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# Pinch Analysis Approach for Segregated Targeting Networks with Forbidden Matches

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Conservation of different resources is an important prerequisite toward overall sustainable development. Pinch Analysis has evolved over the years to address resource conservations in various resource allocation networks (RANs). Segregated targeting problems are a special kind of structurally different, but mathematically challenging, RANs that consist of multiple sets of demands called zones and a set of common internal sources. These problems can be observed in interplant water integration networks, carbon-constrained energy sector planning, integrated iron and steel mill, etc. In the literature, these problems are addressed for resource optimality, cost optimality, and multiple objectives. Recently, these problems are also optimised for multiple objectives with the inclusion of external resources. In addition to the constraints inherited in the segregated targeting problems, allocation of some sources to specific demands may be forbidden in industrial practices due to corrosion and safety issues, operability and controllability issues, topological issues, etc. In literature, such source-sink problems with forbidden matches were addressed mainly by using different mathematical programming approaches. However, constrained segregated targeting problems are not addressed for the inclusion of forbidden matches to date. This work optimises such problems with forbidden matches using the Pinch Analysis approach and illustrated through an example from the water conservation network and a case study from carbon-constrained energy sector planning. It aims to exploit the physical structure of the problem through the analysis of the overall waste generation. The scope to generalise these problems for future perspectives is also discussed.

## 1. Introduction

Sustainable production, consumption, and regeneration of different resources are the most sought-after research topics worldwide in today's context of the climate crisis. Policymakers and stakeholders across the globe make efforts to conserve valuable resources for the current and future generations (IPCC, 2022). Fast-paced technological advancement in the domain of resource conversation, starting from extraction to regeneration of resources, is one of the reliable solutions in this aspect. Another solution that has been proved beneficial for different industries in resource conservation is the technique of Process Integration (PI). PI focuses on the unity of the process rather than optimising each process separately and, in turn, maximising the resource use efficiency of the industry. One of the main techniques of PI is the Pinch Analysis, developed in response to the oil crisis of the 1970s, first used for energy savings in heat exchanger networks (Linnhoff et al., 1982). The analogical similarity of heat exchanger networks (i.e., Temperature and Heat capacity flow rate) with mass exchanger networks (i.e., concentration and mass flow rate) leads to the expansion of Pinch Analysis applications to mass exchanger networks (El-Halwagi and Manousiouthakis, 1989). In the mass transfer domain, water conservation networks (Wang and Smith, 1994) and hydrogen networks (Alves and Towler, 2002) gained more research interest. The applicability of Pinch Analysis got a broader attraction in various domains, for example, aggregate production planning (Singhvi and Shenoy, 2002), material reuse via property integration (Kazantzi and El-Halwagi, 2005), targeting utility gas networks (Foo and Manan, 2006). Pinch Analysis is also

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extended for carbon-constrained energy sector planning (Tan and Foo, 2007), water scarcity Pinch Analysis considering the shortage of water quantity and insufficient water quality (Jia et al., 2020), selection of energy conservation projects (Roychaudhuri et al., 2017), optimizing regional electricity trading (Lopez et al., 2021), implementation of negative emission technologies (NETs) for sustainable energy planning (Nair et al., 2022), etc. All these applications account for single resource optimisation problems, and Pinch Analysis is also extended for optimisation in case of multiple qualities (Chin et al., 2021).

One of the different resource conservation problems where Pinch Analysis is applied is Segregated targeting problems. These problems consist of clusters of demands called zones. Each zone has a resource dedicated to meeting the requirements of the demands present in that zones. These problems were first discovered by Lee et al. (2009) for carbon-constrained energy sector planning. Later, they were addressed for resource conservation using Pinch Analysis tools by Bandyopadhyay et al. (2010), who developed a decomposition algorithm for the optimisation. Chandrayan and Bandyopadhyay (2014) introduced the economic aspect of these problems. These problems are also solved in the literature for resource minimisation with the inclusion of dedicated sources in each zone. Economic optimisation of these problems with dedicated sources was also addressed. For better and more informed decision-making, these problems were also optimised for multiple objectives. Common external resources were then introduced to these problems for further cost reduction (Jain and Bandyopadhyay, 2021), and the corresponding multiple objectives problem was also optimised (Jain et al., 2021). In all of these problems, there exist a set of internal sources which commonly supply flow to the demands of every zone. However, in many industrial cases, there exist certain restrictive or forbidden flows due to safety issues like corrosion or high transportation costs. In those cases, it becomes essential to consider them during the optimisation stage to avoid sub-optimal results. It is to note that only a few attempts were made to optimise the resource allocation network using the concepts of Pinch Analysis. Recently, Wang et al. (2021) extended the Pinch Analysis method to consider forbidden matches in heat exchanger networks.

