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Pinch-Based Synthesis of Plastics Recycling Networks

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Plastic pollution has recently emerged as a major global environmental problem, especially during the global pandemic. The problem spans land, ocean, and air pollution via macro-, micro-, and nanoplastics. Despite the availability of different technologies for recycling plastics under a Circular Economy, their deployment has been hampered by challenges stemming from socio-economic factors. For example, poor segregation of waste by consumers leads to cross-contamination of plastic streams that have recovery potential. Although the enhancement of Plastics Recycling Networks (PRNs) is clearly needed, little progress has been achieved worldwide. In this work, a new class of Process Integration (PI) approaches are developed for optimal planning of PRNs. These approaches draw on the proven capabilities of PI for effective decision support. The basic PRN synthesis problem is defined by a set of sources (waste plastic streams) and sinks (recycling plants) using a systems approach. All streams are assumed to consist of a mix of recyclable polymer and non-recyclable contaminants. Each recycling plant has a predefined processing capacity and upper limit on the contaminant level in its feed stream. Graphical Pinch Analysis (PA) is proposed for this PRN synthesis problem. A scenario-based case study where 95.5% of the available waste is recycled demonstrates its practical application. Prospects for future extensions of the PRN synthesis problem are also discussed.

1. Introduction

Plastic pollution is now considered an environmental issue serious enough to lead to calls for a global treaty (Nordic Council of Ministers, 2020). Macroplastics in waste pose bulk handling and disposal challenges, while smaller fragments (i.e., micro-and nanoplastics) may contaminate terrestrial and aquatic ecosystems (Wong et al., 2020) and cause air pollution (Prata, 2018). There is also growing concern about the risks they pose to human health (Prata et al., 2020). Entrenched waste management practices hinder efforts to implement workable recycling solutions (Carey, 2017); for example, open burning and manual waste picking are widely practised in developing countries (Velis, 2022). Because of the complex socio-economic dimensions of the plastic pollution problem, recent efforts to computing use tools such as Artificial Neural Networks (ANNs) (Fan et al., 2022) and Rough Set-based Machine Learning (RSML) (Gue et al., 2021) to find useful patterns in country-level data. The problem has also recently been exacerbated by responses to the COVID-19 pandemic, such as the increased use of protective apparel and packaging of consumer goods (Klemeš et al., 2020). Implementation of more sustainable production systems under a Circular Economy (CE) framework is hampered by the intertwined decision-making of producers and consumers (Grimes-Casey et al., 2007). However, it has been argued that consumer choices are limited by the options made available by manufacturers (Klemeš et al., 2021), giving the latter a dominant role in the interaction (Chiu et al., 2020).
The goal of zero plastic waste is comparable in scope to that of achieving carbon neutrality (Lau et al., 2020). There is a wide array of available technologies for recycling waste polymers derived from both fossil fuels and biomass to reduce plastic pollution (Aziz et al., 2020). Examples include incineration with energy recovery, thermochemical recycling, enzyme-based chemical recycling, and mechanical recycling (Dogu et al., 2021).

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Mismanagement is a major contributor to the global plastic pollution problem. It is estimated that the total volume of plastic waste can be reduced by 78% by 2040 using established technologies if only these options can be deployed optimally (Lau et al., 2020). Optimisation models have thus been proposed in recent literature to aid in managing plastic waste based on reverse supply chain concepts (Chaudhari et al., 2021). For example, Mohammadi et al. (2018) developed a Mixed Integer Linear Programming (MILP) model to optimise tactical and operational decisions in Municipal Solid Waste (MSW) networks; options for recycling the different (e.g., plastic, paper, and metal) fractions were considered. Castro-Amoedo et al. (2021) used MILP to determine cost-optimal networks for plastic waste management. Fan et al. (2020) developed a P-graph model to optimise handling of mixed MSW with substantial plastic content. Accorsi et al. (2020) developed a model to optimise closed-loop systems for food packaging. Shetty et al. (2022) developed a more generic model integrating forward and reverse supply chains to optimise plastic waste management within a CE framework.

