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Optimising Segregated Resource Conservation Network with Cross-Zonal Transfer for Multiple Resources and Qualities

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Manufacturing industries are continually looking for resource conservation to achieve market competitiveness along with minimum waste discharge for environmental and societal responsibilities. Cooperation between industries to achieve resource sharing through reusing and recycling strategies play a vital role in optimising overall resource consumption, striving towards optimal industrial or urban symbiosis. This paper aims to apply the optimisation framework in a constrained source-sink network considering multiple zones. A special type of constrained resource conservation network, known as segregated targeting problem with dedicated sources and external resources, is considered. The problem contains a set of zones with their own sources and demands and a dedicated resource specified for individual zones. A set of internal sources, freely available for reuse, and external resources are shared among all the zones. In this work, multiple quality constraints that are restricting the allocation of the resources are considered. Unutilised dedicated sources from one zone are reused in other zones through different piping connections with a certain cost associated with it to maximise the utilisation of available sources. The objectives are to minimise the overall resource intake and the total cost for the whole network. This framework enables the selection of optimum zonal integration that yields the optimal cost or maximum resources recycling rate. The distinctive nature of zonal segregation, considering source sharing and multiple qualities, widens the scope of applicability of this approach. The method can be applied to various problem domains, such as regional material recovery networks, sector-wise energy planning, and financial planning.

1. Introduction

Resources recycling and conservation have become the main concern in various industries due to escalation in resources consumption and waste generation rates. The pressure to strengthen the recycling practice is further exerted as the Circular Economy concept is developed to focus on waste recycling, with waste as a secondary resource and recirculation of materials (EC, 2015). The industrial sectors play a critical role in improving resource use efficiency via resources and information sharing to strive toward the goal of waste reductions.

The concept of an eco-industrial park is defined as an area where various businesses cooperate with each other in an attempt to reduce resources use and waste pollution. Liao et al. (2007) presented a Pinch-based transhipment approach to target the minimum fresh material resource consumption in an industrial park, and the network design with a minimum number of cross-plant connections is determined via optimisation. Chew et al. (2009) considered a Pinch-based approach in proposing various schemes for cross-plant transfer. Chin et al. (2021a) extended the cross-plant source transfer schemes to material recycling problems with single quality, and Chin et al. (2021b) used this concept to design the headers/mains connections considering multiple qualities, based on the concept of sequential sink targeting with limiting contaminants (Chin et al., 2020). Alnouri et al. (2018) considered distributive and centralised resources management in an industrial park with water as resources with the aim of zero liquid discharge. Jiang et al. (2019) considered different material utilities (water) options in the industrial park along with waste treatment. Boysen et al. (2020) evaluated the economic and environmental impacts of an industrial park in Germany and suggested that water reuse is the most environmentally beneficial option. Dong et al. (2021) also assessed the grey water footprint in an industrial park

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in Changzhou, China. They found that the critical pollutants are phosphorus and nitrogen compounds. Both of the assessment results suggested that the resources recycling and reducing the pollutants discharged to the natural environment are still the key issues.

The concept of an eco-industrial park is well applicable to a special type of resource conservation problems, called segregated resource conservation network, consisting of multiple set of demands called zones. Each zone has its own dedicated resource and sources, and centralised common resources and internal sources which are available for all the zones. Lee et al. (2009) introduced this problem in the planning of the carbon-emissions constrained energy sector. Bandyopadhyay et al. (2010) proposed an algorithm to arrange the zones based on the Pinch principles and determine the optimal resource allocation for each zone. Extending the previous approach to consider economic feasibility, a prioritised cost concept to identify the sequence of the zones is developed by Chandrayan and Bandyopadhyay (2014). Considering the dedicated sources in segregated targeting problems that can be used only in particular zones, Jain and Bandyopadhyay (2017) introduced the Benefit Number concept based on Pinch Analysis principles to target the zones, and later Jain and Bandyopadhyay (2018) introduced the cost-based Benefit Number considering cost as the main criteria to determine the cost-effective resource allocation to the zones. Jain and Bandyopadhyay (2021) also introduced external resources to segregated targeting problems to exploit the potential of further cost reduction.

