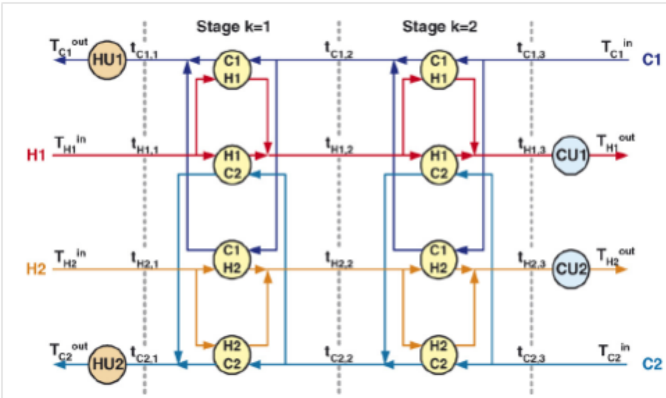

Fig. 1. The illustrative two-stage superstructure with two-hot and two-cold streams for HENS [6]

Post-combustion carbon capturing (PCC) is a mid-term solution for CO2 emission reduction until replacement of the fossil-fuel with renewable energy takes place. PCC is suitable for several sectors, as the steel industry, cement production, petroleum refining, and the biochemical industry [29]. PCC is the separation of CO2 from fuel combustion flue gas and the production of a relatively pure CO2 stream, which is then compressed to a pressure of approximately 110 bars. It can be stored in geological formations or used for other applications, such as Enhanced Oil Recovery (EOR) [30].

In this work, we formulated a multi-objective simultaneous methodology for designing HEN with least cost and minimum gasses emission which was solved by the mathematical solver software (GAMS). Application of the technique on a case study proved its validity, where energy recovery only reduced (GHG), combining it with fuel switching improved the results. Several alternatives for revamping designs are available depending on minimum temperature difference approach and the fuel type.

2. SIMULTANEOUS OPTIMIZATION OF HENS

The first step for designing a HEN is classification the process into a group of hot streams HP (heat source) and a group of cold streams CP (heat sink). Secondly, the definition of streams data (Flowrates, Input and output temperatures, specific heat, and heat transfer coefficient) took place. Also, specification of both hot utilities HU and cold utilities CU and their corresponding temperatures are required.

The model divides the process into stages which allows for different possibilities and sequences of matching streams [6] see Fig. 1.

Simultaneous area and energy targeting at a defined minimum temperature approach determines area and energy consumption to minimize overall cost. Where the used economic evaluation equations are as follows:

$$OverallAnnualCost = AnnualOperatingCost(OC) + AnnualCapitalCost(CC) \quad (1)$$

$$AnnualOperatingCost(OC) = Fuelcost + ColdWaterCost \quad (2)$$

$$AnnualCapitalCost(CC) = CapitalCostofHEN/plantlifetime \quad (3)$$

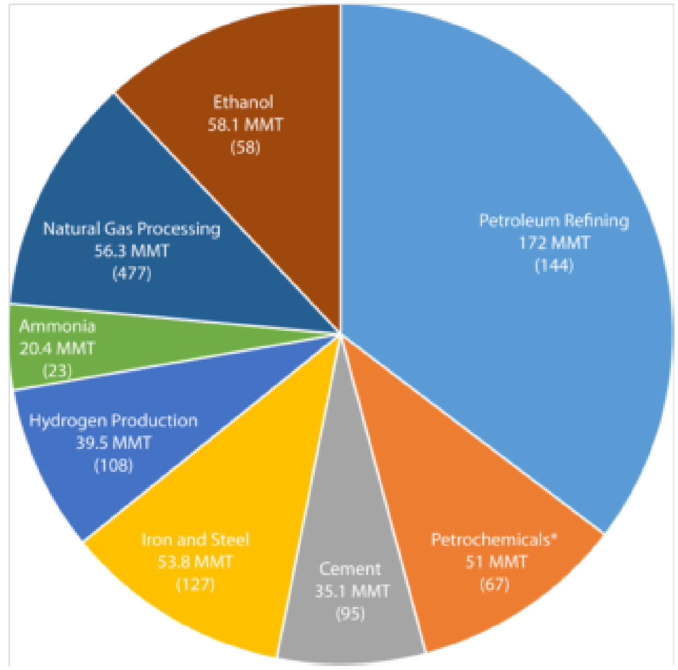

Fig. 2. The international industrial emitter of CO2 [31]

$$UnitCapitalCost(\$) = 8600 + 670(area)^{0.83} \quad (4)$$

$$Area = Q/U \times \Delta T_{lm} \quad (5)$$

$$1/Uij = 1/hi + 1/hj \quad (6)$$

Plant life time = 5 years
No. of working days/y = 330

3. CONTROL OF GREENHOUSE GASES EMISSION

Greenhouse gases are a responsible and effective factor for climate disturbances and environment pollution which cause global warming effect. Carbon dioxide makes up the majority of GHG emissions. There have been many studies that have focused on the top four emitting industries (iron and steel, cement, petroleum refining and petrochemical). Beginning with Kyoto protocol, many conferences supported by the united nation have been held where 190 countries agreed to curb GHG emissions to limit climate changes [32].

A. CO_2 Emission in Refineries

As shown in Fig. 2, petroleum refineries placed in position No.1 in emitting CO2. The four largest sources of CO2 in a refinery are heaters of process, utilities, fluid catalytic cracker (FCC), and hydrogen production. Between 30% up to 60% of total refinery emissions come from process heaters due to combustion of conventional fossil fuel.

