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Incorporating Uncertainties in Pinch Analysis

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Conservation of resources is a crucial prerequisite for sustainable developments. Pinch Analysis helps in conserving resources through efficient solution procedures in source-sink networks. Different approaches and applications of Pinch Analysis mainly consider exact parametric values. Parametric uncertainties in these networks result from variations in environmental and operating conditions and the deficiency in a comprehensive understanding of the process operations. This paper reviews recent developments in Pinch Analysis to incorporate probabilistic and epistemic uncertainties in synthesising reliable resource conservation networks.

1. Introduction

Incorporating fundamentals of thermodynamics, Pinch Analysis was initiated as a conceptual optimisation method for energy conservation in process industries (Linnhoff and Flower, 1978). Over the years, it was evolved to attain sustainable developments through the conservation of precious resources. Pinch Analysis helps in the design and optimisation of source-sink resource conservation networks, such as conservation of thermal energy through a network of heat exchangers (Linnhoff and Flower, 1978), conservation of mass separating agents in a network of mass exchangers (El-Halwagi and Manousiouthakis, 1989), conservation of freshwater in water reuse system (Wang and Smith, 1994), conservation of hydrogen in refinery hydrogen system (Alves and Towler, 2002), conservation of raw materials through material reuse (Kazantzi and El-Halwagi, 2005), etc. Klemeš (2013) summarised various applications of Pinch Analysis for conservations of resources such as energy and raw materials. Over the last decade, Pinch Analysis was further evolved as a holistic tool for sustainable development by conserving various other resources. Such diverse applications include industrial risk management (Tan et al., 2016), planning for resource subsidy (Bandyopadhyay and Desai, 2016), healthcare gap identification (Basu et al., 2017), identification and managing risks (Wang et al., 2017), reduction of fire-susceptibility in an urban area (Kumar et al., 2020), and water scarcity analysis (Jia et al., 2020).
The above-mentioned applications can be represented as a source-sink bipartite network (Figure 1). Pinch Analysis helps in conserving resources in such source-sink networks. While synthesising and optimising such a network through Pinch Analysis, the associated parameters in the underlying optimisation problem are considered exact.

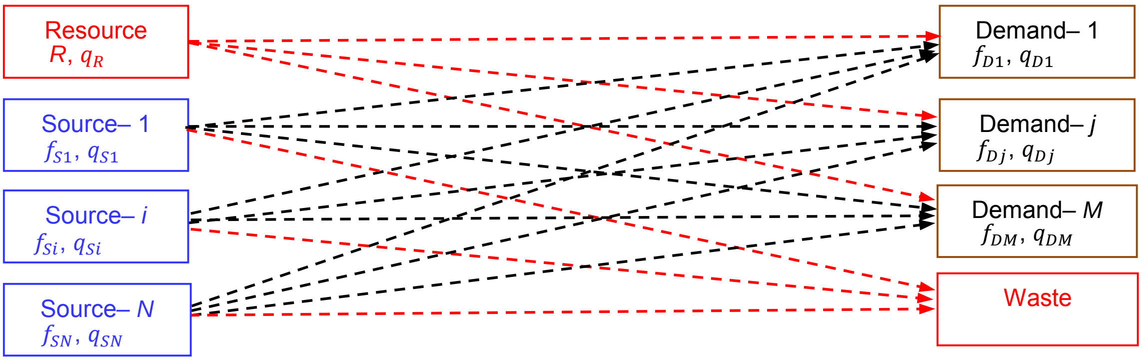

Figure 1: Schematic representation of a bipartite source-sink resource conservation network.

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Changes in operating (such as changes in feedstock or product demands) and environmental (such as ambient temperatures) conditions lead to uncertainties in design parameters. In addition to these, the deficiency in a comprehensive understanding of the processes involved leads to epistemic uncertainties. For practical applications of Pinch Analysis, it is imperative to account for uncertainties associate with these parameters and to synthesise a reliable source-sink network. This paper briefly reviews recent developments in Pinch Analysis to incorporate parametric variabilities and uncertainties for resource conservation.

