CHEMICAL ENGINEERING TRANSACTIONS

VOL. 94, 2022

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at www.cetjournal.it

Guest Editors:Petar S. Varbanov, Yee Van Fan, Jiří J. Klemeš, SandroNižetić

ISBN978-88-95608-93-8;**ISSN** 2283-9216

DOI: 10.3303/CET2294106

Segregated Targeting of Hydrogen Allocation Network using Pinch Analysis

Gaurav Shukla, Nitin Dutt Chaturvedi*

Department of Chemical and Biochemical Engineering, Indian Institute of Technology Patna, Bihta, Patna, 801106, Bihar, India
nitind@iitp.ac.in

Hydrogen, as a resource is widely used in refineries in hydrocracking and hydrotreating processes. As hydrogen demand in the refineries is increasing, hydrogen management strategies are of great interest to the refineries. Hydrogen management deals with the optimal distribution or allocation of hydrogen gas within a refinery linking the hydrogen internal sources, and external sources to demand units. Generally, it comprises multiple zones of demands with a dedicated resource for each zone and sources shared by all zones i.e. segregated targeting. The flow is supplied for satisfying the demand via compression. The compression procedures involve huge amounts of investment and also the compression energy. So energy management and investment management in hydrogen allocation networks (HANs) is a very important aspect. To reduce investment and save energy for the petrochemical industry, the hydrogen system in a refinery should be operated under the optimal scheme to meet the varying hydrogen demands of hydrogen consumers. In this paper, a mathematical formulation based on the Pinch Analysis approach is presented to address such problems. The applicability of the proposed methodology is explained via an illustrated example which helps to optimize HAN with multiple zones. The result shows that there is an almost 18% decrease in resource requirement while almost the same energy is utilized. When the next highest CBN is added then there 10% decrease in resource requirement but at the same time a slight increase in energy requirement. It can be concluded from the example that the result allows the decision-maker to utilize in such a way that the common resources can minimize the compression energy in all the zones while satisfying the demand.

1. Introduction

Hydrogen is used in huge amounts in the oil refining business. Demand will continue to be largely focused on industry sectors, either expanding in existing sectors, such as fertilizers and refineries or growing into new sectors, such as steel. Because hydrogen demand in refineries is continually increasing, refinery hydrogen management capabilities are of major importance. These supplies should be used in such a way that they meet current demands without affecting future needs. Hydrogen Allocation Network (HAN) is associated with the transportation, effective supply, and flow distribution of hydrogen within a refinery, which combines the source and demand stations. Apart from reducing the amount of fresh hydrogen required, it is important to limit the amount of compression energy requirement in any HAN (Birjandi et al. 2014). Supplying the flow via compression procedures involves a huge amount of energy often provided by compressors. Because of the increased sensitivity to global warming and the use of renewable energy sources, every region must energy efficient.

Segregated targeting issues were first discovered as a result of a planning issue in the carbon-constrained energy sector (Lee et al., 2009). The economic side of the segregated targeted problem was introduced by Chandrayan and Bandyopadhyay (2014). This work is characterized by each resource by the quality and per-unit cost. The objective of the problem has been modified to minimization of the total cost. Yang et al. (2014) used pinch technology to find the best filtration technique for hydrogen networks that saves the most hydrogen as a resource. According to Tan et al. (2015), it is critical to examine several objectives to make better and more informed decisions. This is very crucial to achieving long-term development. Considering the dedicated sources

Paper Received: 16 April 2022; Revised: 08 May 2022; Accepted: 12 May 2022
Please cite this article as: Shukla G., Chaturvedi N.D., 2022, Segregated Targeting of Hydrogen Allocation Network using Pinch Analysis, Chemical Engineering Transactions, 94, 637-642 DOI:10.3303/CET2294106

in segregated targeting problems that can use only in particular zones, Jain and Bandyopadhyay (2017) developed a methodology for segregated targeting in resource allocation network with an objective to minimize external resource requirements in zones. Kang et al. (2019) look at how the synthesis affects hydrogen networks in terms of fuel, network sophistication, total annual cost, and increased efficiencies in single and multiple-period operations. For the dual aims of chemical production planning for the methanol sector in China, Qin et al. (2018) proposed a sequential graphical as well as statistical Pinch Analysis (PA) based approach. Liu et al (2019) proposed a fuzzy optimization model for the design of a multi-component hydrogen network with parametric uncertainties is developed. Chaturvedi (2020) utilized the PA approach to compute the power rating of resources necessary in a hybrid power system to reduce the total cost of electricity. Recently Shukla and Chaturvedi (2021a) proposed the PA approach for minimizing compression energy requirements in batch gas allocation networks. Haider and Chaturvedi (2021) developed segregated targeting for resource conservation with dedicated sources for the batch process.