Process Integration (PI) is a sub-area of chemical engineering which originally emerged in response to the need to increase the energy efficiency of industrial plants. The central methodology of Pinch Analysis (PA) used a set of procedures and algorithms with thermodynamic foundations for the synthesis of Heat Exchanger Networks (HENs) (Linnhoff et al., 1982). Approaches based on Mathematical Programming (MP) were initially developed as a separate branch of PI, but these alternatives have seen greater complementary use in recent years (Klemeš and Kravanja, 2013). Applications have also diversified beyond HEN synthesis, as documented in a handbook dedicated to PI (Klemeš, 2013) and a comprehensive survey of the field (Klemeš et al., 2018). Although PI was originally applied at the scale of individual plants and later to industrial clusters or Total Sites, the possibility of using these principles and tools to address sustainability issues in systems of grander scale has been discussed in the literature (Walmsley et al., 2019). An implication of the latter work is that PI can be used to improve the management of plastic waste, but there remains a research gap in the actual use of PA or MP methods for this purpose.

To address this research gap, a novel PI-based methodology is developed for the synthesis of Plastics Recycling Networks (PRNs), which is formulated as a special case of Resource Conservation Network (RCN) synthesis (Foo, 2012). A graphical solution approach is described based on the Material Recovery Pinch Diagram (MRPD) (El-Halwagi et al., 2003). This article is organized as follows. Section 2 gives a formal problem statement of the PRN synthesis. Section 3 describes the graphical MRPD approach. Section 4 presents a hypothetical but representative PRN synthesis case study. Section 5 gives the conclusions and discusses future research directions.

2. Problem statement

PRN synthesis is defined as a quality-constrained source-sink matching problem, where stream quality is quantified by purity (analogous to temperature in HEN synthesis). The concentration of the undesirable contaminant is taken as the inverse stream quality metric (i.e., lower values signify higher quality). The problem can be formally stated as follows. Given:

- A system concerned with the management of a single type of plastic waste;
- A contaminant that limits the processing (i.e., treatment or recycling) of the plastic waste;
- A set of sources of plastic waste, each with a known annual flowrate, S_i , and average contaminant level, q_i;
- A set of sinks for plastic waste (i.e., treatment or recycling facilities), each with fixed limits for both annual capacity, D_j , and feedstock contaminant level, c_j;
- A source of zero-contaminant plastic waste (i.e., sorting facility) that can supply a high quality stream F_j to each sink, but which is only used if needed due to its higher cost;
- A final sink with variable annual capacity, determined by the total unallocated plastic waste from each source i, W_i , and a high tolerance for contaminated plastic waste (e.g., landfilling or incineration), but which is considered only as an option of last resort.

The problem is to determine the allocation of plastic waste from the sources to sinks, r_{ij}, and the amount of zero-contaminant plastic needed by each sink, F_j, such that the required annual capacity of the final sink is minimised, and all flowrate and contaminant limits of the other sinks are met.

The superstructure for this problem is shown in Figure 1. Note that this problem is clearly a special case of the conventional RCN synthesis problem (Foo, 2012). The MRPD approach to solving this problem is discussed in the next section. However, it can also be solved using other equivalent graphical or algebraic PA methods (Bandyopadhyay, 2015). Potential alternative solution approaches to the PRN synthesis problem include MP (Prakash and Shenoy, 2005) and P-graph (Friedler et al., 2019) models.

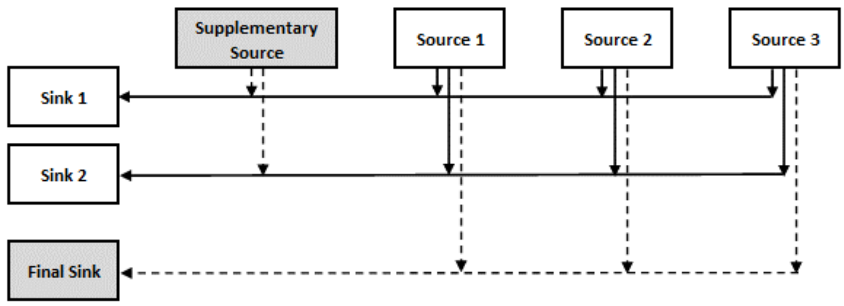


Figure 1: Superstructure for PRN synthesis problem

3. Solution approach

This section briefly describes the alternative PA approach for solving the PRN synthesis problem. The graphical MRPD approach was originally developed for the general RCN synthesis problem (El-Halwagi et al., 2003). The main steps are as follows.

