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Optimization of Hydrogen Distribution Network by Imperialist Competitive Algorithm

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ABSTRACT

In modern refineries, hydrogen is widely used for the production of clean fuels. In this paper, a new method is presented in order to use hydrogen more effectively in refineries. This new method is based on combination of linear programming with imperialist competitive algorithm (ICA) in order to optimize the hydrogen distribution network. In this new approach, optimization is performed in two levels. In one level the hydrogen network layout is proposed by ICA and in the other level the total annual cost and utility are optimized by the linear programming. Thus, the minimum cost and the optimal configuration of the hydrogen distribution network are obtained. Finally, to illustrate the application of this method two cases are studied.

1. Introduction

As crude oil becomes heavier, impurities (such as sulfur, nitrogen and aromatics) increase, the environmental regulations are intensified and the demand to produce clean fuels increases, and the consumption of hydrogen in refineries is increased [1]. There are two ways to reduce the hydrogen consumption: (1) to improve the design of every hydrogen consuming unit (2) to improve distribution network. The second is economically and environmentally effective [2].

The number of published papers on the design and optimization of hydrogen distribution network is limited [2]. Alves in 1999 proposed a variation of the pinch method to minimize the consumption of hydrogen. This method is based on the pinch technology and heat exchanger analysis and was useful for the industry. In its method, the sources (units that produce hydrogen such as catalytic reforming units and hydrogen plant) and the sinks (units that use hydrogen such as hydrocracker and hydro-treater) were defined. Alves proposed a linear programming (LP) model to optimize the hydrogen network. The main limitation of this approach is that it considers only the current flow rate and

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purity. In this method it is assumed that each stream containing hydrogen regardless of pressure can be sent to all consumers. In practice, this assumption is true only when the pressure is high enough [3,4]. Then, Liu and Hallale in 2001 offered a new mathematical approach to more effective use of hydrogen in refinery. This method is based on a superstructure that contains all possible connections, and the maximum hydrogen content of the plant is considered. It leads to a nonlinear programming (NLP) and mixed-integer linear programming (MINLP) problem. The main feature of this method is the use of pressure constraints and its calculation for existing equipment, which makes this method more efficient. Another advantage of this method is that the economic aspects such as payback time, the maximum total investment and total annual costs are calculated, as well as the correct way to consider a new compressor in order to avoid unnecessary consumption of power compression [5]. Zhang and Liu in 2004 proposed a systematic methodology to select appropriate purifiers from pressure swing adsorption processes, membranes or hybrid systems for recovering hydrogen from refinery off-gases. Through the understanding of the trade-offs between hydrogen saving, compression costs and capital investment, a superstructure is built to include possible purification scenarios [6]. Kumar in 2010 proposed a mathematical model for optimal hydrogen distribution based on pressure constraints, sources and sinks constraints, compressor flow rate recycle and purity constraints, flow combinations, hydrogen consumption, operating cost, capital cost, payback period, etc. [2]. Sarabia in 2012 suggested an NLP technique to optimize the management of a complex network of hydrogen in refinery operations. The model can systematically reduce utility costs by increasing hydrogen recovery in consumer units and reduce production costs [7].

In the present work, by using a combination of ICA and linear programming (LP), refinery hydrogen management is investigated. In general, the sources and the sinks are identified and then superstructure is proposed by ICA. With known structure mass balance equations can be written and an LP model can be developed and solved. Finally, the least amount of total annual cost and the optimal structure is obtained.

2. Imperialist competitive algorithm

In this paper, imperialist competition algorithm is used for the production and optimization of the hydrogen network structure. The goal of the optimization is to find the optimal values of the variables of the objective function. These variables can be arranged as a vector of *1*N*, where *N* is the number of variables. In the genetic algorithm, this vector of variables is called the chromosome and in the ICA each vector represents a country. From a historical-cultural perspective, social and political characteristics of a country can be inspired from components of culture, language, economic structure and other characteristics. Therefore a country consists of various properties such as:

$$\mathrm{country} = [\mathrm{p}_1, \mathrm{p}_2, \mathrm{p}_3, \ldots, \mathrm{p}_{\mathrm{N_{var}}}] \qquad (1)$$

Where each P_i represents one of the characteristics or variables of a country [8,9].

In this work each country represents a potential solution to the problem. Therefore properties of the country are mapped to the various variables of the network configuration.

Fig. 1 shows the flowchart of the algorithm in this paper. The steps are as follows:

1. To start the algorithm, the number $N_{country}$ of initial countries (i.e., a hydrogen network) is created. The variables are produced randomly [8,9].
2. In the next step, the cost of each of these countries, to be described in section 3 of this paper, is calculated using the linear programming. Based on estimated costs, countries are sorted from the best to the worst. The best countries are to be assigned as imperialist [8,9].
3. N_{imp} members of the initial population are selected as imperialists, N_{col} of the remaining countries are assigned as colonies and are possessed by an empire. Initially, a normalized cost is calculated for each empire [8,9]:

$$C_n = \max_i\{c_i\} - c_n \tag{2}$$

Where c_n is nth imperialist cost, $max_i\{c_i\}$ is the highest cost between imperialists and C_n is normalized cost of the imperialist. An imperialist that has higher cost (weaker imperialist) will have a lower normalized cost. With normalized costs, normalized relative power of each imperialist as equation (3) is calculated, and based on this, the colonies are distributed between imperialists [8,9].

$$P_n = \left|\frac{C_n}{\sum_{i=1}^{N_{imp}} C_i}\right| \tag{3}$$

Therefore, the initial number of colonies of the imperialists will be equal to the equation (4):

$$N.C._n = \text{round}\{P_n.(N_{col})\} \tag{4}$$

Where $N.C._n$ is the number of colonies of an empire, N_{col} is the number of colonized countries in the initial population of countries. *Round* is a function which returns the nearest integer number [8,9].