The fuel heat duty and the pollutants emission rate for a given fuel can be estimated through the equations: [22–25]

$$\eta_{furnace} = T_{TFT} - T_{STACK}/T_{TFT} - T_o \quad (7)$$

$$Q_{fuel} = Q_{proc.}/\eta_{furnace} \quad (8)$$

$$M_{pol} = \{Q_{fuel}/NHV\} \times \beta \times \Phi \quad (9)$$

$$CER = \beta \times \Phi/NHV \quad (10)$$

where,
$\eta_{furnace}$: the efficiency of furnace (dimensionless)

Table 1. Properties and cost of fuels [25]

	Natural gas	Diesel	Fuel oil	Coke
NHV (MJ/kg)	51.2	42	40	30.0
β	0.76	0.87	0.85	0.74
Φ	3.5	3.7	3.7	5.3
CER	0.052	0.077	0.079	0.131
Cost ($/kg)	0.34	0.33	0.28	0.04

T_{TFT}: the temperature of flame (around 1800 °C)
T_{STACK}: the temperature of stack (around 160 °C)
T_o: the ambient temperature °C
Q_{fuel}: fuel heat duty MJ/h
Q_{proc}: the process heat duty MJ/h
M_{pol}: the pollutant flow rate kg/h
NHV: the net heating value of fuel MJ/kg
β: the percentage of non-oxidized pollutant
Φ: the ratio between oxidized to non-oxidized form of the pollutant.
CER: Carbon to Energy Ratio

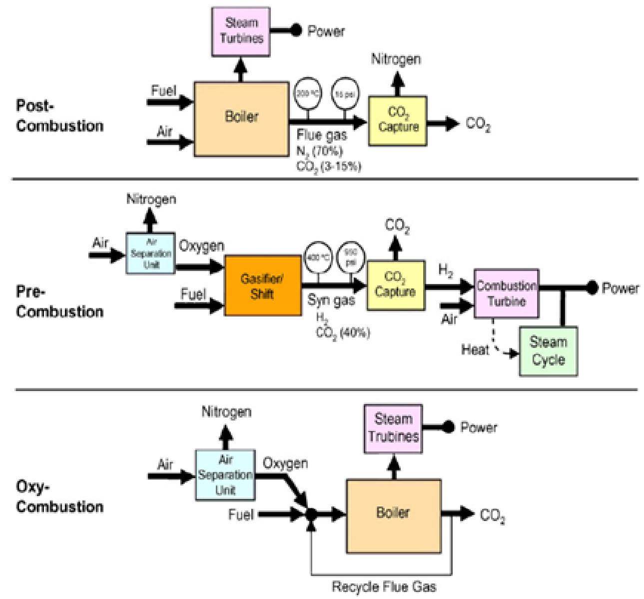

Fig. 3. Different techniques of CO_2 capturing

B. CO_2 Emission Reduction

One of refineries' restrictions is the reduction of emission according to the legal percentage of Kyoto protocol for a clean environment. Three search topics can help with this target:

1 **Energy Conservation** whereas fuel combustion decreases then, the emission would decrease; HENS is the most effective way of minimizing fuel consumption.

2 **Fuel switching** replacement of the used fuel with a less emission one like natural gas is affected directly on emission control. Other factors as cost, availability, and operability of fuel are taken into consideration. As shown in the table 1 according to CER values; the cleanest fuel is natural gas but it is not cheap, while the cheapest one is coke but it is a high emitter.

3 **CO2 Capturing** where the aim of this technology is capturing carbon dioxide from power stations, refineries and other industrial sectors compress and finally transport it for storage locations. Three techniques for CO2 capturing are used: pre-combustion, post-combustion, and oxy-combustion. See Fig. 3.

Post-combustion capture (PCC) mechanism depends on CO2 separation from flue gas and production of the pure CO2 stream, which is then compressed for storage. Many technologies are available for CO2 separation through PCC as adsorption, cryogenics, membranes, and absorption. While chemical absorption technique for CO2 separation is the best compared to other techniques due to its high capturing efficiency, the lowest energy use, and costs [30]. The Sherwood analysis yielded a capturing cost rang from $35 to $100 per MT of CO2 captured [32, 33].

4. METHODOLOGY

The aim of this work is an automatic designing of HEN with optimality condition of least utilities considering least overall cost and combination of HEN designing with fuel switching to achieve least gasses emission.

The heat integration superstructure by Yee et al. [6] is the base for this work. Our model applied thermodynamics' rules for formulation which the mathematical solver (GAMS) total heat balances for each stream; heat balance of each sub-stream for every stage took place. Estimation of hot and cold utilities, detection of stage temperatures, and calculation for defined approach temperatures are solver results. Binary variables are introduced to detect the possibility of streams matching through heat exchanger with its load in the superstructure. Formulation of exchanger fixed cost charges and continuous variables are assigned to temperatures and heat loads to estimate HEN total cost.

A. Multi-Objective Functions for Optimum HEN

This technique has three scenarios; First scenario depends only on heat integration by HEN synthesis for realizing minimum cost and control emission reduction comparing to the exciting unit. The second scenario depends on replacementof the base fuel with another one to reduce emissions. While last scenario adds the fuel switching emission reduction accomplished with heat integration whereas overall cost is minimized, emission reduction is maximized. The flowchart of the methodology is presented in Fig. 4 several alternative designs are available according to fuel types and minimum temperature approach.

