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Mathematical modeling and optimization of hydrogen distribution network used in refinery

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ABSTRACT

In the present investigation, mathematical models have been developed to optimize hydrogen distribution in the refinery. Five models, Model-0, Model-1, Model-2, Model-3 and Model-4, have been formulated to determine the optimal hydrogen network. Amongst these, Model-0 and Model-1 are NLP networks, whereas the remaining three are MINLP networks. The NLP models are improved gradually to develop MINLP models which incorporate new compressor and PSA. The model considers pressure constraints, source flow balance, sink flow balance, compressor flow balance, sink purity constraint, operating cost, capital cost associated with new equipment, payback period and export cost. Amongst five models, Model-4 is predicted as optimal network which is MINLP model incorporating new compressor and PSA. It predicts reduction in hydrogen by 21.74% and annual profit of $ 16.57 million. The present work selects the optimal type of new compressor based on different capital cost functions. Further, the reliability of the present work is checked through comparison of its results with published models.

1. Introduction

In the current world scenario, the demand for energy is increasing at an alarming rate. Alternate sources of energy are being explored to compensate the depleting conventional energy sources. One of the sources which have grabbed the attention of the academia and industries is hydrogen, which is presently considered to be the energy source for future. Hence, it is relevant for the scientific community to manage hydrogen effectively [1].

Hydrogen resources are units that either consume or produce hydrogen. Management of these resources leads to lower consumption of hydrogen from external sources. The literature available for optimization of hydrogen networks in refineries seems scarce and insufficient. Towler et al. [2] drew an analogy between optimization of heat exchanger network and hydrogen network. They plotted marginal cost of hydrogen recovered against the value of hydrogen added and considered it analogous to the composite curves. However, the authors did not consider practical constraints pertaining to flow rates and purity of hydrogen. The most prominent graphical technique of hydrogen management was hydrogen pinch analysis approach [3]. It segregates resources as either sources or sinks. Sources are hydrogen generating units while sinks are termed as the units which consume hydrogen. Subsequently, Alves et al. [3] developed a LP based approach to minimize the fresh hydrogen required from the external hydrogen plant. However, the LP model predicted optimistic targets as it did not include pressure considerations. Later, Hallale and Liu [4] removed this gap by developing NLP model based on superstructure to account pressure constraints. Along with pressure constraints they also considered the

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Table 1 – Process data for refinery in case study.

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_2 Plant	45		50		0.92		300
CRU	23.5		23.5		0.75		300

incorporation of new equipment such as compressors and PSA. They accounted that the inlet pressure of the compressor was designated as that of the lowest pressure source. However, in actual scenario, inlet pressure of the compressor is variable. Considering this factor Kumar et al. [5] developed NLP and MINLP models to optimize the refinery hydrogen network. However, they did not consider the incorporation of compressor or PSA in the MINLP model.

Based on the above backdrops, the present investigation aims at developing a MINLP model incorporating new compressor and PSA along with different constraints such as source flow balances, sink flow balances, compressor flow balances, hydrogen balance around compressor, compressor capacity limit, sink purity and pressure constraint. It also considers various aspects of economic analysis such as payback period, export cost, capital cost, etc. The present work considers different types of compressors to select optimal type of compressor based on economic analysis. Further, based on payback period and profit the optimal network is selected.

2. Problem statement

The models that are formulated in the present work are solved for a case study adapted from Hallale and Liu [4]. It consists of six consumers of hydrogen, called as sinks, such as hydrocracking Unit (HCU), diesel hydrotreater (DHT), naphtha hydrotreater (NHT), cracked naphtha hydrotreater (CNHT), kerosene hydrotreater (JHT) and isomerization unit (IS4). To these units hydrogen is supplied from hydrogen plant and catalytic reforming unit (CRU). To facilitate the flow of hydrogen from the sources to various sinks, two make-up compressors are installed in the system. All sinks have recycle stream apart from IS4. The process data and existing hydrogen network is shown in Table 1 and Fig. 1, respectively. The operating cost data is provided in Table 2.

The capital costs of different compressors and PSA are given as:

For reciprocating compressor without a driver [6]:

$$CC = 7.90 \times (\mathrm{pow})^{0.62} \tag{1}$$

For centrifugal compressor without a driver [6]:

$$CC = 7.19 \times (\mathrm{pow})^{0.61} \tag{2}$$

For screw compressor with a driver [6]:

$$CC = 1.81 \times (\mathrm{pow})^{0.71} \tag{3}$$

For PSA [2]:

$$CC = 503.8 + 347.3 \times (\mathrm{feed\ flow}) \tag{4}$$

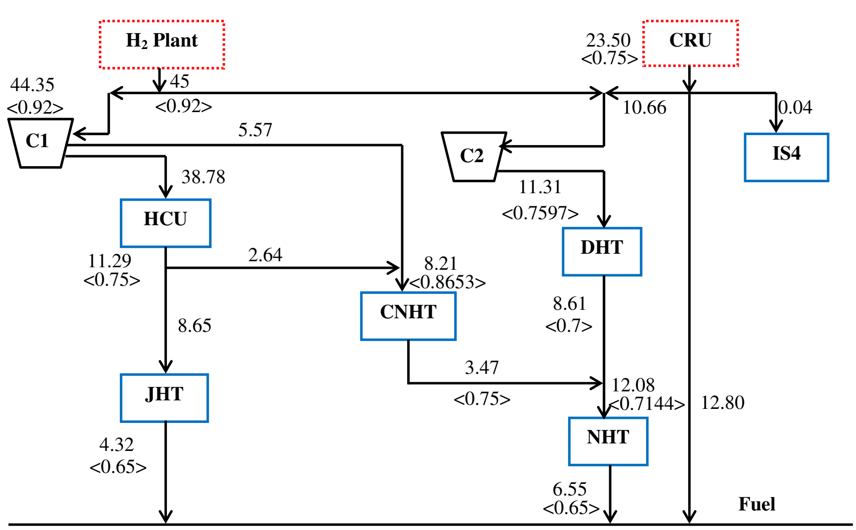

Fig. 1 – Existing network for case study.

Table 2 – Operating cost data for the case study [4,7].

Particular	Cost
Hydrogen cost	\$ 2000/MMscfd
Electricity cost	\$ 0.03/kWh
Fuel costs	\$ 2.5/MMBtu
Export Cost	16.85 \$/GJ

The piping cost of the network is assumed to be 10% of total capital cost [8].

The following factors, imposed by the refinery, should be considered while solving the present problem:

1. The network has additional space to accommodate only one new compressor and purifier.
2. PSA units are preferred as purifiers as they do not require any pre-treatment.
3. The maximum allowable payback period for the modified network is two years.

3. Model development

Five models have been developed in the present investigation – Model-0 to Model-4. Amongst these Model-0 and Model-1 are NLP Models whereas others are MINLP. The objective function of NLP and MINLP models is the total operating cost of the hydrogen network, which is to be minimized. The total operating cost is given as:

$$\text{Total operating cost} = \text{Hydrogen cost} + \text{Electricity cost} - \text{Fuel cost} \tag{5}$$

The fuel cost is denoted with a negative sign as it is cost of low purity hydrogen stream, which is sent to the fuel gas system.

3.1. *NLP model*

A NLP model was first developed to reproduce the existing network [4] hence, it is named as Model-0 and considered as base case. The constraints of the model are flow rate balance for all hydrogen sources and sinks, sink purity, flow rate balance around compressors, hydrogen flow rate balance around compressors and compressor capacity limit as described by Hallale and Liu [4].

Further, Model-0 is modified to Model-1 which accounts the effect of pressure constraints as well as recycles. Along with constraints of Model-0 following constraints are also used in Model-1:

Source flow rate

The net source flow rate is the sum of purge flow rate and recycle flow rate.

$$\mathrm{srprg}(i) + \mathrm{srrec}(i) = \mathrm{fsr}(i) \tag{6}$$

The net flow from a source to all sinks is equal to the purge flow rate of the source.

$$\sum_{j=1}^{sk} \mathrm{fkl}(i,j) = \mathrm{srprg}(i) \tag{7}$$

Sink flow rate

$$\mathrm{skmup}(j) + \mathrm{skrec}(j) = \mathrm{fsk}(j) \tag{8}$$

$$\sum_{i=1}^{sr} \mathrm{fkl}(i,j) = \mathrm{fsk}(j) \tag{9}$$

Recycle equivalence constraint

The source and sink recycles of the same unit are equal to each other. This is true for all units.

$$\mathrm{srrec}(i) = \mathrm{skrec}(j) \tag{10}$$

Pressure constraint

$$P_{source} \geq P_{sink} \tag{11}$$

Hydrogen balance for sinks

Quantity of hydrogen in the sink is the sum of hydrogen available in the makeup and recycle streams.

$$(\mathrm{ym}(j) * \mathrm{skmup}(j)) + (\mathrm{yr}(j) * \mathrm{skrec}(j)) = (\mathrm{ysk}(j) * \mathrm{fsk}(j)) \tag{12}$$

3.2. *MINLP model*

The MINLP model optimizes the refinery hydrogen network by minimizing the total operating cost shown in Eq. (5). The MINLP model considers both binary and continuous variables. The binary variables denote the existence of connection between source and sink, whereas the continuous variables denote the flow between source and sinks. These binary variables are represented as $\upsilon(i,j)$, denoting the existence/non-existence of a connection between the ith source and jth sink. These models are complex in nature and difficult to solve as these are highly dependent on initial guess values of parameters. These are a combination of Mixed Integer Program (MIP) and NLP. The constraints of the model are:

