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Extending Pinch Analysis to Address Forbidden Matches in Resource Allocation Networks

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This paper develops a Pinch Analysis based understanding of resource allocation networks (RANs) involving forbidden matches. Prior works on Pinch Analysis have ranged from a simple source-sink model to segregated demand zones, from continuous processes to batch processes, etc. However, RANs with forbidden matches are addressed mainly by mathematical optimization approaches. This paper extends the concept of Pinch Analysis to exploit the underlying structure of problems involving forbidden matches and provides some essential physical insights to these problems. A methodology is developed for minimizing resources in problems involving forbidden matches and identifying whether the obtained solution is optimal or not. The proposed methodology solves the overall problem by taking a demand at a time with the unutilized sources left after solving the previous demands. The methodology establishes that the optimality of the solution depends on the final left over sources and the distribution of pinch qualities obtained while solving each demand in a sequential manner. The applicability of the proposed methodology is demonstrated through an illustrative example of carbon constrained energy sector planning.

1. Introduction

Resource conservation and environmental protection are two predominant areas of concern for almost all the countries in the world. The governing bodies of different countries make different rules and regulations to combat these challenges. Recently, these rules and regulations have become more stringent towards waste disposal, particularly for industries, as they generate a considerable amount of pollutes and waste every year. Therefore, industries are making several attempts to minimize their waste disposal as well as resource consumption. One of the techniques adopted by industries for this purpose is Pinch Analysis.

Pinch Analysis, a technique of Process Integration, is widely used for resource conservation in many RANs. It was originally developed for energy integration in heat exchanger networks (HEN) (Linnhoff et al., 1982) and extended later for resource conservation in water networks (Wang and Smith, 1994), hydrogen networks (Alves and Towler, 2002), Power Pinch Analysis (El Elmi et al., 2016), Pinch Analysis for safety and related financial management issues (Varbanov et al., 2016) and for many other industrial problems as described by Jain and Bandyopadhyay (2017). Pinch Analysis has also been extended to account for time dimension in conserving fresh water in source-sink problems involving batch processes (Gouws et al., 2010). It is also applied to problems consisting of multiple resources (Shenoy and Banyopadhyay, 2007). Many of these complexities are discussed in the handbook by Klemeš (2013).

Along with these complexities, in many industrial applications, allocation of some sources to certain sinks may be forbidden because of various reasons, such as corrosion and safety issues, operability and controllability issues, topological issues like the long distance between source and sink. In literature, such source-sink problems with forbidden matches were addressed mainly by using different mathematical programming approaches. Bagajewicz and Savelski (2001) proposed linear programming (LP) and mixed integer linear programming (MILP) formulations, based on transhipment model, for minimizing fresh water in water allocation problems. Similarly, Hul et al. (2007) also developed LP and MILP models for an operational plant, by using source-sink allocation approach for water network retrofit cases. The authors of both the papers have shown with the help of examples, that their models were robust enough to address forbidden matches. Chen et al. (2008) introduced forbidden matches in batch processes and developed the concept of fictitious contaminants

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to solve such problems. The introduction of fictitious contaminants converted the single contaminant problem to a multi-contaminant problem. The resultant non-linear programming (NLP) problem was then solved using the mathematical model developed in the study. The advantage of the model is that it was able to address forbidden matches in a multiple contaminant batch problem. However, all the above-mentioned studies use the mathematical programming approach for dealing with forbidden matches but fail to provide the Pinch Analysis based physical insight to the problem. In another development, Chen and Lee (2008) introduced a graphical representation, based on the principles of necessary conditions of optimality (Savelski and Bagajewicz, 2008) and nearest neighbour algorithm (Prakash and Shenoy, 2005), for designing water-using networks in batch processes. The authors additionally addressed forbidden matches through this graphical representation with the help of an example in the paper. However, it did not provide a detailed physical or analytical understanding of the effect of forbidden matches on a generalised RAN.

This paper extends the application of Pinch Analysis to source-sink problems involving forbidden matches. It aims to develop the physical understanding of RANs with forbidden matches through the analysis of the overall waste generation and the qualities of different Pinch points. A methodology is proposed for minimizing the resource requirement for such problems by using Pinch Analysis and identifying whether the obtained solution is optimal or not optimal. The applicability of the proposed methodology is demonstrated through an illustrative example of carbon constrained energy sector planning.

2. Problem statement and mathematical formulation

A resource allocation problem involving forbidden matches consists of a set of sources called internal sources, a set of demands and an external source called resource. Each internal source is allowed to satisfy a certain number of demands and may be forbidden for other demands. The objective of the problem is to minimize the total resource requirement while taking into account the forbidden matches between different sources and demands.