It can be established, from the above literature review that researchers have proposed several graphical and mathematical programming-based works on segregated targeting for batch processes and also for the continuous process. However, a key domain of the HAN, that has been comprehensively researched for continuous processes is not focused on segregated targeting. The objective of this study is to develop an algorithm for segregated targeting problems with dedicated source stations and common internal stations in HANs. In segregated targeting, there are various zones. In each zone, there are several internal source compressor stations (CSs), resources CSs, dedicated sources CSs, and demand stations available. The objective of this study is to provide a result to the decision-maker to allow in such a way that the common resources can minimize the compression energy in all the zones while satisfying the demand. The remainder of this paper is organized as follows. Section 2 describes the problem statement of this work. In Section 3, the mathematical background and targeting algorithm is presented. An illustrative example is performed to demonstrate the proposed framework in Section 4. Section 5 concludes the finding of this study.

2. Problem Statement

The overall problem for segregated targeting for minimizing compression work with dedicated internal source CSs and a set of common internal source CSs associated with multiple zones in the HAN may be mathematically stated as follows.

Each zone consists of a set of demand CSs, a resource CS, and a set of dedicated source CSs. Dedicated CSs are those that can exclusively transfer flow to the demands of the zone in which they have located i.e. the flow from specific sources in one zone cannot be transferred to the requirements of other zones. The objective of the problem is to minimize the compression energy in the HAN. The numerical description of the aforementioned problem is as follows.

A set of N_s internal sources CSs is given. Each source station ($i = 1, 2, ..., N_s$) a flow F_{si} with quality q_{si}. A set of zones (k = 1, 2, ..., N_z) is also given. Each zone consists of a set of dedicated sources, a resource, and a set of demands. Each dedicated source station ($l = 1, 2, ..., N_{dsk}$) of the kth zone supplies flow F_{dslk} with quality q_{dslk}. The resource station has no supply limitations and each resource station corresponding to zone k has a quality q_{rk} associated with it. Each demand station (j = 1, 2, ..., N_{dk}) of kth zone accepts a flow F_{djk} with maximum allowable quality of q_{djk} from an internal source, dedicated source, and resource stations.

3. Mathematical Background and Targeting Algorithm

The flow balance for each source CSs, resource station, to demand station may be addressed as follow. Let f_{ijk} be the flow transferred from internal source *i* to demand *j* of zone k. Where f_{iw}flow is transferred from source CSs to waste. (Eq. 1)

$$\sum_{k=1}^{N_z}\sum_{j=1}^{N_{dk}} f_{ijk} + f_{iw} = F_{si} \qquad \forall i \in 1,2,...Ns \tag{1}$$

Similarly, x_{ljk} is the flow transferred from dedicated source CSs to demand *j* of the zone *k*. (Eq. 2)

$$\sum_{j=1}^{N_{dk}} x_{ljk} + x_{lwk} = F_{dslk} \qquad \forall\, l \in \{1,2,...N_{dsk}\}, k \in \{1,2,...N_z\} \tag{2}$$

Where x_{lwk} flow is transferred from dedicated source CSs l to waste.

The flow balance for demand (j) at zone (k) can be expressed as Eq. 3.

$$\sum_{i=1}^{N_s} f_{ijk} + \sum_{l=1}^{N_{dsk}} x_{ljk} + f_{rjk} = F_{djk} \qquad \forall\, j \in \{1,2,...N_{dk}\}, k \in \{1,2,...N_z\} \tag{3}$$

Where, f_{rjk} is the flow transferred from resource to demand *j* of zone k.