(S1) List sources in order of increasing contaminant level.
(S2) List sinks in order of increasing contaminant limit.
(S3) Generate the Source Composite Curve by plotting the sources sequentially in rectangular coordinates, with annual flowrate as the horizontal axis and annual contaminant load (i.e., the product of annual flowrate and contaminant level) as the vertical axis.
(S4) Generate the Sink Composite Curve by plotting the sinks using the same procedure that was previously applied to the sources.
(S5) Inspect the relative positions of the Source and Sink Composite Curves; if the former is completely below the latter, then the initial orientation is already feasible and optimal.
(S6) If the initial orientation of the Composite Curves gives an infeasible solution, shift the Source Composite Curve horizontally to the right until it is completely below the Sink Composite Curve.
(S7) In the final orientation following the horizontal shifting of the Source Composite Curve, take note of three features. The Composite Curves would be tangent to each other at a Pinch Point, which divides the system into a high-quality region to its left, and a low-quality region to its right. Waste plastic allocation in each region can be determined independently of the other. Note that there may be Multiple Pinch Points for some problems.
(S8) There would be a gap on the left of the MRPD where the Sink Composite Curve overhangs without a corresponding section of the Source Composite Curve. The horizontal length of this overhang gives the deficit of high-quality waste plastic streams within this high-quality region in the system. It has to be supplemented by providing a contaminant-free plastic stream at higher cost from a waste segregation facility.
(S9) On the right side of the MRPD, the Source Composite Curve will extend beyond the Sink Composite Curve. The horizontal distance of this protrusion gives the surplus low-quality plastic waste in this low-quality region of the system. As none of the available sinks is suitable for this low-grade stream, all of it has to be handled using the final sink, which is the last resort waste management option (e.g., landfilling or incineration). The minimum required capacity of the latter is the optimal system target.
(S10) The detailed allocation of streams can be determined by inspection (Foo, 2012) or using the Nearest Neighbour Algorithm (NNA) (Prakash and Shenoy, 2005).

This graphical methodology is illustrated with a case study in the next section.

4. Case study

A hypothetical PRN synthesis case study is presented to illustrate the MRPD solution approach. In this example, the major component of the mixed plastic waste are polyolefins such as polyethylene (PE) and polypropylene (PP), which are suitable for incineration with energy recovery or thermochemical recycling (i.e., pyrolysis or gasification) due to their high calorific value (above 40 MJ/kg) and low oxygen content (below 3%). Thermochemical recycling of the waste PE and PP gives simple hydricarbons that can be used as monomer feedstocks or for other applications. It is assumed that a third type of plastic, polyethylene terephthalate (PET), is also present as a contaminant in significant amounts due to its extensive use for packaging applications. Because of its low calorific value (below 25 MJ/kg) and high oxygen content (above 30%), it can cause operating problems in energy recovery or thermochemical recycling plants when present at high levels (Dogu et al., 2021).

It is assumed that the recycling plants designed to handle PE and PP waste can tolerate some degree of contamination with PET provided it is not excessive. In addition, a high-quality waste stream is also available from a waste sorting facility but at a higher cost than the mixed waste streams.
Source and sink data are given in Table 1 and Table 2. These values are fictitious that are intended only to demonstrate the PRN synthesis problem. The total plastic waste flowrate from the sources is 110 kt/y, which apparently matches the combined capacity of three sinks – a pyrolysis plant, a gasification plant, and a waste-to-energy plant. All three sinks are intended to recover value from the waste streams through the production of organic chemicals (Sinks 1 and 2) and electricity (Sink 3). Disposal to the landfill is considered to be the final sink of last resort since it does not recover any value from the waste plastic. The problem is to synthesize the PRN network which optimally allocates waste streams from the four sources to the three sinks.