The problem is mathematically stated as follows:

- A set of N_s internal sources is given. Each source i *(1, 2, ..., N_s)* produces a flow F_{si} at a given quality q_{si}.
- A set of N_d demands is given. Each demand j *(1, 2, ..., N_d)* accepts a flow F_{dj} at a maximum allowable quality of q_{dj}.
- A $N_s \times N_d$ matrix of forbidden matches between different sources and demands is given. Each entry (a_{ij}) of that matrix either takes the value 0 or 1; 0 represents a forbidden match between the i^{th} source and j^{th} demand whereas, 1 represents that the match between them is not forbidden.
- An external resource at quality q_r is given and it does not have any flow limitations.
- There also exists an external demand called waste. The overall unutilized flow from internal sources is thrown to waste. Without the imposition of any environmental norms, waste does not have any flow and quality limitations.
- The objective of the problem is to minimize the total resource requirement by taking into consideration all the forbidden matches.

Let f_{ij} be the flow transferred from internal source i to demand j. Let f_{iw} be the flow transferred from internal source i to the waste. Let f_{rj} be the flow transferred from resource to demand j. The flow balance for internal sources is given by equation 1. The flow and quality load balance for demands are given by equations 2 and 3.

$$\sum_{j=1}^{N_d} f_{ij} a_{ij} + f_{iw} = F_{si} \qquad \forall\, i \tag{1}$$

$$\sum_{i=1}^{N_s} f_{ij} a_{ij} + f_{rj} = F_{dj} \qquad \forall\, j \tag{2}$$

$$\sum_{i=1}^{N_s} f_{ij} a_{ij} q_{si} + f_{rj} q_r \leq F_{dj} q_{dj} \quad \forall\, j \tag{3}$$

The objective of the problem is to minimize the total resource requirement (R).

$$R = \sum_{j=1}^{N_d} f_{rj} \tag{4}$$

The objective function (equation 4) and the constraints (equations 1-3) are linear in nature. It is to be noted that equation 3 is also a linear equation as the values of a_{ij} are given in the forbidden match matrix. Hence, it is a linear programming problem and can be solved by any mathematical optimization technique. In the next section, this problem is physically analyzed and solved using the concepts of Pinch Analysis.

3. Analysis of the problem

Let the first demand (*j*=1) is targeted by using all the allowed internal sources and the resource. Let the quality of Pinch point, obtained for this demand, be q_{p1}. It is to be noted that since a single demand is considered at a time, the demand could lie in two possible regions, either in the below Pinch region or in the above Pinch region. If the demand lies in the below Pinch region, it completely utilizes the flow from the internal sources present in below Pinch region, partially utilizes the flow from the Pinch point and does not utilize any flow from the above Pinch region. Whereas if the demand lies in the above Pinch region, it completely utilizes the flow from the internal sources present in below Pinch region, partially utilizes the flow from above Pinch region and it may or may not utilize the flow from the Pinch point.

The unutilized flows from all the internal sources, left after targeting the first demand, are available for targeting the next demand. Similarly, next demand (*j*=2) is targeted by using the allowed internal sources and the resource. This procedure is repeated until all the demands are targeted and after targeting the last demand, all the unutilized flows are thrown to waste. It is similar to the targeting performed by Bandyopadhyay et al. (2010) for segregated targeting problems after adjusting for forbidden matches. After targeting all the demands in the sequential manner as described above, there are flows that remained unutilized to make up the waste. There are three cases to consider (Figure 1):

Case 1: The waste generated in the problem contains flow from internal sources which have qualities less than the Pinch quality of the last demand.

Case 2: The waste generated in the problem contains flow from the Pinch source of the last demand.

Case 3: The waste generated in the problem contains flow from internal sources which have qualities higher than the Pinch quality of the last demand.

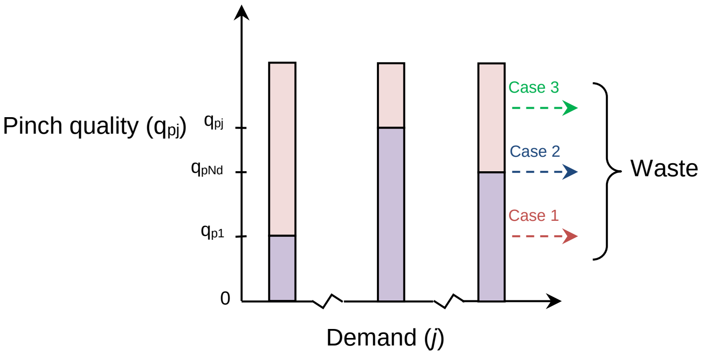

Figure 1: Representation of different cases to depict composition of waste.