This paper recognises the industrial need to optimise constraint resource conservation problems with various restrictions on flow allocation. In the existing literature, the solution procedure for optimising a segregated targeting problem with the inclusion of forbidden matches is not yet discussed so far. This paper addresses this research gap by optimising segregated targeting problems with forbidden matches using the Pinch Analysis approach. The hypothesis is developed using an illustrative example from a water conservation network and a case study from carbon-constrained energy sector planning. The prospects of future research are discussed in various sections of the manuscript.

## 2. Problem statement

A general two-zone segregated targeting problem incorporating forbidden matches is represented in Figure 1. It consists of two zones, each having a dedicated resource and a set of demands. The resource dedicated to a zone supplies flow to the demands of that zone only. For example, R1 supplies flow to meet the demands of zone 1 only and not to zone 2. Similarly, R2 supplies flow to meet the demands of zone 2 only and not to zone 1. A set of common internal sources is also given. The flow matching matrix is given in the problem, represented by the allowable flow in the figure using green lines. The non-allowable/forbidden flows are represented using dashed red lines. The unutilised flows from the internal sources are thrown to the external demand called waste. The objective of the problem is to minimise the overall resource requirement considering all the forbidden matches using the Pinch Analysis approach.

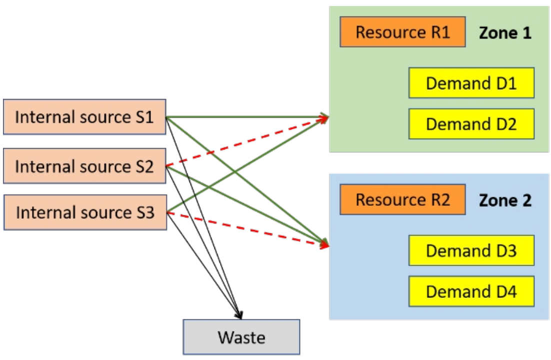


*Figure 1: Structural representation of the segregated targeting problem with forbidden matches*

## 3. Analysis of the problem

The segregated targeting problem with forbidden matches can be analysed considering three possible cases:

Case 1: Flow from an internal source is forbidden in some of the demands of a particular zone.
Case 2: Flow from an internal source is forbidden in all the demands of a particular zone.
Case 3: when both the cases (1 and 2) co-exist for different zones.
In all of these cases, the targeting is performed first for all the zones individually. A zone is selected arbitrarily and targeted using all the allowable internal sources and its dedicated resource. After this targeting is performed, the leftover internal sources are used to target the subsequent zones. The waste generated after targeting all the zones is analysed, and the possibility of further waste reduction is explored to minimise the overall resource requirement. This is represented using a flowchart in figure 2. In this study, the most simplistic case, that is case 2; where an internal source is forbidden in the entire zone, is presented and analysed in detail in the next section using an illustrative example and a case study from the domain of water conservation network and carbon-constrained energy sector planning. Detailed analysis and discussion of all the cases are beyond the scope of this paper and hence are the prospects for future research. It is observed from the analysis of the illustrative example and the case study that the sequential nature of targeting plays an important role in obtaining the optimal solution.

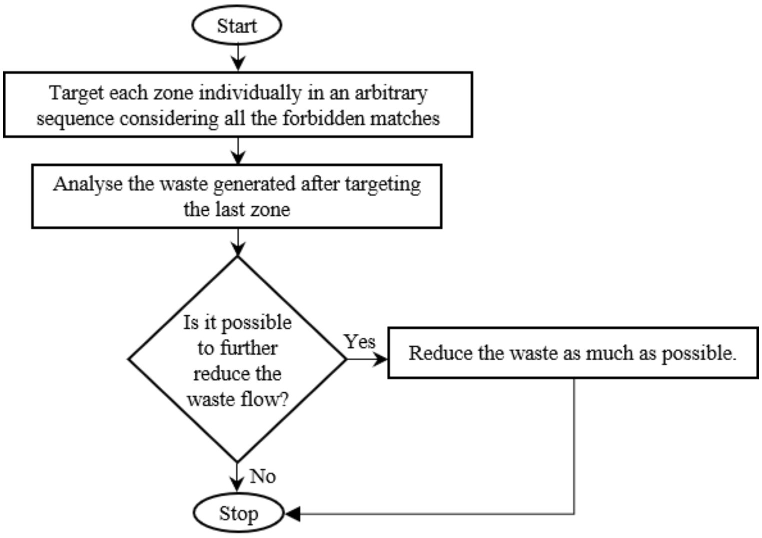


*Figure 2: Flowchart for addressing forbidden matches in a segregated targeting problem*

## 4. Illustrative example

The water conservation problem illustrated in this example consists of three water demand zones (zone 1, zone 2, and zone 3). Each zone has a dedicated resource (R1, R2, and R3) to meet the zonal demands (D1, D2, and D3). Three internal sources are also given to aid the flow requirements of all the demands. It is assumed that due to contaminant build-up from the flow transfer of internal source S2 to zone 2, this flow match is forbidden for the network. The matching  matrix is given in Table 2. The objective of the problem is to minimise the overall resource consumption, that is, from R1, R2, and R3, considering the forbidden match between S2 and zone 2.