The quality load balance for any internal demand station may be mathematically expressed as Eq (4)

$$f_{rjk}q_{rk} + \sum_{i=1}^{N_s} f_{ijk}q_{si} + \sum_{l=1}^{N_{Dsk}} x_{ijk}q_{dSlk} \leq F_{djk}q_{djk} \qquad \forall\, j \in \{1,2,\ldots N_{dk}\},\, k \in \{1,2,\ldots N_z\} \tag{4}$$

The compression energy requirement is directed by the initial and final states along with the volumetric flow. For isothermal compression, the energy requirement (E) can be expressed as Eq (5): (Shukla and Chaturvedi, 2021b)

$$\text{Net Energy, E} = \begin{cases} \mathrm{F}_0^*\left[\left(\mathrm{P}_0\ln\left(\frac{\mathrm{P_j}}{\mathrm{P_0}}\right)\right) - \left(\mathrm{P}_0\ln\left(\frac{\mathrm{P_i}}{\mathrm{P_0}}\right)\right)\right] & \text{For isothermal process} \\ \left(\frac{\mathrm{n}}{\mathrm{n}-1}\right)\mathrm{P}_0^{\frac{1}{\mathrm{n}}}\,\mathrm{P_i}^{\frac{n-1}{\mathrm{n}}}\,\mathrm{F}_0^*\left[\left(\frac{\mathrm{P_j}}{\mathrm{P_i}}\right)^{\frac{n-1}{n}} - 1\right] & \text{For polytropic process} \end{cases} \tag{5}$$

Where F_0^* represents the volumetric flow rate at atmospheric conditions, $\mathrm{P_0}$ is the atmospheric pressure, $\mathrm{P_j}$ and $\mathrm{P_i}$ are the demand and supply pressures while n is the polytropic index.

The Energy Index (EI) can be estimated utilizing Eq (6).

$$\mu_{(\mathrm{i/j/r/l})} = \begin{cases} \mathrm{P}_0\ln\left(\frac{\mathrm{P_{(i/j/r/l)}}}{\mathrm{P_0}}\right) & \text{For isothermal process} \\ \left(\frac{\mathrm{n}}{\mathrm{n}-1}\right)\mathrm{P}_0\ln\left(\frac{\mathrm{P_{(i/j)}}}{\mathrm{P_o}}\right)^{\frac{(n-1)}{n}} & \text{For polytropic process} \end{cases} \qquad \forall\, i \in \{1,2,..Ns\},\, j \in \{1,2,.N_{dk}\} \tag{6}$$

Where $\mu_{(i/j/r/l)}$ shows the energy index for the compressor station.

The quantity $(\mu_j - \mu_i)$ can be stated as the compression energy index, λ_{ij} (CEI) and expressed as Eq (7);

$$\lambda_{(i/r/l,j)} = (\mu_j - \mu_{(i/r/l)}) \qquad \forall\, i \in \{1,2,\ldots Ns\},\, j \in \{1,2,\ldots N_{dk}\} \tag{7}$$

Hence, the compression energy requirement (E_{jk}) can be calculated as Eq (8);

$$f_{rjk}\lambda_{rj} + \sum_{i=1}^{N_s} f_{ijk}\lambda_{ij} + \sum_{l=1}^{N_{dsk}} x_{ljk}\lambda_{lj} = E_{jk} \tag{8}$$

There are two objectives resource requirements and compression work which are minimized sequentially. Initially, the resource requirement is minimized then compression work is minimized.

Based on the model, mathematical analysis can be proposed for segregated targeting of HAN using PA. Initially, each zone is solved to determine resource requirements without the use of internal source CSs. Resource requirements can be calculated via well-established techniques based on PA i.e. Source Composite Curve, and Limiting Composite Curve. Segregated all sources CS and demand CSs according to their pressure level. The CEI can be calculated by utilizing Eq (7) and then required energy can be calculated for all the zones (Eq 8). Sequencing of the internal sources can be determined by the dimensionless number called Compressor Benefit Number (CBN) based on the pinch analysis. Based on the pinch point, CBN can be calculated via Eq (9) in each zone.

$$\text{CBN} = \begin{cases} \frac{(q_p - q_{si})}{(q_{rs} - q_p)} & q_{rs} \geq q_p \\ \frac{(q_p - q_{si})}{(q_p - q_{rs})} & q_{rs} \leq q_p \end{cases} \tag{9}$$

If an internal source has zero or negative values of CBN at all the zones, then the flow from such internal sources station is neglected. Introducing the higher CBN, lower the fresh hydrogen requirement. Based on this result compression energy requirement can be calculated. If all internal sources CSs have been exhausted through sequencing of CBN, the algorithm will come to end. The CBN provides the direction in which internal source stations can be added for minimizing the fresh hydrogen requirement. Now decision-makers can utilize these results according to their requirement. Figure 1 shows the flow chart of the proposed algorithm.