Flow rate balance for all hydrogen sources

The sum of the product of a flow and its corresponding binary variable from a particular source to all sinks is equal to the net flow rate of the source. This is applicable for all sources.

$$\sum_{j=1}^{sk} (\mathrm{fkl}(i,j) * \upsilon(i,j)) = \mathrm{fsr}(i) \tag{13}$$

Flow rate balance for all hydrogen sinks

The sum of flows from any source to a particular sink is equal to the net flow rate of the sink. This is true for all the sinks in the network.

$$\sum_{i=1}^{sr} \mathrm{fkl}(i,j) = \mathrm{fsk}(j) \tag{14}$$

Sink purity constraint

For a particular sink, total hydrogen released from all sources to sink is equal to total hydrogen received by the sink.

$$\sum_{i=1}^{sr} \mathrm{fkl}(i,j) * (\mathrm{ysr}(i) - \mathrm{ysk}(j)) = 0 \tag{15}$$

Compressor flow rate balance

For a make-up compressor, total flow received by the compressor is equal to total flow emanating from the compressor.

$$\sum_{j=1}^{sk} \mathrm{fkl}(\mathrm{comp},j) * \upsilon(\mathrm{comp},j) = \sum_{i=1}^{sr} \mathrm{fkl}(i,\mathrm{comp}) * \upsilon(i,\mathrm{comp}) \tag{16}$$

Hydrogen flow rate balance around compressor

For any compressor, total hydrogen received by the compressor is equal to total hydrogen liberated by the compressor.

$$\sum_{j=1}^{sk} \mathrm{fkl}(\mathrm{comp}, j) * \mathrm{y}(\mathrm{comp}) = \sum_{i=1}^{sr} \mathrm{fkl}(i, \mathrm{comp}) * \mathrm{ysr}(i) \quad (17)$$

Compressor capacity limit constraint

For any compressor, total flow received by compressor is less than maximum specified flow rate.

$$\sum_{i=1}^{sr} (\mathrm{fkl}(i, \mathrm{comp}) * v(i, \mathrm{comp})) \le \sum_{j=1}^{sk} f\mathrm{max}(\mathrm{comp}) \quad (18)$$

Logical flow constraint

In order to ensure that the flow from source to sink does not exceed the minimum of the net flow rate of the source or sink, a logical flow constraint has been incorporated in the present model.

$$(v(i,j) * \mathrm{fkl}(i,j)) - \min(\mathrm{fsr}(i), \mathrm{fsk}(j)) \le 0 \quad (19)$$

Operating cost constraint

The operating cost is composed of three major costs; hydrogen, electricity and fuel. The hydrogen cost denotes the cost of the fresh hydrogen supplied to the system from hydrogen plant.

$$\mathrm{hcost} = \sum_{j=1}^{sk} \mathrm{fkl}(\mathrm{srhplant}, j) * \mathrm{ch2} * v(\mathrm{srhplant}, j) \quad (20)$$

The electricity cost depends on total power in compressors.

$$\mathrm{eleccost} = \mathrm{celec} * \mathrm{pow} \quad (21)$$

where,

$$\mathrm{pow} = \mathrm{pow1} + \mathrm{pow2} \quad (22)$$

Here,

$$\mathrm{pow1} = \frac{C_p T}{\eta} \left(\left(\frac{P_{out,1}}{P_{in,1}} \right)^{\gamma - \frac{1}{\gamma}} - 1 \right) * \frac{\rho_0}{\rho} * \left(\sum_{j=1}^{sk} \mathrm{fkl}(\mathrm{comp1}, j) * v(\mathrm{comp1}, j) \right) \quad (23)$$

$$\mathrm{pow2} = \frac{C_p T}{\eta} \left(\left(\frac{P_{out,2}}{P_{in,2}} \right)^{\gamma - \frac{1}{\gamma}} - 1 \right) * \frac{\rho_0}{\rho} * \left(\sum_{j=1}^{sk} \mathrm{fkl}(\mathrm{comp2}, j) * v(\mathrm{comp2}, j) \right) \quad (24)$$

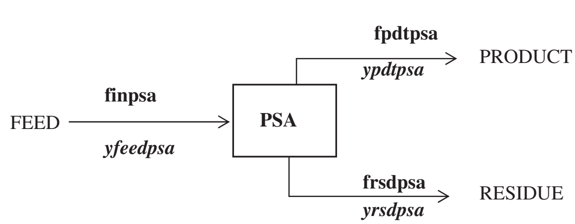

Fig. 2 – Schematic of PSA.