These concepts are beneficial for decision-makers to determine which zone should be prioritised to achieve minimum fresh resource requirement or minimum cost, but these strategies require considerably complex steps for execution. A time-efficient approach that can provide multiple solutions is needed for industrial practitioners. Process-graph (P-graph) studio (P-graph, 2021) provides a powerful open-source search with a graphical visualisation framework for a process network synthesis problem (Friedler et al., 1992a) and various other applications (Klemeš and Varbanov, 2015). The main algorithm: Maximal Structure Generation (MSG) generates the maximal structure of a given problem, and the Solution Structure Generation (SSG) (Friedler et al., 1992b) is used to generate all combinatorially feasible structures of the problem. The accelerated branch-and-bound (ABB) algorithm is then used to solve the problem based on the structures from the SSG outputs. These algorithms allow a more computationally efficient search of the solution space. Recent implementations of the P-graph tool involve Heat Exchanger Network synthesis (Orosz and Friedler, 2020), photovoltaic-based microgrid with energy storage (Mah et al., 2021), and material scheduling (Cao et al., 2020). The readers can refer to Klemeš and Varbanov (2015) that reviewed various applications of the framework.

Based on the literature review, the above-mentioned works on segregated resource conservation problems are mainly focused on the single quality and without considering cooperation between businesses/zones. The resource allocations can be limited by various quality constraints in practical scenarios, and the business collaboration can improve resource use efficiency. Segregating the industrial sites allows easier resource planning and allocation to the multiple businesses within a specific zone. The approach for solving the segregated resource conservation problem has not been solved with P-graph to date. This work aims to address the above-mentioned gaps in the segregating resource conservation problem by introducing the following novelties:

(a) Design of a segregated resource conservation network that is constrained by multiple qualities.
(b) Cross-zonal source transfer via cooperation between businesses that is constrained by the interconnection cost.
(c) Adopting the P-graph framework to synthesis the segregated resource conservation network.

2. Problem statement

The resource conservation problem discussed in this work consists of N^z number of segregated zones, N^s number of internal sources, and N^{cr} number of common resources. Each segregated zone contains a set of N_k^d number of demands, a dedicated resource for that zone, and a set of N_k^{ds} number of dedicated sources. Each source and demand are characterised by multiple parameters; multiple qualities and flow. The resources (dedicated and common) further have a cost associated with their usage.

The demands of each zone are satisfied with their respective dedicated resource, dedicated sources, common resources, and internal sources. The dedicated sources are freely available to the demands of the zone in which they are present, and an interconnection cost is levied for the cross-zonal flow of dedicated sources. The problem is structurally represented in Figure 1. The aim of the problem is to minimise the overall cost of the network while satisfying the flow and quality load constraints of the demands using the P-graph approach. A case study of a cross-plant water integration network is utilised to demonstrate the applicability of the P-graph in optimising the constraint resource conservation network. The method for building the P-graph structure of the water conservation problem is adapted from Lim et al. (2017). The readers can refer to the mentioned work for more detailed information on the methodology.

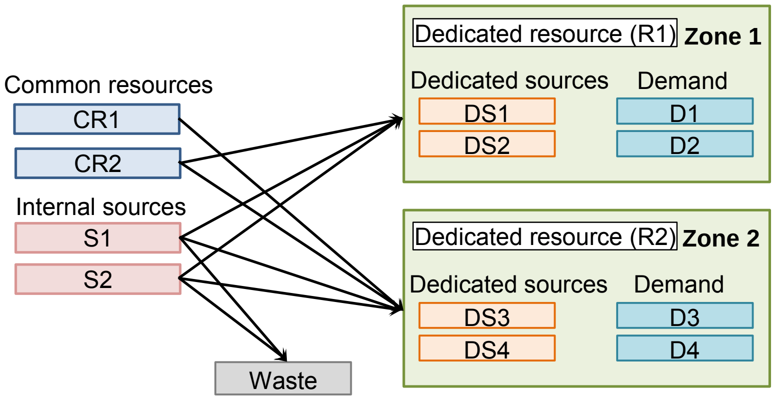

Figure 1: Structural representation of the constraint segregated resource conservation problem.

3. Case study

The case study of the cross-plant water integration network discussed in this work is adopted from Jain and Bandyopadhyay (2017) and presented in Table 1. The problem involves two zones (zone 1 and zone 2) that aim to conserve their water resources usage. Each zone has its own set of demands (D1, D2, and D3 for zone 1; D4, D5, D6, and D7 for zone 2), and some dedicated sources to recycle (DS1 for zone 1; DS2 and DS3 for zone 2). Each zone has its own dedicated resources (R1 for zone 1 and R2 for zone 2), which are only accessible by individual zones. Two internal sources (S1 and S2), which are also water sources to be recycled, are shared among two zones. The problem is modified to include common resources for both the zones and multiple qualities. Two common resources (CR1 and CR2) with their associated cost are added to the problem. In addition, costs of 0.4 $/t, 1 $/t, and 0.5 $/t are levied for cross zonal transfer of flow from DS1, DS2, and DS3.