4. After assigning colonies to the imperialists, the total cost of each empire is calculated as follows:

$$T.C._n = \text{Cost}(\text{imperialist}_n) + \xi\,\text{mean}\{\text{Cost}(\text{colonies of empire}_n)\} \tag{5}$$

Where $T.C._n$ is the total cost of nth empire and ξ is a positive number between zero and one, usually close to zero is chosen. It is a parameter to consider a part of the cost of a colony in the overall cost of the empire [8,9]. In this paper, the value of 0.05 is considered. From this point decades begin.

5. At this point, the policy of assimilation applies. In this policy, the colonies of the empire move to a new location relative to the location of the imperialist. The purpose of moving the colonies is to change the variables characteristics of each colony [8,9]. This change is made by defining a distance vector for each colony of the imperialist.

$$V_i = Icountry_n - Ccountry_i \tag{6}$$

In this equation V_i is distance vector of ith colony, *Icountary*$_n$, from nth imperialist, *Icountary*$_n$.

Ccountry$_i$ and *Icountry*$_n$ are the positions of each country (the colony and the imperialist) respectively. Then the new location of each colony based on the vector defined in equation (6) and the absorption coefficient is defined as:

$$NCcountry_i = Ccountry_i + \beta \times R_i \times V_i \quad (7)$$

In this equation, $NC_{country_i}$ is the new position of the ith Colony and R_i is a random vector whose length is equal to the length of V_i, and its elements are between zero and one. Also, β is the absorption coefficient and is usually greater than 1 and close to 2 [8]. In this paper, its value is considered 2.

6. After producing the new position of each colony, a revolution may occur in some colonies of an empire [8,9]. The number of countries where the possibility of revolution exists can be calculated by the following equation:

$$NCR = round\left(\omega_i \times N.C._n\right) \quad (8)$$

Where ω_i is the revolution rate in ith decade and NCR is the number of colonies in an empire in which the revolution will occur. The number of colonies in which revolution occurs, decreases over decades. To do this, the revolution rate correction is performed at the beginning of each decade:

$$\omega_{i+1} = \lambda \times \omega_i \quad (9)$$

Where ω_{i+1} is the revolution rate in the (i+1)th decade and λ is the damping ratio which is less than or close to one. In this paper, the value of 0.99 is chosen.

7. The next step is to calculate the cost of these revolutionary states or countries. If the cost of one colony is better than the cost of the imperialist, the imperialist and the colony are inter changed [8,9]. Because of changes in the empires, overall cost of the empire is re-calculated by the equation (5) after revolution. Steps 5 to7 for all empires are repeated in each decade.
8. Assimilation: if the position of an imperialist becomes weaker than others, the empire with all of its colonies is absorbed to other empires. This is done as follows:

$$V_{ij} = norm\left(Icountry_i - Icountry_j\right) \quad (10)$$

Where V_{ij} is the norm of distance between ith imperialist and jth imperialist. If its value is less than some specified value which is a percentage of search space, the weaker empire is absorbed to the stronger one. The percentage of the search space is defined by VT as in equation (11):

$$VT = \tau \times norm\left(ss\right)$$
$$ss = \left|ub - lb\right| \quad (11)$$

Where τ is the uniting threshold that is the percentage of search space size, which enables the uniting process of two empires i, j. The ss is the algorithm search space of the problem variables which is obtained by the difference between the upper and lower boundaries of the problem variables.

9. Competition of empires to possess weakest colony of the weaker empire. This is done by calculating the strength of other empires to possess the weakest colony of the weaker empire [8,9].

$$N.T.C._n = max_i\{T.C._i\} - T.C._n \quad (12)$$

Where $T.C._n$ is the total cost of nth empire and $N.T.C._n$ is the normalized total cost of the empire. Each empire which has the lowest $T.C._n$ has the highest $N.T.C._n$. In fact, $T.C._n$ and $N.T.C._n$ are equivalent to the total cost and overall strength of an empire respectively. An empire with the lowest cost has the greatest power. Having normalized total cost, probability of each empire to possess the colony is calculated as [8].