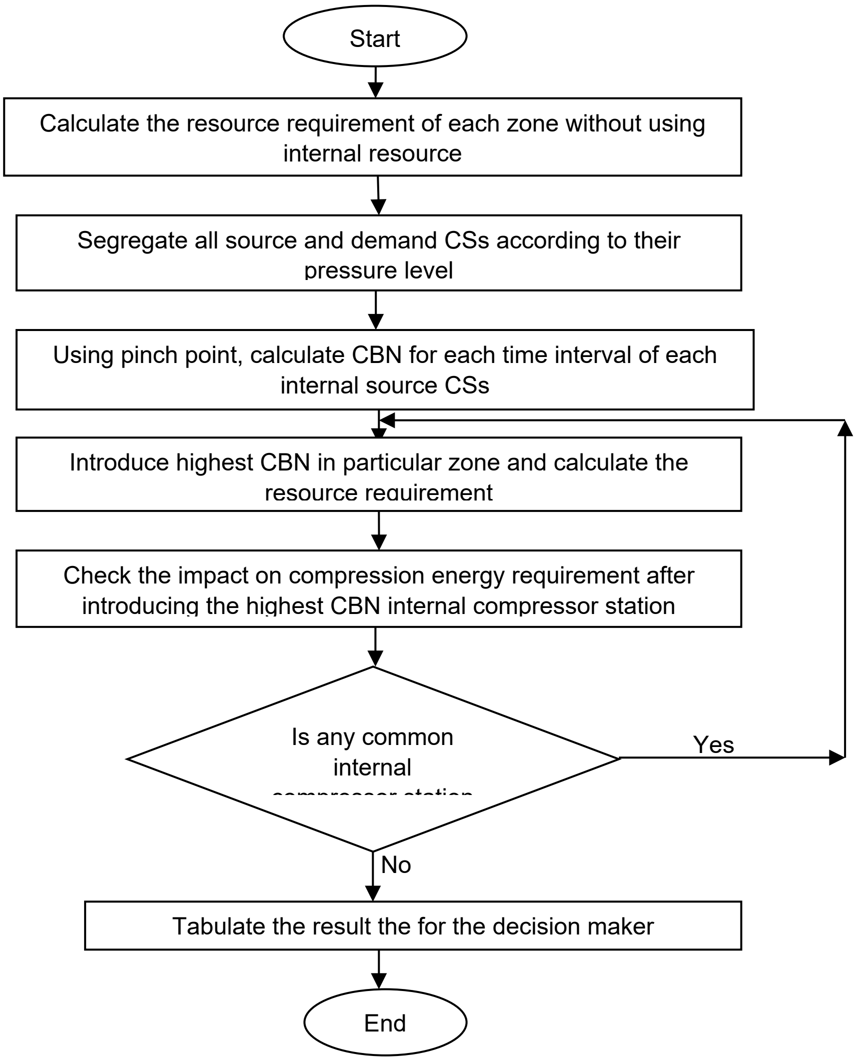

Figure 1: Flow chart showing a proposed algorithm for Segregated Targeting of HAN

4. Illustrative Example

An illustrative example is used to demonstrate the application of the proposed framework. Consider a scenario with two zones in which there are two internal CSs, three dedicated CSs, and a different resource CS is available for supplying the flow to the demand. The data for Zone 1 and Zone 2 is presented in Table 1 and Table 2. Data for internal CSs represents in Table 3.

Table 1: Data for Hydrogen Allocation Network for Zone 1

Dedicated Compressor Station	**Quality (%)**	**Pressure (kPa)**	**Flow (Sm^3/s)**
N_1	0.20	180	150
N_2	0.23	175	180
N_3	0.19	200	220
Demand	**Quality (%)**	**Pressure (kPa)**	**Required Flow (Sm^3/s)**
D_1	0.10	240	180
D_1	0.22	220	230
D_1	0.18	230	200
$Resource\ R_1$	0.05	110	

Table 2: Data for Hydrogen Allocation Network for Zone 2

Dedicated Compressor Station	**Quality (%)**	**Pressure (kPa)**	**Flow (Sm^3/s)**
N_4	0.25	180	400
N_5	0.17	175	300
N_6	0.30	200	380
Demand	**Quality (%)**	**Pressure (kPa)**	**Required Flow (Sm^3/s)**
D_4	0.09	240	230
D_5	0.07	220	250
D_6	0.20	230	250
$Resource\ R_2$	0.02	120	