Minimizing the overall cost and maximizing emission reduction in a simultaneous technique are considered as conflicting objectives for designing the network structure. The objective functions could be stated as follows:

$$f_1(x) = overall\ total\ \cos t$$

$$f_2(x) = \begin{cases} emission\ \ reduction\ \ by\ \ HEN\ only \\ emission\ \ reduction\ \ by\ \ HEN\ \ with\ fuel\ switching \end{cases} \quad and$$

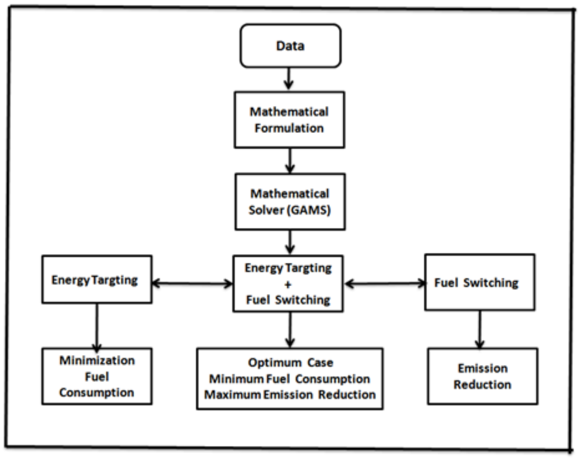

Fig. 4. Flowchart of the methodology

B. Modifying the Multi-objective Mixed Integer Nonlinear Problem

Multi-objective mixed integer nonlinear problems with two conflicting objective functions, may be written as the following [34,35]: (Details are shown in Appendix A)

$$
\begin{aligned}
&F(X) = \sum_{i=1}^{2} w_i * f_i(X), \qquad 0 \le w_i \le 1, \quad \sum_{i=1}^{k} w_i = 1\\
&i.\,e. \quad F(X) = w_1 * f_1(x) + w_2 * f_2(x)
\end{aligned} \tag{11}
$$

The simultaneous technique of the two conflicting objectives for designing the HEN structure is stated as follows: (With equations number (12) (13).

$$
\min w_1 * f_1 = w_1 * \left\{
\begin{aligned}
&\sum_{i\in HP}\sum_{j\in CP}\sum_{s\in ST} q\cos t * \left[q_{i,j,s}/(U_{ij}TMTD_{i,j,s})\right]^{0.83}\\
&+ \sum_{i\in HP} qc\cos t * \left[qcu_i/(U_{i,cu}TMTD_{i,cu})\right]^{0,83}\\
&+ \sum_{j\in CP} qh\cos t * \left[qhu_j/(U_{hu,j}TMTD_{hu,j})\right]^{0.83}\\
&+ \sum_{i\in HP} cu\cos t * qcu_i + \sum_{j\in CP} hu\cos t * qhu_j\\
&+ \sum_{i\in HP}\sum_{j\in CP}\sum_{s\in ST} unit\cos t * z_{i,j,k} +\\
&\sum_{i\in HP} unit\cos t * zcu_i + \sum_{j\in CP} unit\cos t * zhu_j
\end{aligned}
\right\} \tag{12}
$$

$$
\begin{aligned}
&\max w_2 * f_2 = w_2 * \left\{ \frac{QH_{\min}}{\eta}\left(CER_{base_{fuel}} - CER_{other_{fuel}}\right)\right.\\
&\left. + \left(QH_{actual} - \frac{QH_{\min}}{\eta}\right) * CER_{base_{fuel}} \right.
\end{aligned} \tag{13}
$$

where,
Minimum temperature difference of matching formulated as follows [36]:

$$\mathrm{TMTD}_{i,j,s} = \sqrt[3]{dt_{i,j,s} * dt_{i,j,s+1} * (dt_{i,j,s} + dt_{i,j,s+1})/2} \tag{14}$$

$$\mathrm{TMTD_{i,cu}} = \sqrt[3]{dtcu_i * (T_{i,out} - T_{cu,in})\left(dtcu_i + (T_{i,out} - T_{cu,in})\right)/2} \tag{15}$$

$$\mathrm{TMTD_{hu,j}} = \sqrt[3]{dthu_j * (T_{hu,in} - T_{j,out})\left(dthu_j + (T_{hu,in} - T_{j,out})\right)/2} \tag{16}$$

The constraints

- **Total heat balance of each stream**

$$
\begin{aligned}
&(T_{i,in} - T_{i,out})FCp_i = \sum_{s\in ST}\sum_{j\in CP} q_{i,j,s} + qcu_i\,, \quad i \in HP\\
&(T_{j,out} - T_{j,in})FCp_j = \sum_{s\in ST}\sum_{i\in HP} q_{i,j,s} + qhu_j\,, \quad j \in CP
\end{aligned} \tag{17}
$$

- **Heat balance at each stage**

$$
\begin{aligned}
(t_{i,s} - t_{i,s+1})Fcp_i &= \sum_{j\in CP} q_{i,j,s}\,, \quad i \in HP, \; s \in ST\\
(t_{j,s} - t_{j,s+1})Fcp_j &= \sum_{i\in HP} q_{i,j,s}\,, \quad j \in CP, \; s \in ST
\end{aligned} \tag{18}
$$

- **The candidate inlet temperatures of superstructure**

$$t_{i,1} = T_{i,in}\,, \quad i \in HP, \qquad t_{j,NOS+1} = T_{j,in}\,, \quad j \in CP \tag{19}$$

- **The range of temperatures**

$$
\begin{aligned}
&t_{i,s} \ge t_{i,s+1}, \quad i \in HP, \; s \in ST, \qquad t_{j,s} \ge t_{j,s+1}, \quad j \in CP, \; s \in ST\\
&T_{i,out} \le t_{i,NOS+1}, \quad i \in HP, \qquad T_{j,out} \ge t_{j,1}, \quad j \in CP
\end{aligned} \tag{20}
$$

- **The load of both hot and cold utilities**

$$
\begin{aligned}
&(t_{i,NOS+1} - T_{i,out})FCp_i = qcu_i\,, \qquad i \in HP\\
&(T_{j,out} - t_{j,1})FCp_j = qhu_j\,, \qquad j \in CP
\end{aligned} \tag{21}
$$