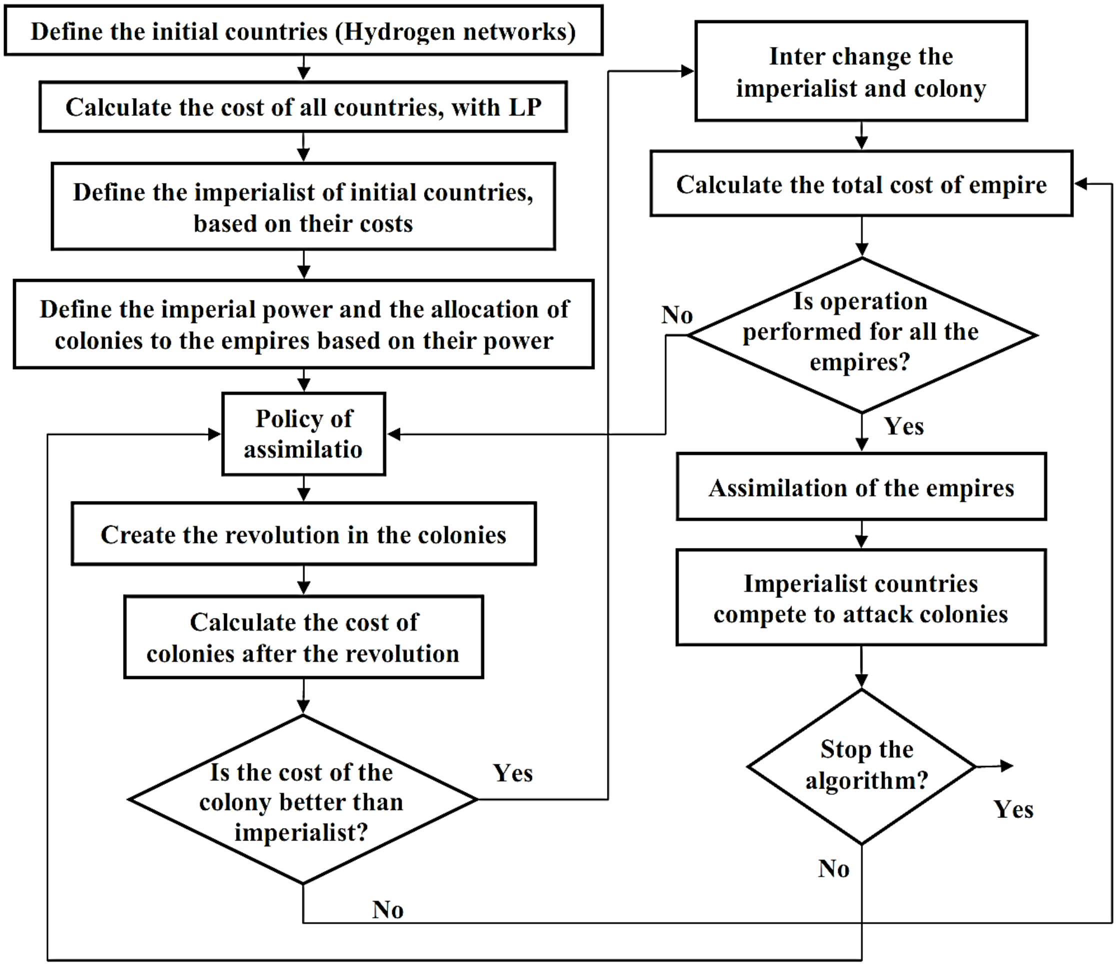

Figure 1. Flow diagram of the imperialist competitive algorithm.

$$P_{P_n} = \left| \frac{N.T.C._n}{\sum_{i=1}^{N_{imp}} N.T.C._i} \right| \tag{13}$$

After determining the empire, the colony is detached from the weakest empire and is joined to the empire. If after detaching the colony no colony is left to the imperialist, the imperialist itself is joined to the empire [7].

Steps 5 to 9 are repeated till the end of selected number of decades. If in the course of decades only one empire remains or the cost of the empire does not change after some decades the algorithm ends [8].

3. The structure of the hydrogen distribution network

Hydrogen distribution network has two types of variables, continuous variables such as flow rate, pressure and concentration and binary variables which determine configuration of the network. In this work linear programming (LP) is used to optimize continuous variables, while configuration variables are treated with Imperialist Competitive algorithm (ICA). ICA initially produces feasible networks considering pressure constraints in the network. Fig. 4 of reference [5] shows a feasible network, Fig. 2 shows a superstructure and Fig. 3 shows the equivalent matrix representation produced by ICA.

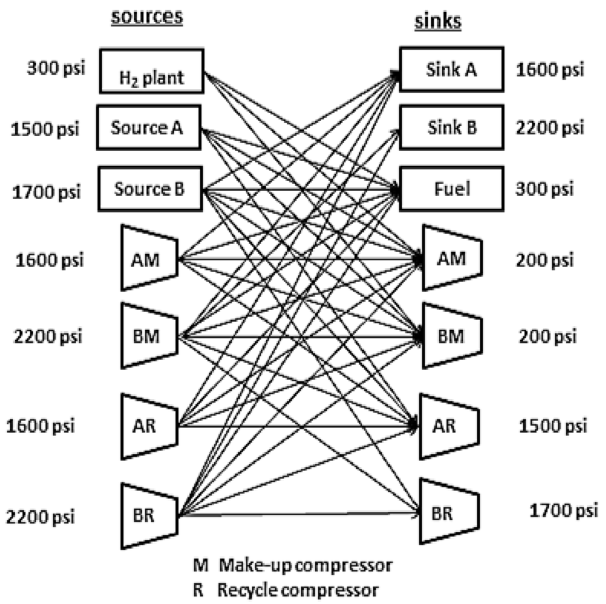

Figure 2. Sample superstructure hydrogen distribution network**.**

$$
\begin{bmatrix}
0 & 0 & 1 & 1 & 1 & 0 & 0\\
0 & 0 & 1 & 1 & 1 & 1 & 0\\
1 & 0 & 1 & 1 & 1 & 1 & 1\\
1 & 0 & 1 & 1 & 1 & 1 & 0\\
1 & 1 & 1 & 1 & 1 & 1 & 1\\
1 & 0 & 1 & 1 & 1 & 1 & 0\\
1 & 1 & 1 & 1 & 1 & 1 & 1
\end{bmatrix}
$$

Figure 3: Matrix equivalent produced by ICA.