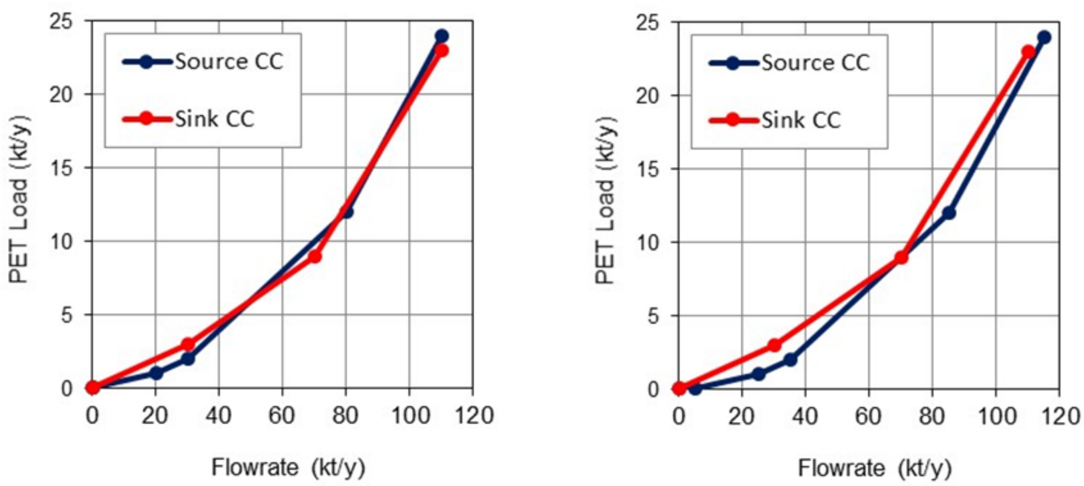
Table 1: Waste plastic sources

	Flowrate (kt/y)	PET content (%)	PET load (kt/y)
Source 1	20	5	1
Source 2	10	10	1
Source 3	50	20	10
Source 4	30	40	12

Table 2: Waste plastic sinks

	Description	Capacity (kt/y)	Limiting PET content (%)	Limiting PET load (kt/y)
Sink 1	Pyrolysis plant	30	10	3
Sink 2	Gasification plant	40	15	6
Sink 3	Waste-to-energy	40	35	14
Final Sink	Landfill	No limit	100	No limit

Applying the graphical MRPD approach first leads to an infeasible solution (using steps S1–S5) as shown in Figure 2a. Shifting the Source Composite Curve gives the optimal solution shown in Figure 2b (S6). The Pinch Point separates the system into a high-quality region, where Sinks 1 and 2 are present, and a low-quality region with only Sink 3 (S7). This solution gives a target requirement of 5 kt/y of pre-sorted, zero-contaminant plastic waste below the Pinch Point to make up for the lack of high-quality (low-PET) plastic waste for the pyrolysis and gasification plants (S8). It also gives a target of 5 kt/y of plastic waste needing to be landfilled (S9). Transfer of this zero-contaminant plastic waste above the Pinch Point for use in the waste-to-energy plant is forbidden. This result means that 105 kt/y of the waste plastic, or 95.5% of the total available amount, can be recycled directly by the three sinks.



(a) (b)

Figure 2: MRPD showing (a) initial infeasible solution and (b) optimal solution

The optimal allocation network can be determined by applying NNA (S10). Alternative allocation networks may also be possible. Procedures for determining alternative optimal are described in detail by Foo (2012). Two alternative networks that achieve the PA targets are shown in Tables 3 and 4. In each of these optimal PRNs, only one of the sinks below the Pinch Point is allocated zero-contaminant waste plastic from the sorting facility.

Table 3: Optimal source-sink allocation matrix (with flowrates in kt/y)

	Supplementary Source	Source 1	Source 2	Source 3	Source 4
Sink 1	0	13.33	10	6.67	0
Sink 2	5	6.67	0	28.33	0
Sink 3	0	0	0	15	25
Final Sink	0	0	0	0	5

Table 4: Alternative optimal source-sink allocation matrix (with flowrates in kt/y)

	Supplementary Source	Source 1	Source 2	Source 3	Source 4
Sink 1	0	20	0	10	0
Sink 2	5	0	10	25	0
Sink 3	0	0	0	15	25
Final Sink	0	0	0	0	5

5. Conclusions

A PI-based methodology for the synthesis of PRNs has been developed. The problem involves optimally matching plastic waste sources and sinks in a reverse supply chain network to effectively utilize available processing capacity while minimising disposal via low-value routes such as incineration or landfilling. The fraction of contaminants in the plastic waste streams is used as the quality metric that limits the use of specified recycling technologies. A graphical PA formulation has been demonstrated in a representative case study where 95.5% of the waste is recycled. This methodology provides a framework for the systematic planning of PRNs using time-tested PI principles. Such capability can contribute to the mitigation of plastic pollution by enabling the optimised deployment of available recycling options while minimising the amount of residual waste streams. In future work, an alternative MP formulation can be developed to account for case-specific features analogous to those found in other conventional PI applications. Examples include consideration of topological constraints (e.g., forbidden or mandatory source-sink matches) and additional system performance measures (e.g., cost, carbon footprint, robustness, or flexibility).

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