The fuel cost accounts for savings in the operating cost. The steams with low purity hydrogen are sent off as fuel gas which can be used for various other applications.

$$\mathrm{fuelcost} = \sum_{i=1}^{sr} \mathrm{fkl}(i, \mathrm{skfuel}) * \Delta H_{\mathrm{comb,H_2}} * \mathrm{cfuel} \quad (25)$$

Pressure constraint is accounted similarly as for NLP model, Eq. (11).

The incorporation of new compressor leads to the addition of source and sink in the indices. Consequently, a few new constraints such as compressor flow balance, compressor hydrogen balance and compressor capacity constraint are also added in the MINLP model.

The inclusion of PSA purifies the inlet steam in hydrogen content and leads to reduction in hydrogen requirement from the hydrogen plant. A schematic diagram of a PSA is shown in Fig. 2. The words in bold above the arrow represent total flow rate of that stream and the italic words represent purity of that stream. Some assumptions are taken while incorporating the PSA into the network which are pointed out below:

- The PSA product purity is 99%.
- The ratio of the amount of hydrogen present in the product stream to that in the feed stream is termed as recovery. A recovery of 90% is assumed for this model.
- The low-purity residue of the PSA is sent to the fuel.

The addition of new PSA leads to the addition of two sources (product stream and residue stream) and a sink (feed stream) in the network. Mathematically, these constraints are described as:

PSA feed flow rate balance

Sum of the product of a flow and its corresponding binary variable from all sources to PSA is equal to net feed flow rate of the PSA.

$$\sum_{i=1}^{sr} (\mathrm{fkl}(i, \mathrm{skfeedpsa}) * v(i, \mathrm{skfeedpsa})) = \mathrm{finpsa} \quad (26)$$

PSA feed hydrogen flow rate balance

Summation of the product of hydrogen content in a stream and its corresponding binary variable from all sources to the PSA is equal to net feed hydrogen flow rate of the PSA.

$$\sum_{i=1}^{sr} (\mathrm{fkl}(i, \mathrm{skfeedpsa}) * v(i, \mathrm{skfeedpsa}) * \mathrm{ysr}(i)) = \mathrm{finpsa} * \mathrm{yfeedpsa} \quad (27)$$

PSA product flow rate balance

For a particular sink, total hydrogen released from all sources to sink is equal to total hydrogen received by the sink.

$$\sum_{j=1}^{sk} (\mathrm{fkl}(\mathrm{srpdtpsa}, j) * v(\mathrm{skpdtpsa}, j)) = \mathrm{fpdtpsa} \quad (28)$$

Overall PSA flow rate balance

Total flow entering the PSA equals the total flow leaving the PSA.

$$\mathrm{finpsa} = \mathrm{fpdtpsa} + \mathrm{frsdpsa} \quad (29)$$

Hydrogen recovery constraint

Table 3 – Summary of models formulated in the present work.

Model name	Type of model	Modification employed	No. of equations	No. of variables	No. of continuous variables	No. of binary variables
Model-0	NLP	Base case	29	52	52	0
Model-1	NLP	Recycle and pressure constraints	53	94	94	0
Model-2	MINLP	MINLP with all constraint of base case	45	100	63	37
Model-3	MINLP	A new compressor	50	139	80	59
Model-4	MINLP	A new compressor and PSA	55	184	106	78

As 90% of hydrogen from PSA feed stream is recovered in the PSA product stream, thus

$$(\text{finpsa} * \text{yfeedpsa}) = 0.9 * (\text{fpdtpsa} * \text{ypdtpsa}) \tag{30}$$

Overall PSA hydrogen flow rate balance

Total hydrogen entering the PSA equals total hydrogen leaving the PSA.

$$(\text{finpsa} * \text{yfeedpsa}) = (\text{fpdtpsa} * \text{ypdtpsa}) + (\text{frsdpsa} * \text{yrsdpsa}) \tag{31}$$

All models formulated in the present investigation are summarized in Table 3.

4. Solution methodology

The NLP and MINLP models developed in the present work have been solved using optimization software, GAMS [9]. The NLP and MINLP models are solved using MINOS as a solver and DICOPT as a solver, respectively [10]. The flow diagram for solution of MINLP model is shown in Fig. 3; however, solution of NLP model does not require iterations.

5. Results and discussion

In the present work five models have been formulated and these are named as Model-0 to Model-4. The discussion on the results predicted for these models is carried out in the subsequent paragraphs:

5.1. *NLP model*

Two NLP models, Model-0 and Model-1, are compared with the existing system, shown in Fig. 1, and results are presented in Table 4.

Table 4 shows that Model-1 consumes 7.78% and 7.77% less hydrogen than Model-0 and existing network, respectively. The fuel recovered in the network predicted by Model-1 has also plummeted in comparison by Model-0 and existing network. The reductions observed are 14.77% and 14.79%. Due to incorporation of recycle and pressure constraints in Model-1, operating cost is reduced by 4.10% and 4.15% than that predicted by Model-0 and existing network, respectively. If export cost is considered, then the modified total annual cost (TAC) of the network predicted by Model-1 is 28% lower in comparison to existing network. An annual profit of $ 6.681 million is found by the implementation of network predicted from Model-1.