4. Problem constraints

Constraints of the problem are expressed as mass balances around sinks and sources of hydrogen as follows:

a) Mass balance in sinks: Feed entering each sink has a specified flow rate and concentration, therefore sum of feed entering and also sum of concentrations of feed entering each sink is expressed as follows [2,5]:

$$\sum_i F_{i,j} = F_{sink,j} \tag{14}$$

$$\sum_i F_{i,j} y_i = F_{sink,j} y_{sink,j} \tag{15}$$

b) Mass balance in the sources output: Hydrogen can be sent to the to the sinks or fuel system; this means that the total flow rate out of each source is constant and can be expressed by [2,5]:

$$\sum_j F_{i,j} = F_{source,i} \tag{16}$$

c) Mass balance over the compressor: compressors are considered as sinks or sources, but they differ in that the flow rate and purity of hydrogen is variable. Restrictions on the compressors are expressed as follows [2,5]:

c-1) Mass balance over compressor means that the gas flow rate entering the compressor must be equal to the flow rate exiting the compressor [2,5]:

$$\sum_i F_{comp,j} = \sum_i F_{i,comp} \tag{17}$$

c-2) The amount of hydrogen entering the compressor equals hydrogen exiting the compressor [2,5]:

$$\sum_i F_{comp,j} y_{comp} = \sum_i F_{i,comp} y_i \tag{18}$$

c-3) There is a maximum allowable flow rate for compressors due to design limitation [2,5]:

$$\sum_i F_{i,comp} \le F_{max,comp} \tag{19}$$

It should be noted that equations (15) till (18) are nonlinear, therefore the system is nonlinear. To reduce the complexity of system these equations are expressed as linear equations by conveying multiplication of concentrations and flow rates as hydrogen flow rates.

5. Objective function

In this work, the total annual cost (TAC) (sum of annualized investment cost and operating cost) is considered as the objective function and is expressed as [10,11]:

$$\min TAC = C_{H_2} + C_{power} - C_{Fuel} + Af \times \left(\sum_{n \in NC} C_{NC} + \sum_{p_{new}} C_p + \sum_{pipe_{new}} C_{pipe} \right) \tag{20}$$

$$\mathrm{Af} = \frac{\mathrm{fi}.(1+\mathrm{fi})^{\mathrm{ny}}}{(1+\mathrm{fi})^{\mathrm{ny}} - 1} \tag{21}$$

5.1. Operating cost

The operating cost includes the sum of the utility cost and the power consumption cost of compressors in the network minus the fuel cost [5,10]. It is expressed as follows:

5.1.1. Utility cost

This cost includes the cost of hydrogen produced by the hydrogen plant or the cost of hydrogen imported from other plants, which is directly proportional to the flow rate [5,6,10]:

$$\mathrm{C_{H_2}} = \sum_{\mathrm{u \in NHU}} \mathrm{e_u \times FHU_u \times t_u} \tag{22}$$

5.1.2. Compressor power cost

This is calculated by using the following relation in which a_{power} and b_{power} are known power coefficients [5,6,10]:

$$\mathrm{C_{power}} = \sum_{\mathrm{k}} \mathrm{e_k \times power_{comp_k} \times t_k} \tag{23}$$

$$\mathrm{power_{comp_k}} = \mathrm{a_{power}} \left(\left(\frac{\mathrm{p^{out}_{comp_k}}}{\mathrm{p^{in}_{comp_k}}} \right)^{\mathrm{b_{power}}} - 1 \right) \times \mathrm{F^{in}_{comp_k}} \tag{24}$$

5.1.3. Fuel calorific value

The cost of the gas sent to the fuel system is calculated by heating value of gas. In this work, the gas is considered as a mixture of methane and hydrogen. The following equation is used to calculate the fuel value per unit flow rate of gas [5,10]:

$$\mathrm{C_{Fuel}} = \mathrm{e_{Heat}} \times \left(\mathrm{y_{H_2}} \times \Delta \mathrm{H^{\circ}_{c,H_2}} + \left(1 - \mathrm{y_{H_2}}\right) \times \Delta \mathrm{H^{\circ}_{c,CH_4}} \right) \tag{25}$$

5.2. Capital cost

Capital cost includes the cost of new compressors, new purifiers and piping. The relations of each are as follows [5,10]:

5.2.1. The new compressor cost

The investment cost of a new compressor added to the network is related to its power consumption and can be calculated from the following equation [5,10,12]:

$$C_{\mathrm{NC}} = \mathrm{a_{cap} + b_{cap} \times power_{NC}} \tag{26}$$

5.2.2. The new purifier cost

The cost of a new purifier is calculated from the following equation [5,10,13]:

$$C_{\mathrm{p}} = \mathrm{a_p + b_p \times F^{in}_p} \tag{27}$$

5.2.3. Piping costs

The cost of installation of a new pipeline is a function of length and square of its diameter:

$$C_{pipe} = \left(a_{pipe} + b_{pipe} \times D^2\right) \times l \tag{28}$$

The diameter squared, D^2, of a pipe is determined from the flow rate through it:

$$D^2 = \frac{4 \times \mathrm{F} \times \rho_{\circ}}{\pi \times \mathrm{u} \times \rho} \tag{29}$$

Where u is the gas velocity in the pipe (usually 15-30 m/s), ρ is the density of the gas at the design conditions and $\rho_{\circ}$ is the density at standard conditions [5,10].