In case 1, first consider the internal source, *i*, with the lowest quality (q_{si}) among all the internal sources that generate the waste. Since this internal source is generating the waste and its quality is less than the Pinch quality of the last demand, it implies that it is forbidden in the last demand. Apart from the trivial case of *i*th internal source being forbidden in all the demands, there are two possibilities for the location of this internal source with reference to different Pinch regions of other demands. The internal source is either the Pinch source for a demand or it may lie in the above Pinch region of the demand.

It is to be noted that the results obtained in the trivial case, of *i*th internal source being forbidden in all the demands, are optimal as the internal source does not have the potential to reduce the resource requirement any further. The resource requirement can only be reduced if it is possible to further utilize the flow from this internal source and in turn generating waste from some higher quality Pinch source (q_{pm}) than q_{si}. One of the cases in which it is possible is if the *i*th internal source lies in the above Pinch region of a demand such that it is not forbidden in that demand and the unutilized flow from the Pinch source (q_{pj}) of that demand is getting completely utilized in targeting the subsequent demands. In addition, an increase in flow from q_{pj} to subsequent demands leads to an increase in the waste generation from the Pinch source q_{pm}. Therefore, by utilizing flow from q_{si} in the demand with Pinch quality q_{pj}, more flow from q_{pj} is made available to the subsequent demands which in turn lead to the waste generation from q_{pm} (Figure 2). Since waste is generated from a higher quality Pinch source (q_{pm}) by utilizing the waste generated by a lower quality source (q_{si}), it leads to the reduction in the overall waste and hence also leads to the reduction in the resource requirement (Pillai and Bandyopadhyay, 2007). Therefore, the results obtained in this type of cases, where further reduction of resource is possible, may not be optimal. Other such cases which may not generate optimal results are not discussed in this paper due to page restrictions. However, the basic concept of resource reduction discussed earlier is followed for all such cases. The results obtained are optimal only if it is not possible to further utilize the flow from the *i*th internal source to generate waste from q_{pm}. This may happen because of different reasons, for example, due to the presence of certain forbidden matches or due to the non-existence of higher quality internal source than q_{si}.

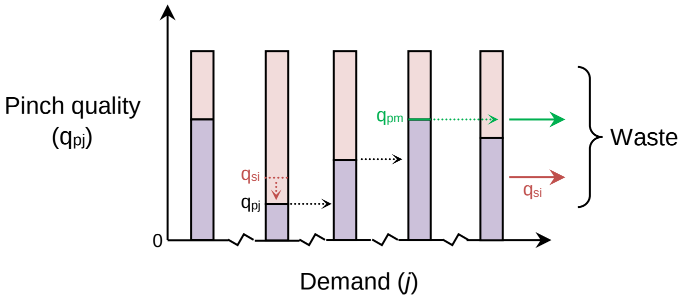

Figure 2: Representation of non-optimal distribution of internal sources for case 1.

Following this concept of identifying optimal and non-optimal solutions, all the remaining internal sources present in case 1, case 2, and case 3 are analyzed. The overall solution becomes optimal if the optimality is achieved in all the three cases.

The applicability of these results is demonstrated through an illustrative example from carbon constrained energy sector planning in the next section.

4. Illustrative example

This example serves to illustrate the Pinch Analysis based approach for RANs involving forbidden matches. The example is based on carbon constrained energy sector planning and the data for this example, given in Table 1, are adopted from Lee et al. (2009). It consists of four internal sources namely biodiesel, natural gas, oil, and coal. Two different demand sectors are considered, transportation sector and industrial sector, and each sector consists of three demands based on region (Lee et al., 2009). In recent years, the economy of transportation sector is shifting towards oil and petroleum products and there is a declining trend in the utilization of coal in transportation sector. Therefore, it is assumed that coal is forbidden to be used in transportation sector. Similarly, due to high production cost, Biodiesel is forbidden for industrial sector and in addition, only 250 PJ of biodiesel is available in total for transportation sector. These forbidden matches are depicted with the help of forbidden match matrix in Table 2. On the other hand, carbon-neutral energy source, hydropower (0 t/TJ) is considered as an external resource for both the sectors. In this example, energy supply and demand in TJ is considered as the flow and CO_2 emission factor in t/TJ is considered as the quality index. The objective of the problem is to minimize the usage the energy from hydropower while taking into consideration all the forbidden matches.