- **Logical constraints**

$$
\begin{aligned}
&q_{i,j,s} - \Omega_{i,j}\, z_{i,j,s} \le 0\,, \quad i \in HP, \; j \in CP, \quad s \in ST\\
&qcu_i - \Omega_i\, zcu_i \le 0\,, \quad i \in HP\\
&qhu_j - \Omega_j\, zhu_j \le 0\,, \quad j \in CP
\end{aligned} \tag{22}
$$

- **constraint for non-splitting**

$$
\begin{aligned}
&\sum_i z_{i,j,s} \le 1 \quad j \in CP, \; s \in ST\\
&\sum_j z_{i,j,s} \le 1 \quad i \in HP, \; s \in ST
\end{aligned} \tag{23}
$$

- **Deviation in cost due to fuel switching with equation number (17)**

$$
\begin{aligned}
&C_{fuel_{switching}} = \left(Cost_{base_{fuel}} * \frac{QH_{existe}}{NHV_{base\ fuel}} - Cost_{other_{fuel}} * \frac{QH_{\min}}{NHV_{other_{fuel}}}\right) *\\
&24 * 330
\end{aligned} \tag{24}
$$

- **Equations of approach temperatures**

$$
\begin{aligned}
&dt_{i,j,s} \le t_{i,s} - t_{j,s} + \Gamma_{i,j}(1 - z_{i,j,s})\,, \quad i \in HP, \; j \in CP, \quad s \in ST\\
&dt_{i,j,s+1} \le t_{i,s+1} - t_{j,s+1} + \Gamma_{i,j}(1 - z_{i,j,s})\,, i \in HP, \; j \in CP, s \in ST\\
&dtcu_i \le t_{i,NOS+1} - T_{cu,out} + \Gamma(1 - zcu_i)\,, \quad i \in HP\\
&dthu_j \le T_{hu,out} - t_{j,1} + \Gamma(1 - zhuj), \quad j \in CP
\end{aligned} \tag{25}
$$

To solve the problem of infinite areas, we add small positive bounds to the temperature variable of approach that is:

$$
\begin{aligned}
&dt_{i,j,s} \ge \Delta T_{\min}\,, \quad i \in HP, \; j \in CP, \quad s \in ST\\
&dtcu_i \ge \Delta T_{\min}\,, \quad i \in HP, \quad dthu_j \ge \Delta T_{\min}\,, \quad j \in CP
\end{aligned} \tag{26}
$$

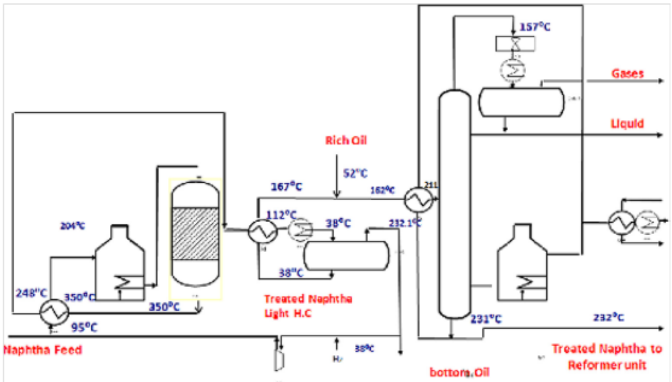

Fig. 5. Flowsheet of the existing hydrotreater unit

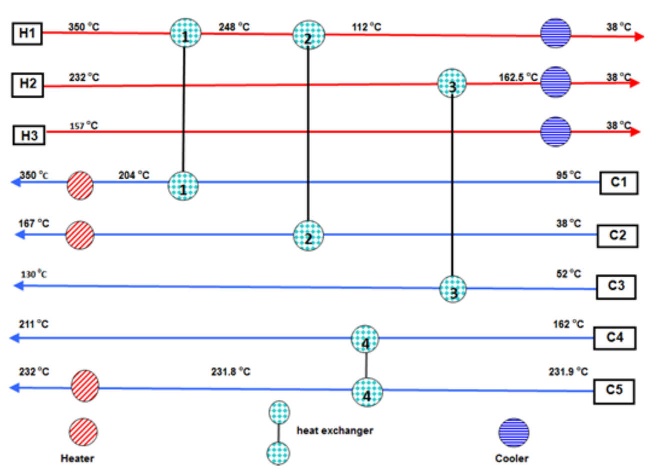

Fig. 6. Grid diagram of the existing hydrotreater unit

where,

$$\frac{1}{U_{i,j}} = \frac{1}{h_i} + \frac{1}{h_j}, \quad \frac{1}{U_{hu,j}} = \frac{1}{h_{hu}} + \frac{1}{h_j} \quad \frac{1}{U_{i,cu}} = \frac{1}{h_i} + \frac{1}{h_{cu}} \tag{27}$$

$$\Gamma_{i,j} = Max \left\{ \begin{array}{c} 0, \left(t_{i,in} - t_{j,in}\right), \left(t_{i,out} - t_{j,in}\right), \\ \left(t_{i,in} - t_{j.out}\right), \left(t_{i,out} - t_{j,out}\right) \end{array} \right\} \quad , i \in HP, j \in CP \tag{28}$$

The corresponding upper bound Ω represents the less load content of the suggested streams for matching

$$\begin{aligned} &\Omega_i = FCp_i(T_{i,in} - T_{i,out}), \quad i \in HP \\ &\Omega_j = FCp_j(T_{j,out} - T_{j,in}), \quad j \in CP \\ &\Omega_{i,j} = \min(\Omega_i, \Omega_j), \quad i \in HP, j \in CP \\ &z_{i,j,s}, zcu_i, chu_j = 0,1, \qquad i \in HP, \ j \in CP, \quad s \in ST \end{aligned} \tag{29}$$

5. APPLICATION OF THE METHODOLOGY ON A CASE STUDY

To examine the validity of our simultaneous model, we applied it on a naphtha treating unit of a refinery, which is common and effective unit in refineries. The function of this unit is removing sulfur compounds from naphtha by catalytic hydrogenation. The naphtha treating is the third unit of any refinery in fuel consumption and it deserved more effort to apply techniques for minimizing both of operating cost and emissions. This unit has been tested before by the sequential technique [23] A comparison between the simultaneous and sequential techniques' results is explained in section (5.2). The flow sheet and grid diagram of the existing unit are shown in Figs. 5, 6. As shown in table 2, the streams' data of the case study are listed. Where the base fuel of this unit is fuel oil and actual consumption of hot and cold utilities was 54803.1 MJ/h and 47266.8 MJ/h respectively.