*Table 1: Quality and flow data for the illustrative example*

| | Quality (ppm) | Flow (t/h) |
|---|---|---|
| Internal sources | | |
| S1 | 20 | 1,000 |
| S2 | 30 | 1,500 |
| S3 | 40 | 2,000 |
| Zone-1 | | |
| Resource (R1) | 12 | |
| Demand (D1) | 25 | 2,000 |
| Zone-2 | | |
| Resource (R2) | 10 | |
| Demand (D2) | 30 | 1,000 |
| Zone-3 | | |
| Resource (R3) | 5 | |
| Demand (D3) | 15 | 1,500 |

*Table 2: Matching matrix for the illustrative example*

| | D1 | D2 | D3 |
|---|---|---|---|
| S1 | 1 | 1 | 1 |
| S2 | 1 | 0 | 1 |
| S3 | 1 | 1 | 1 |

The first step towards achieving the minimum resource requirement is targeting the zones in a specified sequence. First, all the zones are targeted in the sequence suggested by Bandyopadhyay et al. (2010), that is, in the decreasing order of numerical value of the resource quality. In this case, zone-1 is targeted first, as it has the highest numerical value of resource quality (12 ppm), then zone-2 is targeted, and at last, zone-3. The zones can be targeted using any of the Pinch-based methods. In this work, the Source Composite Curves are adopted for targeting the zones.

While targeting zone 1, it is obtained that the entire flow from S1 gets utilised while only 1,000 t/h of flow is utilised from S2 to satisfy the demands. It is to note that the flow from R1 is not required to meet the demands of zone-1. After targeting zone-1, 500 t/h and 2,000 t/h of flows are left unutilised from the internal sources S2 and S3. These utilised flows are used for targeting the subsequent zones. However, as S2 is forbidden in zone-2, S2 cannot be used in zone-2. Zone-2 is targeted using S3 only. It is obtained that 333.3 t/h of flow is also required from R2. The remaining flows from the internal sources S2 (500 t/h) and S3 (1,333.3 t/h) are then used to target the demands of zone-3. The flows from S2 get entirely utilised in meeting the demands of zone-3, and an additional 928.6 t/h of flow is required from R3. The overall resource required is 1,261.9 t/h. The source composite curves of all the zones are shown in figure 3. In this case, the overall waste generated is also 1,261.9 t/h, and the waste is generated from the worst quality internal sources, S3. Since the waste is generated from the worst quality source, and it is analysed that it cannot be reduced further by any flow perturbations, the result obtained is optimum. This result is verified using mathematical optimisation techniques.

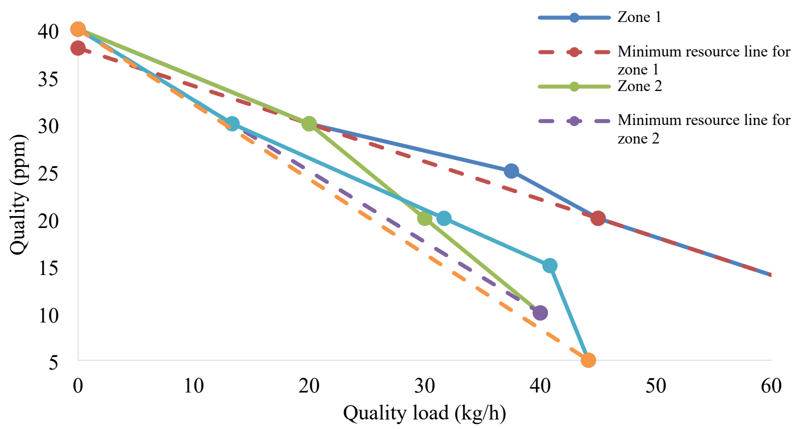


*Figure 3: Source composite curves for different zones of the illustrative example.*

It is interesting to note that in this illustrative example, the sequence [zone-1, zone-2, zone-3] is not the only sequence that gives the optimum solution. The problem is solved for all the 6 (i.e., 3!) possible sequences, and it is determined that the sequence [zone-1, zone-3, zone-2] also provides the optimal solution. However, rest of the four targeting sequences [zone-2, zone-1, zone-3], [zone-2, zone-3, zone-1], [zone-3, zone-1, zone-2], and [zone-3, zone-2, zone-1] produce sub-optimal solutions. Therefore, the strategy for determining the minimum resource requirement for segregated targeting problems with forbidden matches is sequence-dependent. It may be specific to this illustrative example that another sequence also produces the optimal solution, and may not be valid for other examples. The sequence-dependent indication observed in this example can be analysed analytically for a general segregated targeting problem in the future.