The methodology developed in the previous section is applied to achieve the desired objective. D1 is targeted first by using all allowable internal sources (S1, S2, and S3) (Table 2). The targeting is performed in this example by using source composite curve (Bandyopadhyay, 2006). After this targeting is performed, it is observed that S2 serves as the Pinch source for D1 and the energy required from external resource (hydropower) is 6.82 PJ. The unutilized energy from different internal sources left after targeting D1 is, 656.82 PJ from S2 and 1,000 PJ from S3. It is to be noted that S1 gets completely utilized in targeting D1. This unutilized energy is used for targeting the next demand, that is, D2. It is observed that S2 serves as the Pinch source for D2 and the energy required from hydropower to target D2 is 196.36 PJ. The unutilized energy left after targeting D2 is 133.18 PJ from S2 and 1,000 PJ from S3. This unutilized energy is then used to target D3. After targeting D3, it is observed that S3 serves as the Pinch source and 204.48 PJ of energy is required from hydropower. The unutilized energy left in S3 after targeting D3 is 617.67 PJ. It is to be noted that S2 gets completely utilized in targeting D3. Next, D4 is targeted by using S4 and the unutilized energy available from S3. It is observed that S4 serves as the Pinch source for D4 and the energy required from hydropower is 966.38 PJ. It is to be noted that S3 gets completely utilized in targeting D4 and the unutilized energy left in S4 is 4,984.05 PJ. Next, D5 is targeted by using this unutilized energy and after targeting, it observed that S4 serves as the Pinch source for D5 as well. The energy required from hydropower is 297.14 PJ and the unutilized energy left in S4 is 4,801.19 PJ. Finally, D6 is targeted by using the unutilized energy from S4. After targeting D6, it is observed that S4 serves as the Pinch source for D6 and the energy required from hydropower is 41.9 PJ. The unutilized energy left in S4 after targeting D6 is 4,763.1 PJ. Since D6 was the last demand to be targeted, the unutilized energy from S4 is thrown to waste. The total energy required from hydropower in the overall problem is calculated to be 1,713.1 PJ.

Table 1: Flow and quality data for the example

Si	Internal Sources	CO_2 emission factor in t/TJ	Energy in TJ
S1	Biodiesel	16.5	250,000
S2	Natural Gas	55	800,000
S3	Oil	75	1,000,000
S4	Coal	105	5,000,000
Dj	Demands		
	Transportation sector		
D1	T1	30	400,000
D2	T2	40	720,000
D3	T3	50	720,000
	Industrial sector		
D4	I1	30	1,600,000
D5	I2	40	480,000
D6	I3	50	80,000

Table 2: Forbidden match matrix for the example

	D1	D2	D3	D4	D5	D6
S1	1	1	1	0	0	0
S2	1	1	1	1	1	1
S3	1	1	1	1	1	1
S4	0	0	0	1	1	1

After targeting all the demands, the waste generated in the problem is analysed for further resource reduction (Figure 3). As seen from Figure 3 and observed earlier, 4,763.1 PJ of waste is generated from S4 and it is the only source from which waste is generated. S4 is the highest quality internal source among all the internal sources and waste is generated from the highest quality internal source in this problem. Therefore, there is no possibility of resource reduction as the waste generated from S4 cannot be further utilized to generate waste from some higher quality internal source than S4. Hence, the results obtained in this case are optimal and are verified by using GAMS 24.2.2 with the solver CONOPT3 (version 3.15N).