A. Alternatives for Grass-root HEN Designs of Hydrotreater unit

In designing HEN, minimum temperature approach ($\Delta Tmin$) has direct effect on minimizing hot utility and on GHG emission reduction. The application of the model for case study at ΔT min of 5, 10, 15, 20, 25, and 30°C was performed and the HEN designs are shown in Fig. 7. Comparing results to actual unit's data proved that saving of hot utility rangs between 18% up to 27% is realized. This saving is responsible for the reduction of GHG by percentage between 12% - 21%. As energy targeting reduced emissions, the fuel type has an obvious effect on emissions and cost. See Figs. 8, 9, where coke is the cheapest fuel but it is the highest emitter, while natural gas is the lowest one. Several alternatives designs according to Δt min and fuel type are available. A summary of results is shown in Table 3.

Table 2. The data of streams in case study

Stream NO.	Stream description	Inlet temperature (Tin)°c	Outlet temperature (Tout)°c	FCP MJ/h°C	H MJ/m^2°C
h1	Reactor effluent	350	38	165.6	2.02
h2	Lean oil	232	38	13. 5	1.7
h3	Stripper condenser	157	38	273.9	2.02
C1	Reactor feed	95	350	167.3	2.02
C2	Stripper feed	38	167	117.8	2.02
C3	Stripper feed 2	52	130	12.0	2.02
C4	Mixed stripper feed	162	211	212.6	2.02
C5	Stripper reboiler	231.9	232	249690.0	2.02
Hu	Hot utility	400	400	—	2
Cu	Cold utility	20	40	—	2

B. The Optimum HEN of Hydrotreater Unit

We need to define optimum Tmin, where the base fuel used. See Fig. 10 it shows the intersection between percentage emission reduction and HEN cost curves. Designing HEN for the case study at optimum ΔTmin of 18^{circ}C is the best beginning step for naphtha hydrotreater revamping unit. Comparison between results of applying both sequential and simultaneous models on the HEN design of (ΔTmin = 18°C) is shown in table 4 where the results are approximately similar. The HEN is shown in Fig. 11. According to fuel type specification, revamping technique is differed.

B.1. Revamping according to less emitter fuels

The application of the model by using natural gas and diesel oil as fuel switching alternatives got excellent results compared to actual conditions of the existing unit.

Where three scenarios are available:

Table 3. A summary of results for the model application on the hydrotreater unit

ΔT_{min}	QH_{min} MJ/h	Emission reduction By HEN only kg/h	Overall Cost HEN$/yr	Emission Reduction by HEN Coupled with Fuel Switching kg/h			Profit due of Fuel Switching $/yr			Overall Cost of unit HEN and Fuel switching $/yr		
				Natural Gas	Diesel Oil	Coke	Natural Gas	Diesel Oil	Coke	Natural Gas	Diesel Oil	Coke
5	39896.5	903.5	3367161	2074.4	990.3	-1351.5	757516	339695	2580342	2609645	3027466	786819
10	40485.9	853	3408207	2041.1	941	-1435.4	723822	299827	2573576	2684385	3103830	834631
15	41045.4	804.9	3446112	2009.5	894.1	-1515	691837	261983	2567154	2754275	3184129	878958
20	42190.7	706.5	3531835	1944.7	798.3	-1678.2	626357	184508	2554007	2905478	3347327	977828
25	43070.4	631	3600211	1895	724.6	-1803.4	576073	125013	2543911	3024138	3475198	1054300
30	44616.9	498.2	3716546	1807.6	595.2	-2023.6	487665	20408	2526160	3228881	3696138	1190386