The network obtained for Model-1, shown in Fig. 4, is predicted as the optimal network amongst two NLP models based on hydrogen consumption. It can be seen from Fig. 4 that the entire hydrogen produced in CRU is not utilized. The remaining hydrogen is sent to fuel system, which aids in reducing the operating cost of the network. Now, as pressure constraints are considered in this case, hydrogen is rerouted back to the make-up compressor C2, which has an inlet pressure of 300 psia from HCU (operating at 1200 psia), JHT (operating at 350 psia) and DHT (operating at 400 psia). From CNHT, hydrogen is sent back to compressor C1. JHT, CNHT, NHT, DHT and HCU have a recycle streams also which help in meeting a part of the hydrogen requirement of these units. It actually reduces the hydrogen requirement from CRU and H_2 plant. Hence, there is a lower consumption of hydrogen in Model-1 in comparison to Model-0. The complexity of the network shown in Fig. 4 can be attributed to the incorporation of recycle and pressure constraints in Model-1.

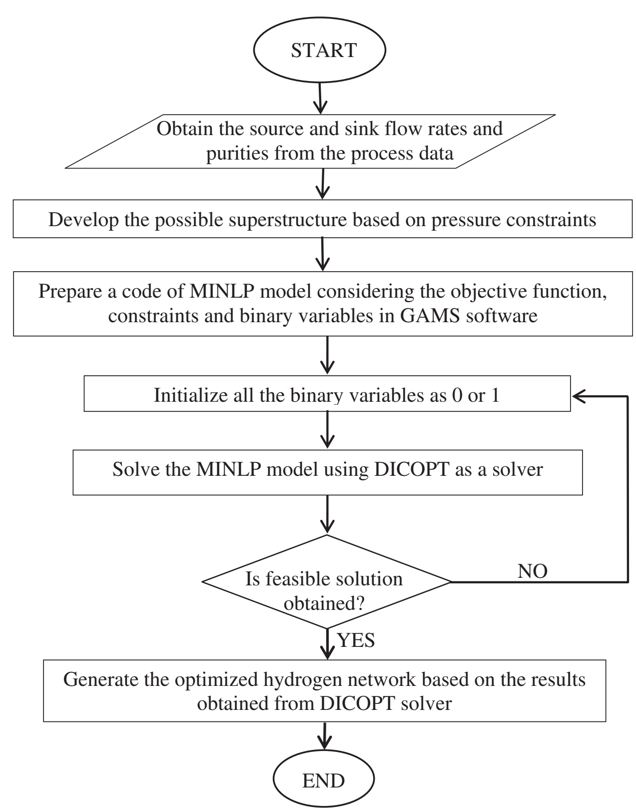

Fig. 3 – Flow diagram adopted for solution of MINLP model.

Table 4 – Comparison of results of NLP models with existing network.

Network	Hydrogen from H_2 plant (MMscfd)	Fuel recovered (MMscfd)	Total operating cost (million $/year)	Export cost (million $/year)	Modified TAC (million $/year)	Profit (million $/year)
Existing	45	23.67	23.858	–	23.858	–
Model-0	44.994	23.664	23.845	0.010	23.835	0.023
Model-1	41.5	20.170	22.867	5.690	17.177	6.681

5.2. *MINLP model*

There are 3 MINLP models formulated in the present work as Model-2, Model-3 and Model-4. The results of these three models are compared with existing network, shown in Fig. 1, and presented in Table 5.

It is observed from Table 5 that the network of Model-4, shown in Fig. 5, consumes 35.217 MMscfd of hydrogen from the H_2 plant. The hydrogen consumption is reduced by 10.7%, 12%, and 21.74% in comparison to Model-3, Model-2 and existing network, respectively. However, the fuel recovered in this network is less than that in other models. The fuel recovery in the network predicted by Model-4 is lowered by 17.5%, 49.9% and 36.94% when compared to the networks obtained by Model-3, Model-2 and the existing network, respectively. The addition of PSA has resulted in the consumption of low purity hydrogen which is utilized in C1 and IS4 after purifying the inlet stream to 99%. This is the main reason behind the decrement in fuel recovery in Model-4. Thus, based on hydrogen consumption Model-4 is selected as optimum model amongst the three MINLP models.