Table 1: Quality, flow, and cost data for the case study.

	Contaminant Concentration (ppm)		Cost ($/t)	Flow (t/h)
	Contaminant a	Contaminant b		
Common resources				
CR1	12	20	4	100
CR2	15	30	2	100
Internal sources				
S1	50	70		50
S2	100	60		220
<u>Zone 1</u>				
Dedicated resource				
R1	0	5	10	
Dedicated sources				
DS1	800	300		50
Demands				
D1	0	10		20
D2	50	40		140
D3	400	200		10
<u>Zone 2</u>				
Dedicated resource				
R2	10	5	5	
Dedicated sources				
DS2	150	100		70
DS3	250	400		60
Demands				
D4	20	40		50
D5	50	30		100
D6	100	200		80
D7	200	350		70

The objective of the problem is to minimise the overall cost of the network using the P-graph framework. The maximal structure of the problem obtained through the P-graph is depicted in Figure 2, and one of the 84 feasible structures which generate the optimal solution is shown in Figure 3.

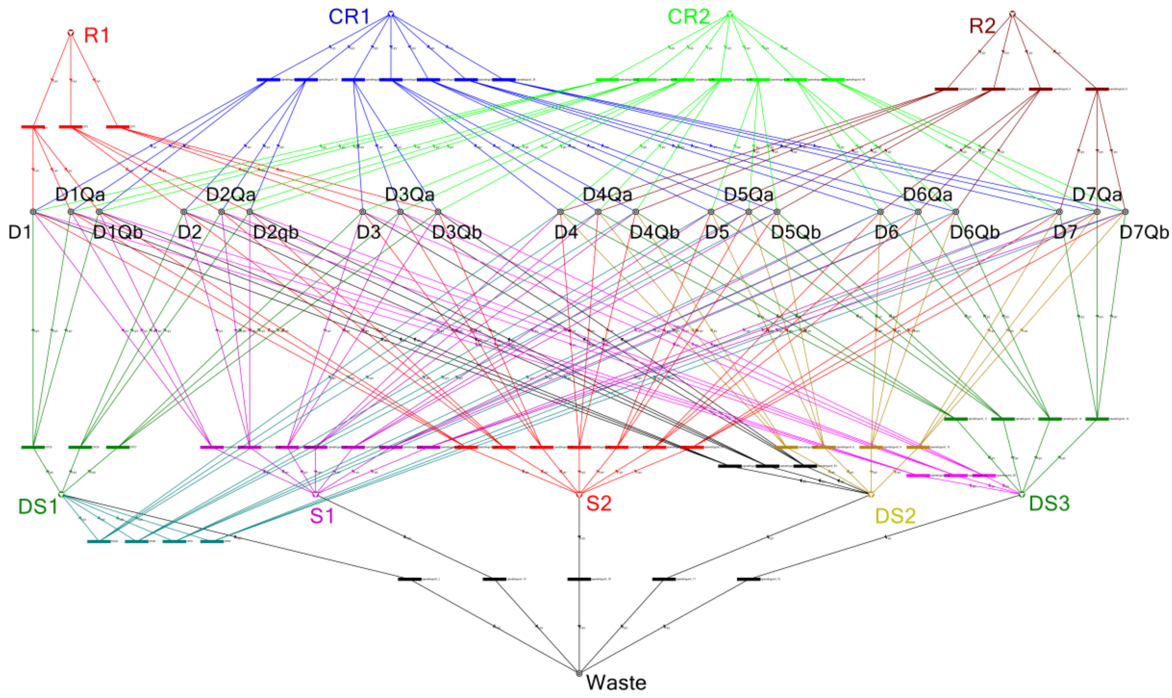

Figure 2: Maximal structure obtained through P-graph for the case study.