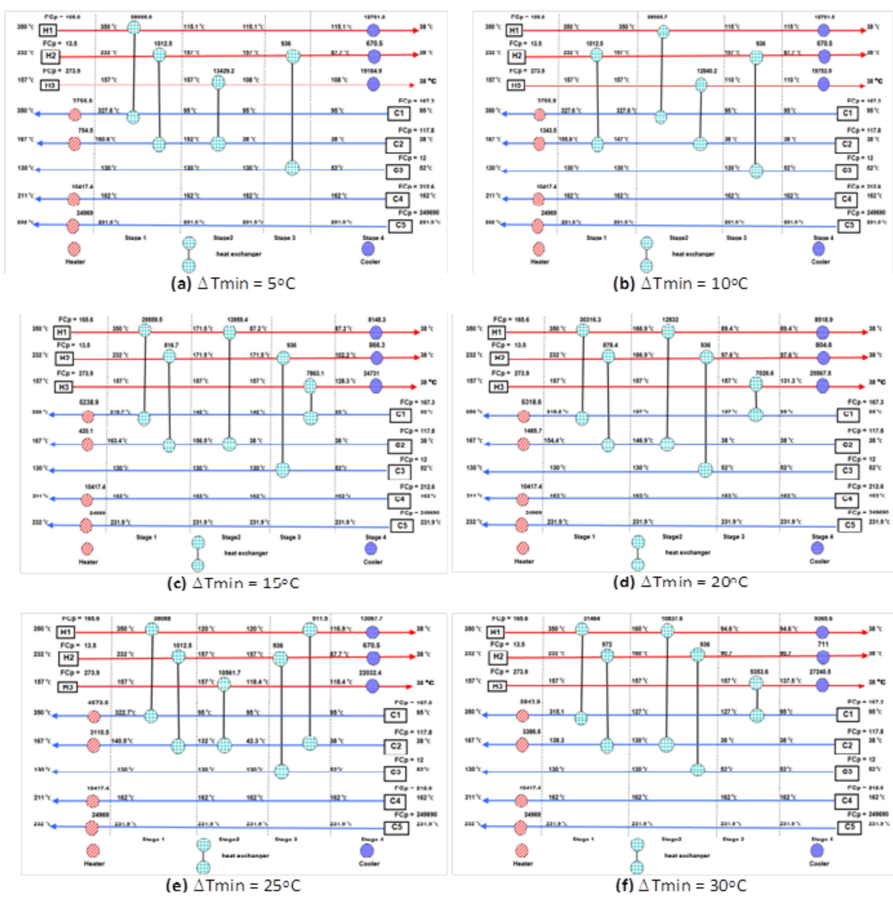

Fig. 7. Alternative Design of Hen for hydrotreater unit at several values of $\Delta Tmin$

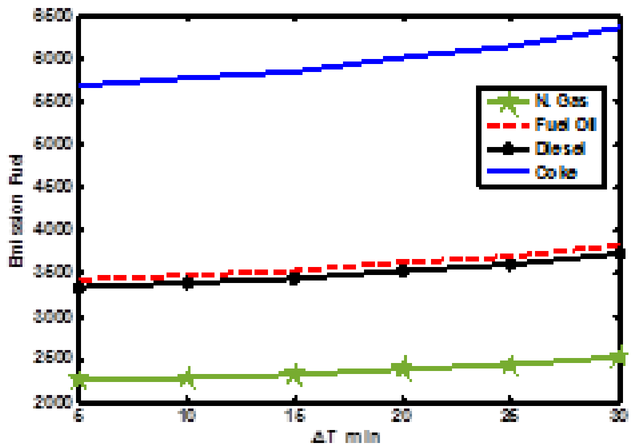

Fig. 8. Fuel emission (Kg/h) of HEN designs at different values of ΔTmin

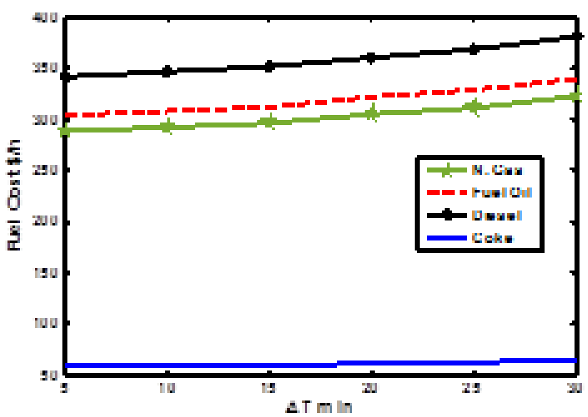

Fig. 9. Fuel cost ($/h) of HEN designs at different values of ΔTmin

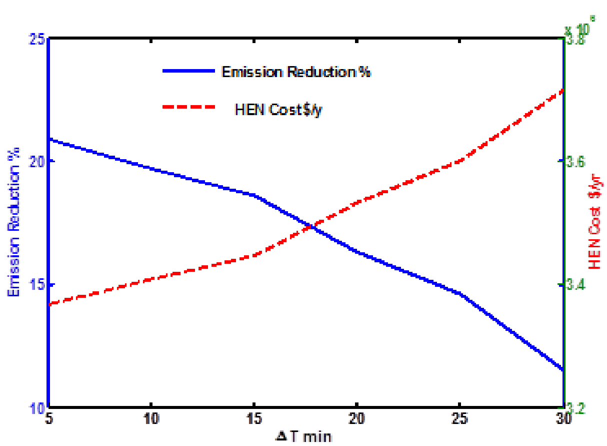

Fig. 10. The relation between the percentage of emission reduction, HEN cost, and different values of ΔTmin

The first scenario:
Energy targeting without fuel switching: through heat exchanger network synthesis (HENS), reduction of GHG emission was 24.4% while saving of fuel cost was 24.5%.

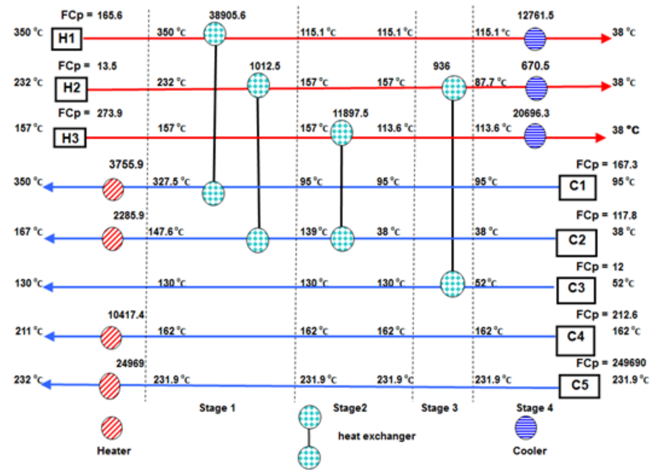

Fig. 11. HEN design of hydrotreater unit at 18°C with QHmin = 41428.2 MJ/h & QCmin=34128.3 MJ/h

Table 4. Comprison between results of sequential and simultaneous applications for designning HEN with ΔTmin=18 °C