Further, it is evident from Fig. 5 that hydrogen is obtained from hydrogen plant and CRU. The hydrogen plant sends hydrogen to make-up compressor C1. It compresses hydrogen to 2000 psia and sends it to HCU, which requires high purity hydrogen. The hydrogen from the HCU is disbursed to CNHT and JHT. The stream from JHT is then directed to the PSA. It divides product stream into two branches having 99% purity each. One of these is sent to IS4 to partially fulfill its hydrogen requirement. The other branch is re-sent to compressor C1. The residue stream from the PSA is directed to the fuel system. On the other hand, hydrogen from CRU is sent to make-up compressors C1 and C2. The remaining hydrogen of 6.62 MMscfd is purged to the fuel system. The make-up compressor sends hydrogen to CNHT and DHT, which send it to NHT. From the NHT, the stream is compressed to a higher pressure and partly sent to IS4 and the remaining is purged to the fuel system.

The network developed by Model-4, shown in Fig. 5, has lower hydrogen consumption from H_2 plant than other developed MINLP models. This is mainly due to the incorporation of new compressor and PSA. The new compressor receives hydrogen from NHT and compresses it so as to meet the requirement of IS4 along with purging it to the fuel system. The PSA consumes low purity stream as feed and produces product stream of 99% purity, and low purity residue stream which is sent to the fuel system.

5.3. *Selection of optimal type of compressor*

In the present investigation, three types of compressors are considered such as reciprocating, centrifugal and screw. A comparison of capital cost of these three compressors with Model-4 is shown in Table 6. The annual capital investment required for a PSA is $ 2 million. Piping cost is assumed to be 10% of total capital cost of new equipment [8].

Table 6 shows the modified TAC of various compressor configurations along with the profit and payback period. Based on these parameters, it can be seen that the implementation of screw compressor is the best choice as compared to reciprocating or centrifugal compressor. A profit of $ 16.573 million/year has been observed on the incorporation of screw compressor.

5.4. *Comparison of results of optimum NLP and MINLP models*

As Model-1 and Model-4 are optimum NLP and MINLP models these must be compared with each other to select best hydrogen network. The results of comparison are shown in Table 7 which indicates that as the model progresses from Model-1 to Model-4, the hydrogen consumption from H_2 plant declines. The progression from Model-1 to Model-4 denotes the increasing complexity of the model either in terms of addition of constraints or change in type of model or incorporation of new equipment. This complexity in the model leads to simplicity in solution and provides better optimized results for the same problem. When the model becomes MINLP problem from NLP or when new compressor or PSA is added, the network gets additional options to develop a feasible network. As the number of options increases in the network its dependence on the fresh hydrogen supply from the hydrogen plant decreases. Hence, the trend observed in Table 7 for hydrogen consumption appears logical.

Further Table 7 shows the deviation of values of different parameters of the networks predicted by Model-1 and Model-4 with the existing network. Table 7 shows that in both models, hydrogen requirement from H_2 plant, the fuel recovered from the network, total electricity costs, operating costs and total annual cost are lower than that for existing network. It can be seen that a profit of $ 16.573 million/year is obtained for Model-4, which is more than that of Model-1. Thus, it is selected as best model and optimum hydrogen distribution network of refinery.

5.5. *Comparison of results of optimal model with that of published models*

The optimal network predicted by the present investigation, shown in Fig. 5, can be compared with the results obtained by Hallale and Liu [4] and Kumar et al. [5] to check the reliability of the present work. The optimal networks proposed in these two articles have incorporated new compressor and PSA in

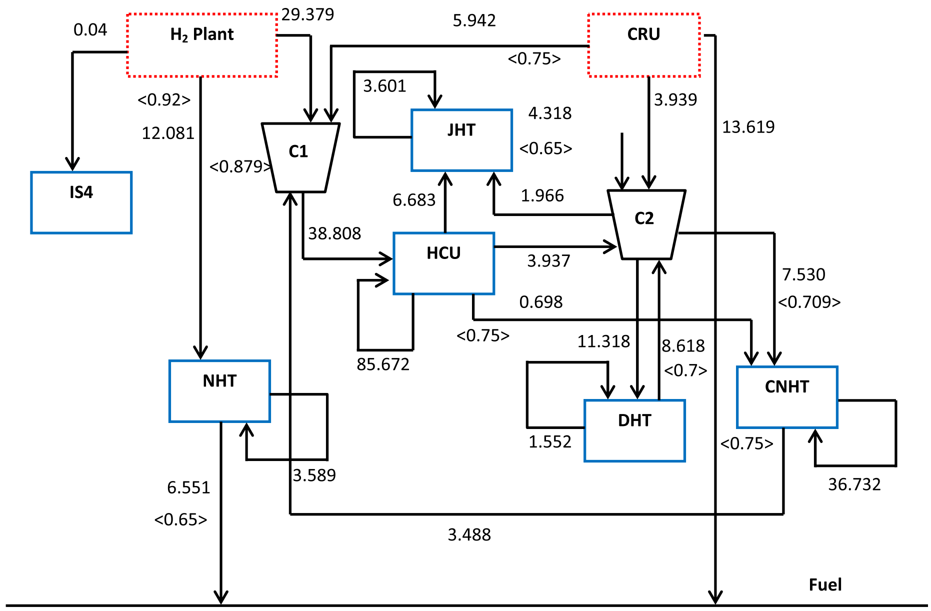

Fig. 4 – Optimized refinery hydrogen network obtained by Model-1.