6. The first case study

The first case study was optimized for the first time with mathematical methods in 2001 by Hallale and Liu [5], then in 2010 by Kumar *et al*. [2]. As shown in figure twelve of reference [5], the system consists of six hydrogen consumers and two make-up compressors. All hydrogen consumers except isomerization plant have internal recycle compressors. In this system hydrogen is supplied by hydrogen plant and catalytic reforming unit. Economic data and data of the sinks and the sources are given in Table 1 and Table 2 respectively.

For this system, several restrictions are imposed by the refinery, including:

a) The maximum payback period is two years for this network.
b) Only a new compressor and a new purification unit can be added to the network.
c) In the case of using purification unit, its waste must be sent to the fuel system.

The system was optimized in two versions; in the first version, optimization was performed without adding any new device in the network and in the second version, a new compressor was added to the system. Fig. (4) and (5) show the final network for the first and the second version respectively. The colored lines represent the new connections. In Table 3 the results obtained by this method were compared with results obtained by others. All costs are in (million dollars/year) and hydrogen consumed is in million standard cubic feet per day (MMscfd).

Table 1.
Economic data for the first case [2,5].

Operating cost	Cost	Capital cost	Cost
Hydrogen cost	2000 (\$/MMscfd)	Compressor(k\$)	115 + 1.91power(kw)
Electricity cost	0.03 (\$/kwh)	PSA(k\$)	503.8 + 347.4 feed flow(MMscfd)
Fuel cost	2.5 (\$/MMBtu)	Piping(\$/m)	3.2 + 11.42 $D^2(in^2)$

Table 2.
The data of the sources and the sinks for the first case [2,5].

Process	Make-up			Purge			Recycle
	Flow rate (MMscfd)	Purity	Pressure (Psia)	Flow rate (MMscfd)	Purity	Pressure (Psia)	Flow rate (MMscfd)
DHT	11.31	0.7597	600	8.61	0.7	400	1.56
CNHT	8.21	0.8653	500	3.47	0.75	350	36.75
JHT	8.65	0.75	500	4.32	0.65	350	3.6
NHT	12.08	0.7144	300	6.55	0.6	200	3.59
IS4	0.04	0.75	300	-	-	-	-
HCU	38.78	0.92	2000	11.29	0.75	1200	85.7

H_2 supply

	Flow (MMscfd)	Max flow (MMscfd)	Purity	Pressure (psia)
H_2plant	45	50	0.92	300
CRU	23.5	23.5	0.75	300

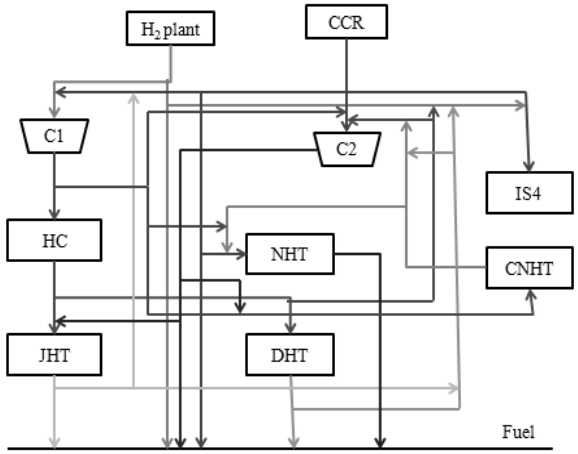

Figure 4. The final form of the first case, without adding a new device.

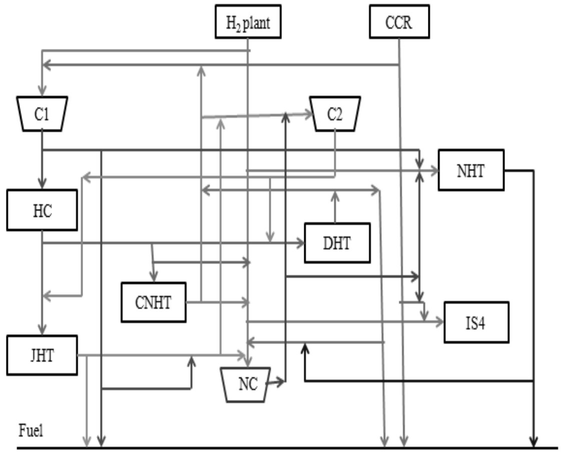

Figure 5. The final form of the first case, with a new compressor.

Table 3.
Comparison of the results with others.

	Hydrogen consumed	Operating cost	Capital cost	Total annual cost	Payback
The system studied	45.62208	22.5	-	22.5	-
The results of Ref.[5]	35.4	19	5	24	1.4
The results of Ref. [2]	45.10778	21.90416	0.38324	22.2874	0.643
The results obtained in this work (first state)	39.38	17.0595	-	17.0595	-
The results obtained in this work (second state)	38	17.16321	3.05393	20.21714	0.572

Fig. (6) and (7) represent the best cost and the average cost of structures versus the number of decades for the first and the second versions of the first case. The best structure for the first version was obtained after 24 decades and for the second case after 9 decades. The parameters used in ICA for the first case study are shown in Table 4.

In the present work, for the first version, optimum use of an output from a process in other processes resulted in 24% reduction in the cost compared to the base case. In the second version, the optimization added a new compressor. The compressor output is divided into three branches, two branches are sent directly to the units NHT and ISO4. The third branch after passing through the second compressor (C2) is used in DHT and JHT. The results obtained in this case show that total annual cost is reduced 9.3% and 15.7% relative to the reference [2] and the reference [5] respectively.