	Sequential Model	Simultaneous Model
Minimum hot utility (OHmin) (MJ/h)	41014.8	41428.2
Minimum cold utility (OHmin) (MJ/h)	33712	34128.3
No of units	12	11
Percentage of hot utility saving	25%	24.4%
Percentage of cold utility saving	28.6%	27.8%
Capital cost ($/y)	187643.8	165206.5
Operating cost ($/y)	3548183	3314180
Rate of CO_2 emission (kg/h)	3508.9	3557.4

The second scenario:
Fuel switching: a) Switching from fuel oil to natural gas realized the reduction of GHG emission and fuel cost as 34% and 5.3% respectively.
b) Switching from fuel oil to diesel oil reduced GHG emission

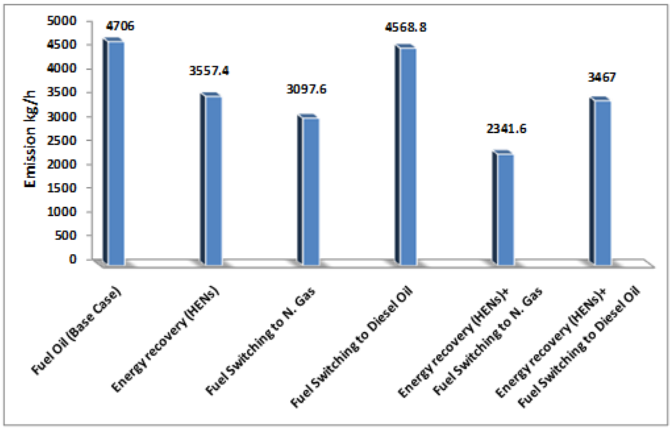

Fig. 12. Comparison between existing unit and revamping scenarios according to emission rate

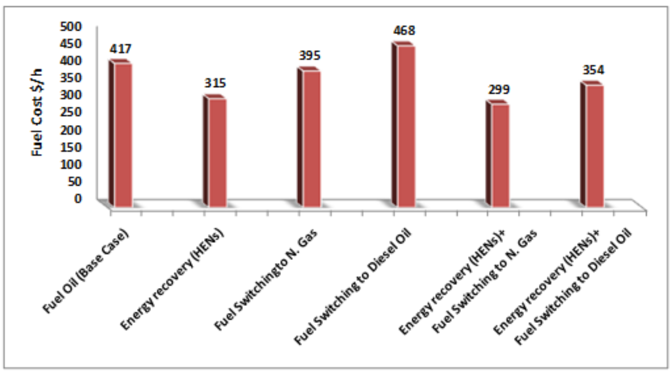

Fig. 13. Comparison between existing unit and revamping scenarios according to fuel cost

by 3% while the fuel cost increased by 12%.

The third scenario:

Energy targeting combined with fuel switching: a) Designing HEN coupled with replacement of fuel oil with natural gas improved results where emission reduction and saving of fuel cost became as 50% and 29% respectively.

b) Another alternative of this scenario is designing HEN which coupled with fuel switching from fuel oil to diesel oil. So, it realized emission reduction and fuel saving as 26% and 15% respectively.

As shown in Figs. 12, 13, many alternatives and choices are available for modification to improve the unit. But the best technique for revamping the treating unit is designing HEN that coupled usage of natural gas instead of fuel oil, where minimum cost and emissions are realized.

B.2. Revamping according to Fuel Price

Due to the shortage of energy resources and features of energy crisis, using coke as fuel switching is a solution sometimes. Coke is the cheapest fuel type but it is the highest emitter. Passing combustion flue gasses through post-combustion carbon capturing (PCC) would overcome the emission problem of coke, where CO2 absorbed through mono-ethanolamine (MEA) the agent of absorption tower. The stripper separated CO2 which can be used commercially in production of dry ice, urea, beverages, and absorbing agent recycled after regenerated. So in case of using coke which replaced with fuel oil, we have two techniques:

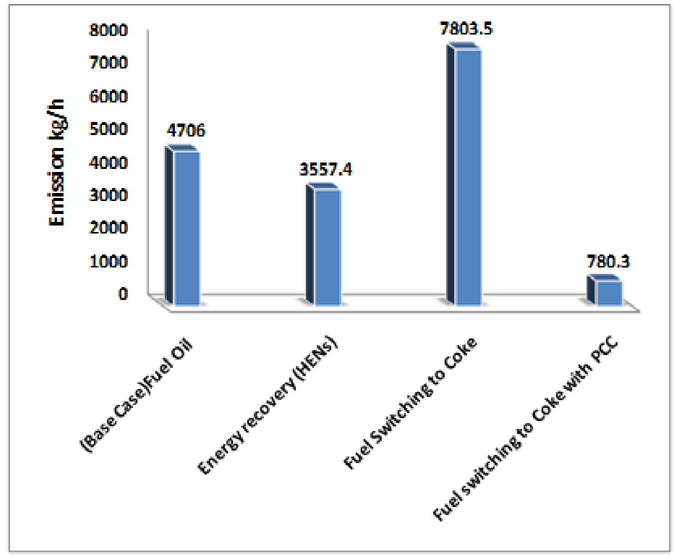

Fig. 14. Comparison between existing unite and revamping scenarios according to emission rate