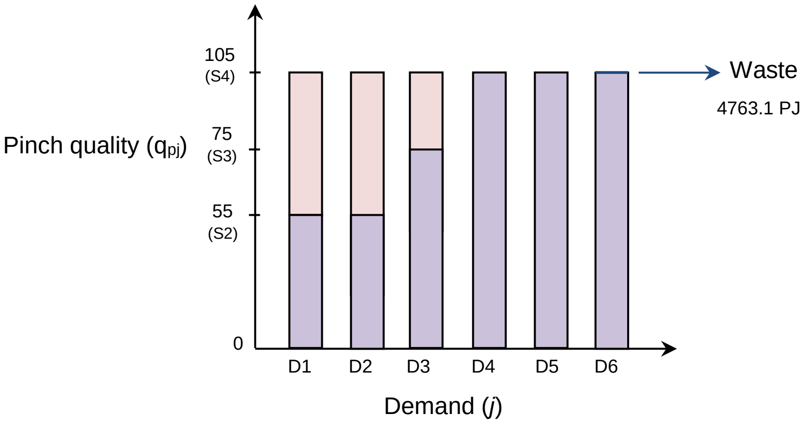

Figure 3: Analysis of constituents of waste for the example

5. Conclusions

This paper presents a novel Pinch Analysis based methodology which gathers the physical insights for RANs involving forbidden matches. The overall problem is solved sequentially by taking a demand at a time with the unutilized sources that are not forbidden for this demand and left after solving the previous demands. The optimality of the overall solution depends on the relative location of different Pinch points, obtained during sequential solution procedure, and the constituents of the overall waste. It is also shown that when the potentially useable flow from any of the internal sources is thrown to waste, the solution obtained might not be optimal. The significance of the physical insights developed in this paper is that they may broaden the applicability of Pinch Analysis to RANs involving different topological constraints, which were solved mainly by mathematical optimization approaches in the literature. The applicability of the proposed methodology is demonstrated with an illustrative example from carbon constrained energy sector planning. The future research is focused on developing a methodology to achieve optimality in non-optimum cases.

References

Alves J.J., Towler G.P., 2002, Analysis of refinery hydrogen distribution systems, Industrial and Engineering Chemistry Research, 41, 5759–5769.

Bagajewicz M., Savelski M., 2001, On the use of linear models for the design of water utilization systems in process plants with a single contaminant, Chemical Engineering Research and Design, 79, 600-610.

Bandyopadhyay S., 2006, Source composite curve for waste reduction, Chemical Engineering Journal, 125, 99-110.

Bandyopadhyay S., Sahu G.C., Foo D.C.Y., Tan R.R., 2010, Segregated targeting for multiple resource networks using decomposition algorithm, AIChE Journal, 56, 1235–1248.

Chen C.L., Chang C.Y., Lee J.Y., 2008, Continuous-time formulation for the synthesis of water-using networks in batch plants, Industrial and Engineering Chemistry Research, 47(20), 7818-7832.

Chen C.L., Lee J.Y., 2008, A graphical technique for the design of water-using networks in batch processes, Chemical Engineering Science, 63(14), 3740-3754.

El Elmi A., Er-rbib H., Bouallou C., 2016, Power-to-gas storage optimization through power pinch analysis, Chemical Engineering Transactions, 52, 1213-1218.

Gouws J.F., Majozi T., Foo D.C.Y., Chen C.L., Lee J.Y., 2010, Water minimization techniques for batch processes, Industrial and Engineering Chemistry Research, 49, 8877-8893.

Hul S., Ng D.K.S., Tan R.R., Chiang C.L., Foo D.C.Y., 2007, Crisp and fuzzy optimisation approaches for water network retrofit, Chemical Product and Process Modeling, DOI: 10.2202/1934-2659.1040.

Jain S., Bandyopadhyay S., 2017, Cost optimal segregated targeting problems with dedicated sources, Process Integration and Optimization for Sustainability, doi:10.1007/s41660-017-0028-8.

Klemeš J.J. (Ed), 2013, Handbook of Process Integration (PI): Minimisation of Energy and Water Use, Waste and Emissions, Woodhead Publishing Limited, Cambridge, UK.

Lee S.C., Ng D.K.S., Foo D.C.Y., Tan R.R., 2009, Extending pinch targeting techniques for carbon-constrained energy sector planning, Applied Energy, 86, 60-67.

Linnhoff B., Townsend D.W., Boland D., Hewitt G.F., Thomas B.E.A., Guy A.R., Marsland R.H., 1982, User guide on process integration for the efficient use of energy, The Institution of Chemical Engineers, Rugby, UK.

Pillai H.K., Bandyopadhyay S., 2007, A rigorous targeting algorithm for resource allocation networks, Chemical Engineering Science, 62, 6212-6221.

Prakash R., Shenoy U.V., 2005, Targeting and design of water networks for fixed flowrate and fixed contaminant load operations, Chemical Engineering Science, 60(1), 255-268.

Savelski M.J., Bagajewicz M.J., 2000, On the optimality conditions of water utilization systems in process plants with single contaminants, Chemical Engineering Science, 55(1), 5035-5048.

Shenoy U.V., Bandyopadhyay S., 2007, Targeting for multiple resources, Industrial and Engineering Chemistry Research, 46, 3698–3708.

Varbanov P.S., Klemeš J.J., Liu X., 2016, Process integration contribution to safety and related financial management issues, Chemical Engineering Transactions, 53, 241-246.

Wang Y.P., Smith R., 1994, Wastewater minimisation, Chemical Engineering Science, 49, 981–1006.