The second study was selected from reference [10], which was designed in 2014 by Deng *et al*. as shown in Fig. (8). The system consists of five hydrogen consuming

processes, all of which include internal recycle compressor. The inlets and outlets of these processes are considered as internal hydrogen sinks and internal hydrogen sources

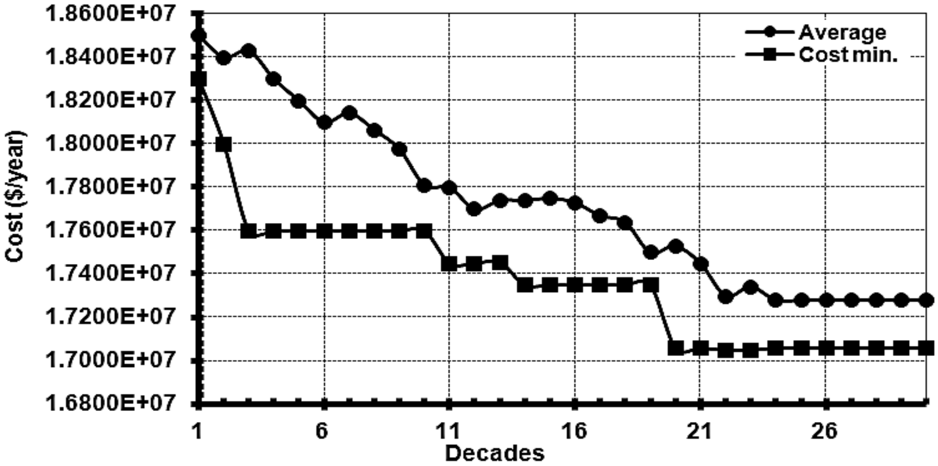

Figure 6. The average cost and the best cost obtained versus the number of decades (the first state).

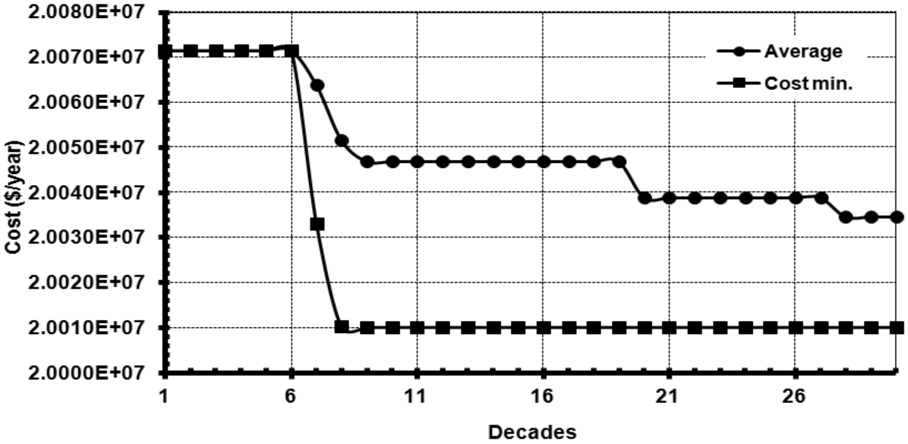

Figure 7. The average cost and the best cost obtained versus the number of decades (the second state).

Table 4.
Parameters used in imperialist competitive algorithm for the first case study.

ζ	λ	β	ω	$N_{country}$	N_{imp}	N_{col}	N_{decade}
0.05	0.99	2	0. 5	30	5	25	30

respectively. Catalytic reforming unit is considered as an internal source of hydrogen and fresh hydrogen is supplied by the hydrogen plant. Data of the make-up compressors, the sinks and the sources of system are given in Tables 5 and 6 respectively. Economic data are shown in Table 1.

This system was optimized in two versions similar to the first case. The first version was performed without adding any new device in the network. In the second case a purification

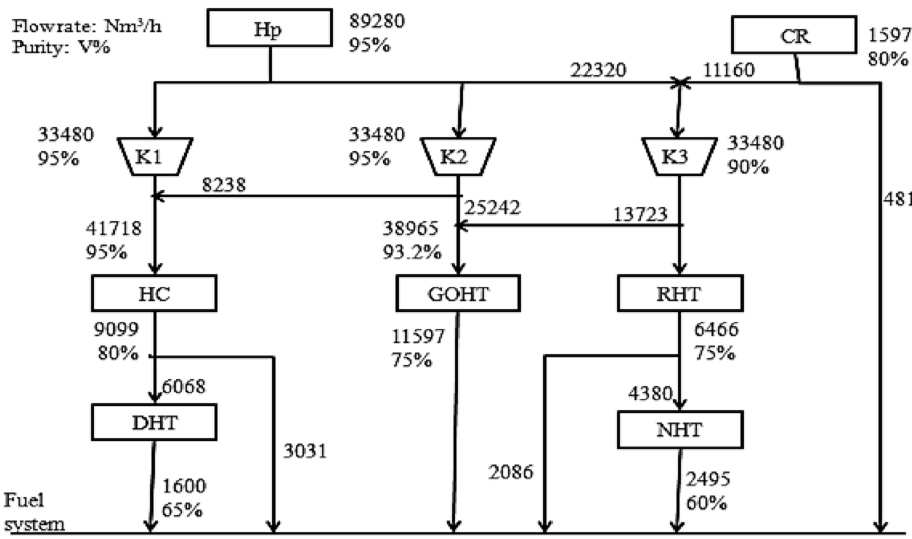

Figure 8. Hydrogen network for the second case study [10].