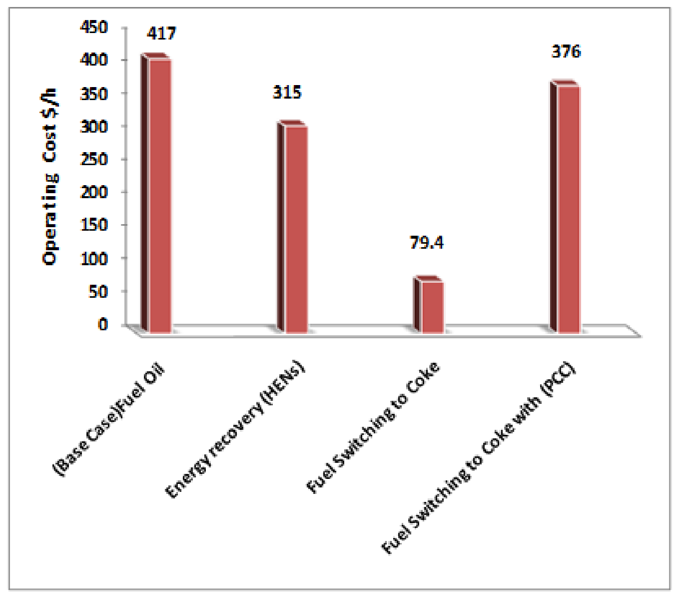

Fig. 15. Comparison between existing unite and revamping scenarios according to operating cost

- Switching with coke without PCC, where the cost saving reached 81% while the harmful GHG emission increased sharply by 66%
- Switching coke in the presence of PCC, solved the last emission problem where GHG emission reduction became 83.4% and saving of operating cost by 10% is also realized. See Figs. 14, 15.

The modified hydrotreater Flowsheet is shown in Fig. 16.

Comparison between base case of the existing unit and alternative revamping techniques' results are shown in table 5.

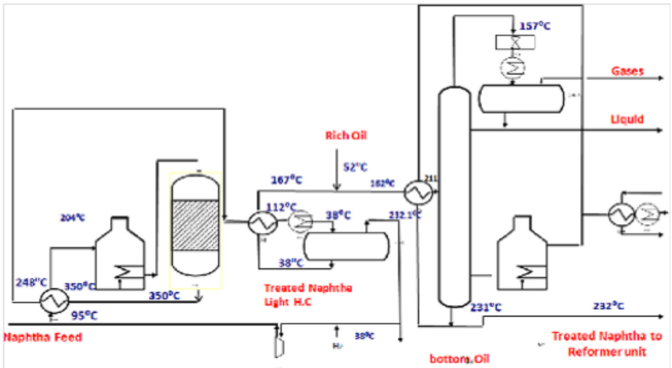

Fig. 16. The flowsheet of the revamped hydrotreater unit through fuel switching to coke (combustion flue gases collected and is passed to PCC unit)

Table 5. Comparison between base case and alternatives revamping techniques of hydrotrater unit

	Base case fuel oil	Energy recovery HEN	Fuel switching to natural gas	Fuel switching to diesel oil	HEN+ fuel switching to natural gas	HEN+ fuel switching to diesel oil	Fuel switching to coke	Fuel switching to coke + PCC
Gases emissions (kg/h)	4706	3557.4	3097.6	4568.8	2341.6	3467	7803	780
%of emission reduction	—	24.4%	34.1%	3%	50%	26%	-66%	83%
Operating cost ($/h)	417	315	395	468	299	354	79.4	376
%of operating cost saving	—	24%	5.3%	-12%	28.3%	15%	81%	10%

6. CONCLUSION

Optimization with simultaneous technique, saves time and guarantees accurate results. Application of our model for HEN designing with least cost and emissions realized excellent results. The hydrotreater process is a common unit in refineries which consumes a large quantity of fuel and so on causes high emission. By applying the model on the hydrotreater unit we got several alternative designs of HENs which achieve saving of fuel consumption ranges between 18%-27% and reduction of GHG emission ranged between 12% - 21%. While fuel switching technique (natural gas replaced fuel oil) can raise the emission reduction to 34% and the best reduction percentage (50%) achieved through energy targeting which combined with natural gas switching.

According to fuel type, we suggest two scenarios for revamping the existing hydrotreater unit. The first one depends on energy target added to natural gas fuel switching which achieved reduction in cost and GHG emissions by 29% and 50%. The second scenario for revamping used coke with the advantage of its least price and passing combustion flue gases through post-combustion carbon capturing (PCC) to solve the coke emission problem where reduction of cost and emissions reached to 10% and 83% respectively.

RECOMMENDATION

- The analysis shows that the consumption of fossil fuels still is in the same high rate for the next fifteen years; so more researches and applications required for energy conservation and reduction of greenhouse gases emissions.
- Energy conservation through HEN design gathering of fuel switching is recommended to apply in refineries and petrochemical industries.
- Adding a carbon capturing unit to a refinery or chemical industry solves emission problem.
- More researches and applications in the renewable energy sources and nuclear power generations are required to face energy crisis and emission problem.
- Bio-fuel is an energy solution but needs more researches and application to be economically commercial.

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APPENDIX (A)

Weighted sum approach

In the weighing method, the multiple objectives functions are transformed into a single objective function.

$$Min \sum_{j=1}^{k} w_j f_j(x)$$

$$\text{Subject to } x \in S$$

where, $wi \geq 0$ for all $i = 1, \ldots, k$ and $\sum_{i=1}^{k} w_i = 1$.

Multiple optimization runs are conducted with different weighting vector (W) in order to locate multiple points on the Pareto front. This method is the simplest and the most straight forward way of obtaining multiple points on the Pareto-optimal front [33, 34].

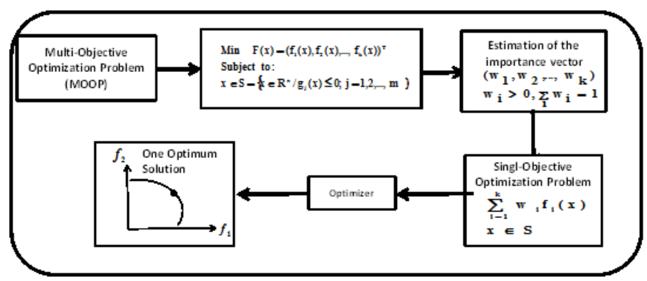

Fig. 17. Schematic of a preference-based multi-objective optimization procedure