## 5. Case study

The case study discussed in this section is from the domain of carbon-constraint energy sector planning and is adopted from Lee et al. (2009). The data for the case study are tabulated in Table 3. It consists of two energy-consuming sectors: the transportation sector and industrial sector, three energy-providing internal sources: coal, oil, and natural gas. Each sector has its own low-carbon fuel, a resource for that sector. Biodiesel is considered a resource for the transportation sector, and hydropower is considered a resource for the industrial sector. With the advancement of technology in the transportation sector, coal powdered vehicles are shifted to oil-powered vehicles and even to more advanced technologies. That is why coal is considered forbidden for the transportation sector in this case study. The problem aims to minimise the usage of external resources (biodiesel and hydropower) by maximising the usage of internal sources (coal, oil, and natural gas) considering the limit on the carbon intensity of demands and accounting for the forbidden use of coal for transportation.

*Table 3: Quality and flow data for the case study*

| | Quality (t/TJ) | Flow (MJ) |
|---|---|---|
| Internal sources | | |
| Coal | 105 | 5 |
| Oil | 75 | 1 |
| Natural Gas | 55 | 0.8 |
| Transportation sector | | |
| Resource (Biodiesel) | 16.5 | |
| Demands | | |
| D1 | 30 | 0.4 |
| D2 | 40 | 0.72 |
| D3 | 50 | 0.72 |
| Industrial sector | | |
| Resource (Hydropower) | 0 | |
| Demands | | |
| D4 | 30 | 1.6 |
| D5 | 40 | 0.48 |
| D6 | 50 | 0.08 |

To achieve the overall minimum resource requirement, sectors are targeted sequentially based on the sequence suggested by Bandyopadhyay et al. (2010) and the transportation sector with the highest numerical resource quality value (biodiesel, 16.5 t/TJ) is targeted first. It is to note that the targeting is performed considering the forbidden match associated with the sector. It is determined that the entire energy from natural gas (0.8 MJ) is utilised, and 0.27 MJ of energy is used up from oil to meet the demands of the transportation sector. The energy required from biodiesel is 0.77 MJ. The unutilised energy (0.73 MJ) from oil is used to target the industrial sector along with the energy from coal. While targeting the industrial sector, it is observed that the energy from oil gets exhausted, and 4.85 MJ of energy is left unutilised from coal. The energy consumption from hydropower is 1.27 MJ. The total energy required from the resources is 2.04 MJ. It is to note that coal is the only internal source from which energy is not completely utilised. It means that the waste is generated from the lowest quality internal source, and it is analysed that it cannot be utilised further to reduce the overall resource requirement. Hence, it is concluded that the solution obtained is optimal. It is also verified using independent numerical optimisation techniques.

The problem is also solved for the alternative sequence, that is, [industrial sector, transportation sector] to analyse the dependency of optimal solution on the targeting sequence. It is interesting to note that the alternative sequence results in a sub-optimal solution. Thus, proving the need for future research focused on analysing the dependency of optimal solutions on the targeting sequence.

## 6. Conclusions

A segregated targeting problem, which is a different kind of source-sink problem, divided by the set of demands is considered in this paper, including forbidden matches. The sets of demands in the segregated targeting problems are called zones, and the occurrence of forbidden matches becomes inevitable in a process industry that consists of multiple functional zones. This paper investigates the solution strategy for segregated targeting problems considering forbidden matches. The methodology discussed in this work involves analyzing the waste generated from the internal sources after targeting is performed. Intriguing results are observed in the illustrative example of a water allocation network where 1,261.9 t/h of waste is generated from the worst quality internal source (S3; 40 ppm), and it is impossible to reduce this waste further. It is to note that this optimum result is obtained by targeting the zones in the particular sequence of resource quality. It has been shown in this paper that on changing the targeting sequence, the solution may become sub-optimal. In the case of carbon-constrained energy sector planning, 4.85 MJ of waste is generated from the worst quality internal source (Coal; 105 t/TJ), and the reduction of waste is not possible without increasing the overall resource requirement. After a rigorous analysis, it has been observed that the optimum resource requirement can be achieved by the sequential targeting of different zones using only the allowable flows. The sequence followed by the zones should be consistent with the sequence of dedicated resource quality. As discussed in the case study, an alternative sequence results in a sub-optimal solution. It may be noted that this conclusion is based on the analysis of the example and case study discussed in this paper and may not be applicable in a general context. Future research is focused on analysing the sequence targeting using rigorous analytical techniques to generalise the proposed method for including forbidden matches in constraint resource allocation problems.

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