Table 5.
Data of the make-up compressors [10].

Compressor	Inlet pressure(MPa)	Discharge pressure(MPa)	Maximum capacity(Nm^3/h)
K1	2.069	13.79	35154
K2	2.069	13.79	35154
K3	2.069	4.138	35154

Table 6.
Data of the sources and the sinks for the second case study [10].

Sources	Sinks						Current flow rate(Nm^3/h)	Maximum flow rate(Nm^3/h)	Purity (V%H$_2$)	Pressure(MPa)
	HCU	GOHT	RHT	DHT	NHT	FUEL				
HP	41718	38965	8597				89280	89280	95	2.069
CRU			11160			4818	15978	16182	80	2.069
HCU				6068		3031	9099	9099	80	8.276
GOHT						11597	11597	11597	75	2.414
RHT					4380	6466	10846	10846	75	2.759
DHT						1600	1600	1600	65	2.414
NHT						2495	2495	2495	60	1.379
flow rate(Nm^3/h)	41718	38965	19757	6068	4380	30007				
Purity (V%H$_2$)	95	93.2	90	80	75					
Pressure (MPa)	13.79	3.448	4.138	3.448	2.069					

system was added to the network. A purification system improves the quality of hydrogen from internal hydrogen sources. Fig. (9) and (10) show the final network for the first and the second version respectively. The colored lines represent the new connections. In Table 7 the results obtained by this method were compared with results obtained by others. All costs are in (million dollars/year) and hydrogen consumed is in normal cubic meters per hour (Nm^3/h).

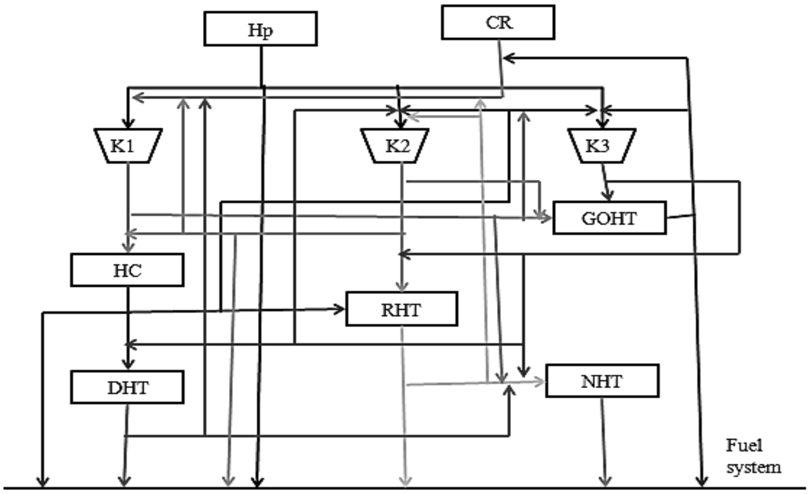

Figure 9. The final form of the second case, without new device (the first version).

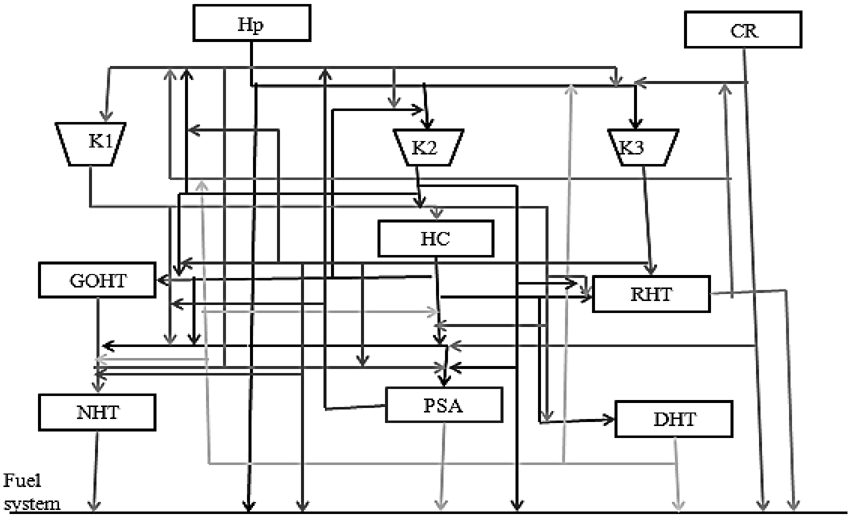

Figure 10. The final form of the second case, with a new purifier (the second version).

Table 7.
Comparison with literature for the second case study.

	Hydrogen consumed	Operating cost	Capital cost	Total annual cost	Payback
The system studied	89280	54.854	-	54.854	-
The results of Ref. [10]	72444	45.884	1.470	47.354	0.165
The results obtained in this work (first state)	81069	37.706	-	37.706	-
The results obtained in this work (second state)	75361	44.952	0.888	45.840	0.09

Fig. (11) and (12) represent the best cost and the average cost of structures versus the number of decades for the first and the second versions of the second case. The best structure for both versions was obtained after 27th decade. The parameters used in ICA for the second case are shown in Table 8.