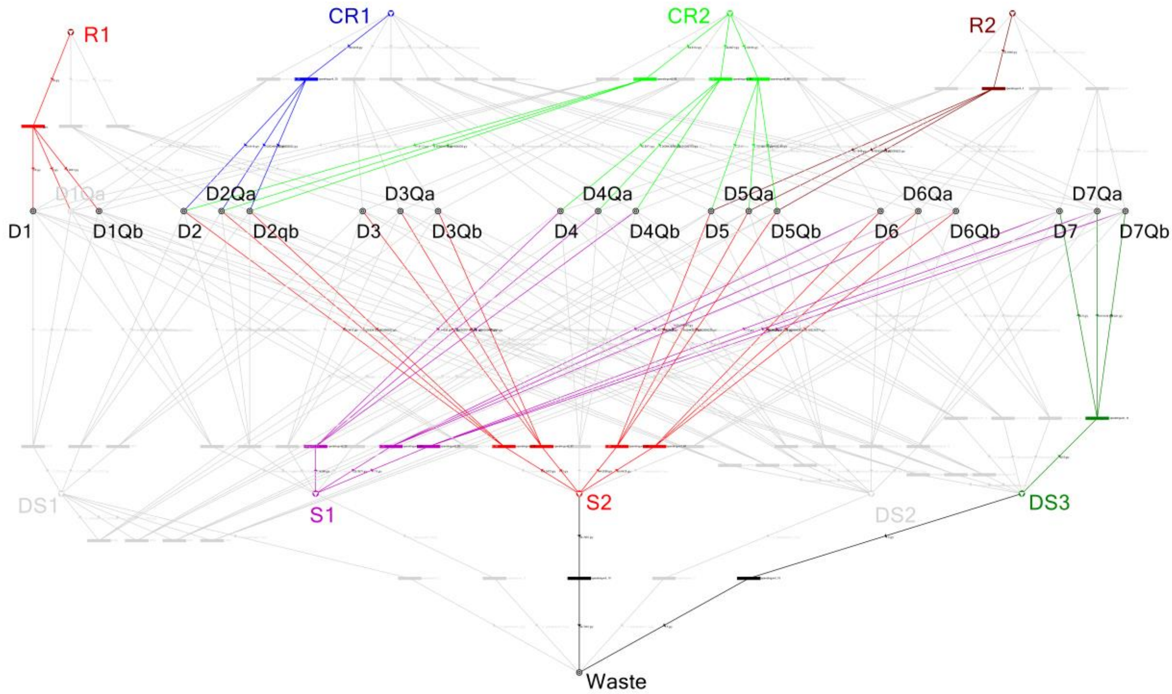

Figure 3: 1st Feasible structure obtained through P-graph for the case study.

The optimal solution of the case study, which minimises the overall cost, is obtained to be 781.99 $/h, and the total resources corresponding to this solution is 202.21 t/h (29.04 from CR1, 100 from CR2, 20 from R1, and 53.17 from R2). Using P-graph, n-best solutions can be obtained; some of the near-optimal solutions are listed in Table 2. It is to note that the cross-zonal transfer of flow from dedicated sources is not observed in any of the 85 feasible networks which generate the first-best solution.
The first solution presents the optimal cost, and it shows that the cross-zonal transfer is avoided to save the piping cost. It is also observed that the cross zonal flow slightly increases the overall cost to 782.32 $/h (the second-best solution). If the objective is to conserve the resources flow, the minimum resources flow achievable is 201.94 t/h, and different cost can be invested to build the network- see the solutions in 3rd, 9th, and 10th ranks in Table 2. In the 3rd solution, the network with optimum resources flow can be synthesised even without the cross-zonal transfer. This suggests that cross-zonal transfer is not encouraged and does not yield better resource conservation. However, this observation is dedicated to this case study only and does not apply in general. The results obtained using the P-graph approach are verified through mathematical optimisation, using the Excel solver.

Table 2: 10 best solutions of the case study obtained using P-graph.

N	Overall resources (t/h)	Overall cost ($/h)	Cross-zonal connection
1	202.21	781.99	No
2	202.21	782.32	Yes, DS3 to D3
3	201.94	782.54	No
4	202.57	782.71	No
5	202.79	782.76	No
6	202.21	782.88	Yes, DS3 to D3
7	202.37	783.08	Yes, DS3 to D3
8	202.79	783.09	Yes, DS3 to D3
9	201.94	783.10	Yes, DS3 to D3
10	201.94	783.61	Yes, DS3 to D3

4. Conclusions

The P-graph approach for constrained segregated resource conservation network is addressed in this paper. Different constraints like multiple qualities, incorporation of common resources and dedicated sources, and cost associated with the cross-zonal transfer of flow from dedicated sources are considered in the holistic framework. It is concluded that these constraints and complexities in the segregated targeting problem can easily be addressed by P-graph in optimising the overall resource or cost. The advantage of the P-graph in generating the near-optimal solutions is exploited in the case study to generate different solutions. The cross-zonal transfer of flow is observed in different N-best solutions. The framework is applied using an illustrative case study, where 85 feasible networks are obtained corresponding to the optimal solution. The minimum cost obtained is 782 $/h. The case study is limited to two qualities only, and more qualities can be included for a more realistic approach to the problem.

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