Table 5 – Comparison of results of three MINLP models with that of existing network.

Network	Hydrogen from H_2 plant (MMscfd)	Fuel recovered (MMscfd)	Total operating cost ($/year)	Total electricity cost ($/year)	Total capital cost ($/year)	Total annual cost ($/year)
Existing	45	23.67	2.3858e + 7	3.245e + 6	–	2.3858e + 7
Model-2	40.028	29.775	1.664485e + 7	2.8181e + 6	–	1.66449e + 7
Model-3	39.425	18.095	2.2343e + 7	2.918e + 6	64.646	2.2408e + 7
Model-4	35.217	14.926	2.095e + 7	2.9595e + 6	2.239.022	2.3190e + 7

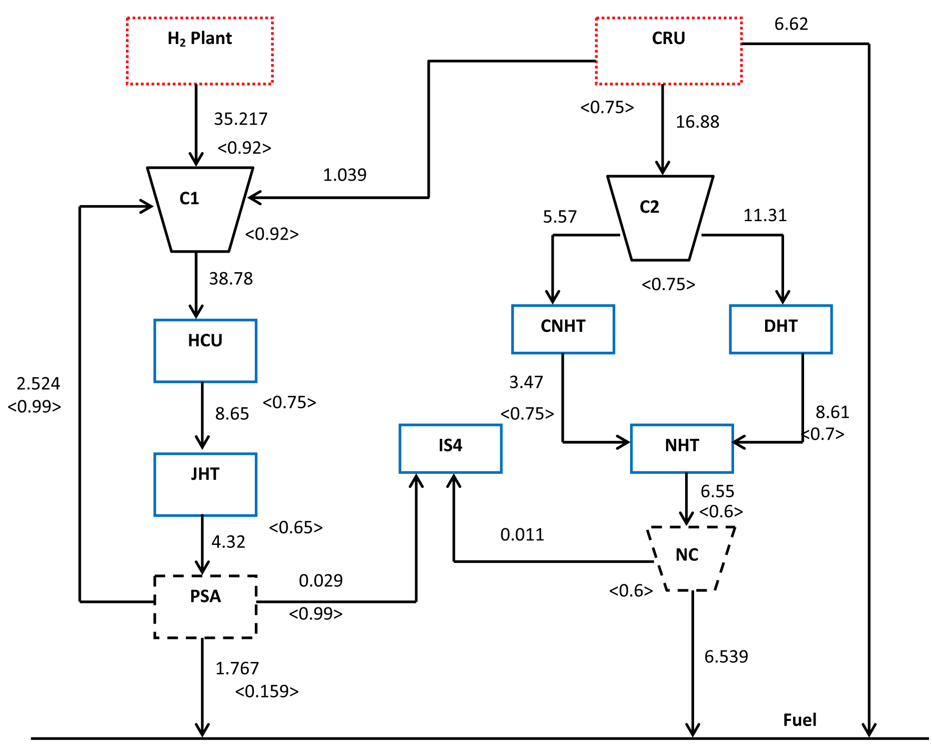

Fig. 5 – Optimized hydrogen network obtained by Model-4.

Table 6 – Comparison of modified TAC, profit and Payback period of different compressor configurations.

Case	Total operating cost (million $/year)	Total capital cost (million $/year)	Export cost (million $/year)	Modified TAC (million $/year)	Profit (million $/year)	Payback period (yrs.)
Existing	23.858	–		23.858	–	–
Model-4 with centrifugal compressor and a PSA	20.951	2.309	15.905	7.355	16.503	0.7941
Model-4 with reciprocating compressor and a PSA	20.951	2.296	15.905	7.342	16.516	0.7897
Model-4 with screw compressor and a PSA	20.951	2.239	15.905	7.285	16.573	0.7702

Table 7 – Comparison of results of Model-1 and Model-4 with the existing network.

Network	Hydrogen from H_2 plant		Fuel recovered		Total electricity cost		Total operating cost		Total capital cost	Export cost	Modified TAC (including export cost)		Profit	Payback period
	Value[a]	% Deviation	Value[a]	% Deviation	Value[b]	% Deviation	Value[b]	% Deviation	Value[b]	Value[b]	Value[b]	% Deviation	Value[b]	(yrs.)
Existing Network	45	–	23.67	–	3.245	–	23.858	–	–	–	23.858	–	–	–
Model-1	41.5	−7.8	20.170	−14.8	2.950	−9.1	22.867	−4.2	–	5.690	17.177	−28.0	6.681	–
Model-4	35.217	−21.7	14.926	−36.9	2.960	−8.8	20.951	−12.2	2.239	15.905	7.285	−69.5	16.573	0.77

[a] Value in MMscfd.
[b] Value in million $/year.