Deng *et al.* added a purification system to optimize the network. This caused a reduction of 7.5 million dollars. In the present work, at first, optimum use of the output of one process was optimized in other processes without adding a new device system. The result indicates reduction of 31.3% in total

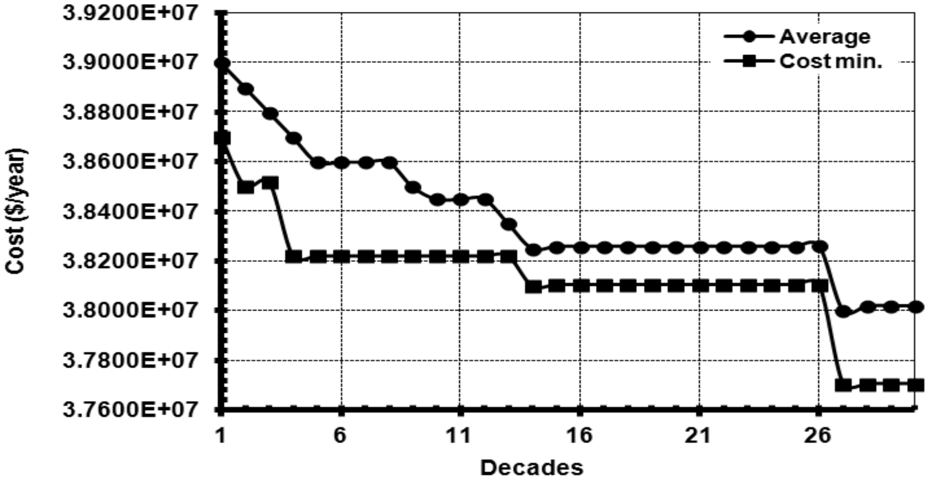

Figure 11. The average and the best cost versus the number of decades (the first version).

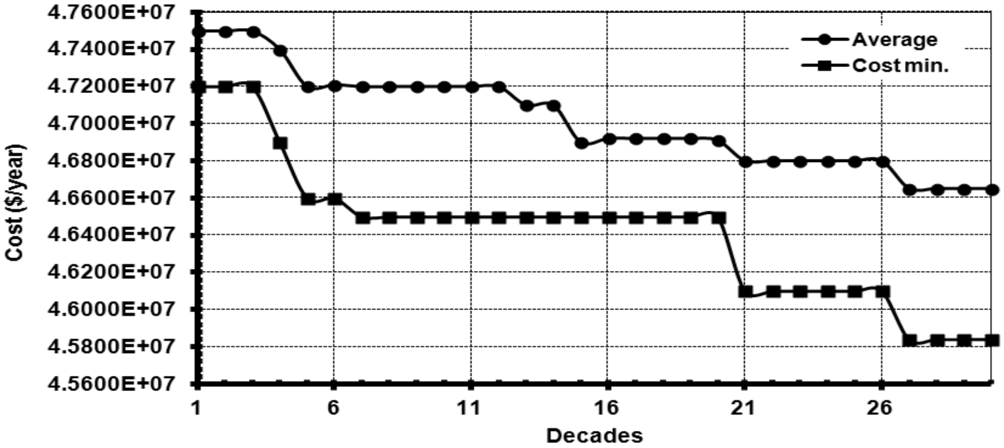

Figure 12. The average and the best cost versus the number of decades (the second version).

Table 8.
Parameters used in imperialist competitive algorithm for the second case study.

ζ	λ	β	ω	$N_{country}$	N_{imp}	N_{col}	N_{decade}
0.05	0.99	2	0. 5	28	4	24	45

annualized cost compared with the base case. In the second version a purification system is used to purify hydrogen outlet of sources. The purified product stream is divided into two branches, the first branch enters the NHT unit directly and the second branch, after passing through three compressors is used in other processes. The cost obtained from the second version shows 3.2% reduction relative to the work of Deng *et al*.

8. Conclusions

In this work Imperialist Competitive Algorithm was coupled with linear programming (LP) to optimize hydrogen distribution network. The main advantage of the algorithm used in this work is higher speed to find optimal solution and to produce feasible structures by considering all constraints imposed on the network.

Comparing the results with those in the literature, it seems that lower cost for network can be obtained by the suggested method. This reduction in cost is attributed to optimal use of new connections between sources and sinks and also new devices.

Nomenclatures

Af	annualizing factor for investment cost for new unit
A	capital cost coefficient
B	capital cost coefficient
e_{heat}	unit cost of heat energy
e_u	unit price of the uth hydrogen utility
e_k	unit cost of power for kth compressor
fi	fractional interest rate per year
F	flow rate
ny	number of years for depreciation
$Power_k$	power for kth compressor
t_k	annual operating time for kth compressor
t_u	annual operating time for the uth hydrogen utility
TAC	total annualized cost
Y	hydrogen purity
ΔH_c°	standard heat of combustion

Abbreviations

CNHT	Cracked Naphtha Hydro-Treater
CR or CCR	Catalytic Reforming
DHT	Diesel Hydro-Treater
GOHT	Gas Oil Hydro-Treater
HP	Hydrogen Plant
HC	Hydro-Cracker unit
IS4	Isomerization
JHT	Jet Hydro-Treater
NHT	Naphtha Hydro-Treater
PSA	Pressure Swing Adsorption
RHT	Residue Hydro-Treater

Subscripts

comp	compressor
J	index for hydrogen sink
I	index for hydrogen source
Inlet	Inlet
K	index for compressor
Max	maximum
NHU	set of hydrogen utilities
NC	index for new compressor
Out	Outlet
P	index for purifier
U	index for hydrogen utility

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