Table 3: Data for internal compressor station

Internal Compressor Station	**Quality (%)**	**Pressure (kPa)**	**Flow (Sm^3/s)**
Z_1	0.15	140	2000
Z_2	0.13	150	2000

From Table 1, it may be noted that for zone 1, there is three dedicated source station (*N_1, N_2, N_3*) and three demand station (*D_1. D_2, D_3*), and one resource (*R_1*). Following the source composite curve application based on the PA approach, 132 Sm^3/s fresh hydrogen is required the satisfy the demand. For satisfying the demand, there is an 18,480.86 kJ need for energy. The pinch point is found at quality of 0.20%. So utilizing this point CBN can be calculated by using Eq 10. The CBN for Z_1 and Z_2 of zone 1 is 0.25 and 0.35. So introducing the highest CBN which belongs to Z_2, reduces the fresh hydrogen requires 132 Sm^3/s to 107.5 Sm^3/s and energy from 18,480.86 kJ to 18,444.07 kJ. Now introducing the second-highest CBN which is Z_1, reduces the fresh hydrogen required 118 Sm^3/s while the increase in compression energy. So it may be highlighted that the reduction in resource requirement does not guarantee a decrease in the compression energy.

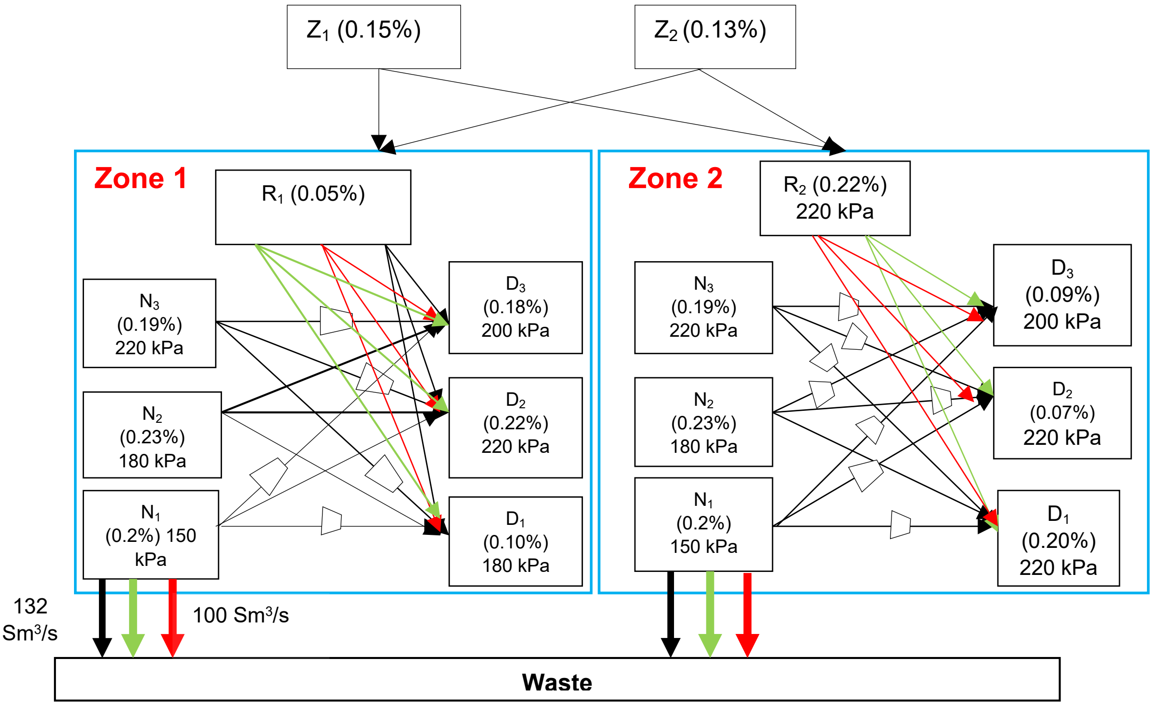

Figure 2: Optimal HAN for minimum compression work for all three scenarios

Similarly, the minimum resource and energy requirement for Zone 2 can be calculated. The optimal HAN for both zones is shown in Figure 2 with their corresponding quality and pressure.