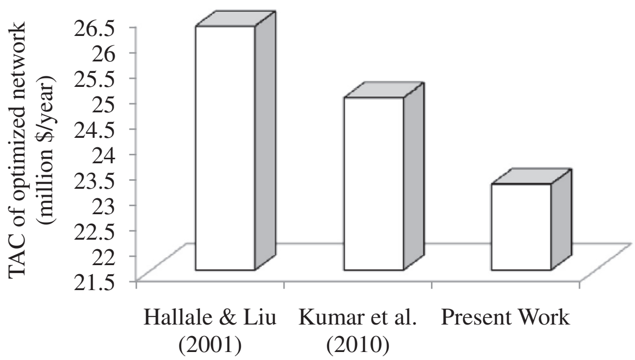

Fig. 6 – Comparison of TAC of optimized network with published models.

the existing network to reduce the overall hydrogen consumption.

Fig. 6 compares the TAC of the optimum hydrogen network predicted by these models. It can be observed that the TAC of optimum network predicted by Model-4 is 11.8% and 6.8% lower than that predicted by Hallale and Liu [4] and Kumar et al. [5], respectively. This difference is attributed to the low capital cost of the new equipment incorporated. The present work employs cost functions for different types of compressors [6], which are specified under Section 2. The capital cost function for a generalized compressor, which have been employed in the published models leads to a higher TAC.

The payback period of optimum hydrogen network predicted in the present work with that of published models are compared in Fig. 7. It shows that the payback period of the present optimum model is 0.7702 years i.e. 9 months as compared to 1.6 years predicted by Hallale and Liu [4] and 1.88 years found by Kumar et al. [5]. The low payback period is mainly due to a low capital investment in the present case.

6. Conclusions

The salient conclusions of the present investigation are listed below:

- The networks predicted by MINLP models are less complex than those found by NLP models.

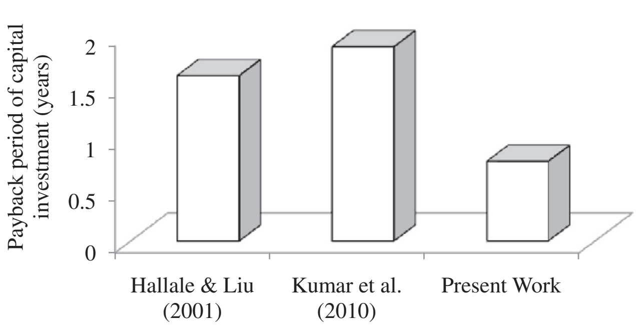

Fig. 7 – Comparison of payback period in optimized network with published models.

- The present work considers three types of compressors such as reciprocating, centrifugal and screw. The capital cost of the network with screw compressor is 0.301% and 0.245% lower than that with centrifugal compressor and reciprocating compressor, respectively.
- The hydrogen consumption from H_2 plant is least for Model-4 amongst all other models developed in the present work.
- In the present investigation export cost is also included while computing TAC as the unused hydrogen of the plant should be exported. The export cost reduces TAC maximum by 68.6%.
- Based on hydrogen consumption, TAC with export cost and payback period the network developed for Model-4 is found as optimum network. It is predicted for MINLP model consists of new screw compressor and PSA.
- The optimum network predicts reduction of 21.74% hydrogen supplied from plant in comparison to the existing network. However, 14.28% is observed in total hydrogen which is provided by CRU and hydrogen plant.
- The TAC of optimum network is 9.3% lower on average than TAC of the networks predicted by published models which shows the effectiveness of the present model. Further, payback period of optimum network is 0.772 years i.e. around 9 months, which is 58.94% less than the published models.

Nomenclature

CC	Capital cost, k$
fkl	Flow rate, MMscfd
υ	Binary variable
P	Pressure, psi
pow	Power, hp
fsr	Total source flow rate, MMscfd
fsk	Total sink flow rate, MMscfd
ysr	Source purity
ysk	Sink purity
y	Purity

Abbreviations

NLP	Non-linear programming
LP	Linear programming
MINLP	Mixed integer non-linear programming
MIP	Mixed integer programming
PSA	Pressure swing adsorber
TAC	Total annual cost
CRU	Catalytic reforming unit
HCU	Hydrocracking unit
DHT	Diesel hydrotreater
NHT	Naphtha hydrotreater
CNHT	Cracked naphtha hydrotreater
JHT	Kerosene hydrotreater
IS4	Isomerization unit
GAMS	General algebraic modeling system

Indices

i,sr	source
j,sk	sink
comp	compressor

Subscripts

source source
sink sink

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