5. Conclusions

Segregated targeting problems (STP) have been identified as an important class where zonal restrictions are addressed. This paper develops methodology for STP in HAN with emphasis on minimization of resource requirement and compression work. Effectiveness of the developed methodology is illustrated via an example. The proposed methodology can be used to solve the situation in HAN where internal source stations are available for several zones while dedicated source stations are only supplied to particular zones. In the illustrative example, it is identified that there is around an 18% decrease in resource requirement while almost the same energy is utilized. Further in addition to the next highest CBN there 10% decrease in resource requirement but at the same time a slight increase in energy requirement for zone 1. Similarly, for zone 2, there is a almost 14% decrease in resource requirement in addition to the highest CBN. A trade-off between the resource and the energy requirement can be carried out which is helpful to the decision-maker to choose suitable operational conditions which minimize energy and resource requirements. In the future, this work can be extended by including more financial aspects of HAN along with prioritization.

Nomenclature

E_{jk}= Energy requirement, (kJ/s)
P_j, P_i= Demand and supply pressure, (kPa)
n= Polytropic index
F_{dj} = Flow requirement of demand, (Sm^3/s)
F_{si}= Maximum limit of supply flow from CS, (Sm^3/s)
F_{si} = flow of ith internal source (Sm^3/s)
F_{djk} = flow of jth demand of zone k (Sm^3/s)
CBN = Compressor Benefit Number
PA= Pinch Analysis
F_{DSlk} = flow of lth dedicated source present in zone k (Sm^3/s)
q_{DSlk} = quality of lth dedicated source present in zone k
q_{dj} = quality of j^{th} demand
q_{rk} = quality of resource at zone k
q_{si} = quality of i^{th} source
q_{sm} = quality of m^{th} internal source
HAN= Hydrogen Allocation Network
CS = Compressor station

References

Birjandi M.R.S., Shahraki F., Razzaghi, K., 2018, A New Optimization Strategy to Improve Design of Hydrogen Network-Based Formulation of Hydrogen Consumers. Chemical and Biochemical Engineering Quarterly, 32(1), 91-101.

Chandrayan A., Bandyopadhyay S. 2014, Cost Optimal Segregated Targeting for Resource Allocation Networks. Clean Technol. Environ. Policy 16, 455−465.

Chaturvedi N.D., 2020, Cost optimal sizing of hybrid power systems: a pinch analysis approach, Chemical Engineering Transactions, 81, 973-978.

Haider, M.A., Chaturvedi N.D., 2021, Segregated Targeting for Resource Conservation with Dedicated Sources for Batch Process. Chemical Engineering Transactions, 88, 175-180.

Jain S., Bandyopadhyay S., 2017, Resource allocation network for segregated targeting problems with dedicated sources. Industrial & Engineering Chemistry Research 56 (46):13831–13843.

Kang L., Jiang Y., Liu Y., 2019., Impacts of synthesis schemes on economy and flexibility of hydrogen networks. Chemical Engineering Science, 207, 1159-1174.

Lee S. C., Ng D. K. S., Foo D. C. Y., Tan R. R., 2009, Extended Pinch Targeting Techniques for Carbon-Constrained Energy Sector Planning. Appl. Energy, 86, 60−67.

Liu J., Zhou Y., Zhu M., Deng C., Lee J.Y., 2019, Optimization of Refinery Hydrogen Network with Parametric Uncertainties. In Computer Aided Chemical Engineering, 47, 77-82.

Qin Z., Tang K., Yu Y., Zhang Z., 2018, Dual-objective chemical production planning by graphical-tabular Pinch Analysis for sustainable methanol industry in China. Journal of Cleaner Production, 186, 978-987.

Shukla G., Chaturvedi N.D., 2021a, Targeting compression energy in batch process. Cleaner Engineering and Technology, 5, 100315.

Shukla G., Chaturvedi, N.D., 2021b, A Goal Programming Approach for Optimizing Natural Gas Transportation Network. Chemical Engineering Transactions, 88, 361-366.

Tan R. R., Aziz M. K. A., Ng D. K. S., Foo D. C. Y., Lam H. L., 2016, Pinch Analysis-Based Approach to Industrial Safety Risk and Environmental Management. Clean Technol. Environ. Policy 18, 2107−2117

Yang M., Feng X., Chu, K. H., Liu G., 2014, Graphical method for identifying the optimal purification process of hydrogen systems. Energy, 73, 829-837.