2. Mathematical formulation

Pinch Analysis solves linear optimisation problems related to source-sink resource conservation networks via efficient algebraic algorithms in conjunction with graphical representations to enhance conceptual understanding. A set of *N* sources is available with the given flow (f_{Si}) and quality (q_{Si}). A set of *M* demands is available with the given flow (f_{Dj}) and maximum acceptable quality (q_{Dj}). In addition to these, a resource with a given quality (q_R) is provided. The overall resource requirement is minimised by transferring flows from sources to demand, satisfying the quality constraint. Representing f_{ij}, f_{iW}, and f_{Rj} as positive flow variables from the source (i) to demand (j), from source (i) to the waste, and from the resource to demand (j), the optimisation problem is expressed as (Bandyopadhyay, 2015):

$$\text{Minimise } R = \sum_j f_{Rj} \tag{1}$$

Satisfying the following constraints:

$$\sum_j f_{ij} + f_{iW} = f_{Si} \;\; \forall i \tag{2}$$

$$\sum_i f_{ij} + f_{Rj} = f_{Dj} \;\; \forall j \tag{3}$$

$$\sum_i f_{ij} q_{Si} + f_{Rj} q_R \le f_{Dj} q_{Dj} \;\; \forall j \tag{4}$$

This linear programming problem is solved efficiently by Pinch Analysis using various graphical and algebraic methods (Pillai and Bandyopadhyay, 2007). These methods include Resource Surplus Diagram (Hallale, 2002), Material Recovery Pinch Diagram (El-Halwagi et al., 2003), Cascade Analysis (Manan et al., 2004), Limiting Composite Curve (Agrawal and Shenoy, 2006), Source Composite Curve (Bandyopadhyay, 2006), and Composite Table Algorithm (Parand et al., 2013). These methods are structurally (Shenoy, 2011) and mathematically (Bandyopadhyay, 2015) equivalent.

2.1 Probabilistic uncertainties

Uncertainties caused by the randomness in environmental and operating conditions with known past data can be incorporated using probability theory. Applications of probabilistic uncertainties in source-sink networks were demonstrated in wastewater reuse network (Suh and Lee, 2002), heat exchanger network (Chen and Hung, 2005), water network (Tan et al., 2007), integrated water system (Karuppiah and Grossmann, 2008), isolated energy system (Norbu and Bandyopadhyay, 2017), site utility network (Sun et al., 2017), hydrogen supply network (Hwangbo et al., 2018), etc. In these papers, parametric uncertainties were accounted for through sensitivity analysis of the parameters, different scenario generations, Monte-Carlo simulations, or stochastic optimisation procedures. These procedures do not incorporate the conceptual framework of Pinch Analysis.

Parametric uncertainties in resource conservation networks can be combined with chance-constrained programming (Charnes and Cooper, 1956) to incorporate it in the overall framework of Pinch Analysis (Arya et al., 2018). Parametric uncertainties are represented employing probability distribution functions in this formulation. Parameters associated with the internal sources (streams) are modified with given means and standard deviations (μ_{Si}^{F} and μ_{Si}^{q} represent mean flows and qualities with standard deviations σ_{Si}^{F} and σ_{Si}^{q}). Resource quality is also represented with a mean μ_R^q and standard deviation σ_R^q. As the source parameters are uncertain, Eq(2) and Eq(4) need not always be satisfied. These constraints are modelled as probabilistic with specified reliability of α for the synthesised network. Eq(5) and Eq(6) represent the probabilistic satisfaction of the source flows and the demand quality requirement. The chance-constrained programming helps convert these probabilistic constraints to their deterministic equivalents (Arya et al., 2018).

$$Probability\left(\sum_j f_{ij} \le f_{Si}\right) \ge \alpha \;\; \forall i \tag{5}$$

$$Probability\left(\sum_i f_{ij}q_{Si} + f_{Rj}q_R \leq f_{Dj}q_{Dj}\right) \geq \alpha \ \forall j \tag{6}$$

For simplicity, all the uncertainties are presumed to be independent and to follow the Gaussian distribution. Deterministic equivalent constraints are written as:

$$\sum_j f_{ij} + f_{iW} = \mu_{Si}^F - z_\alpha \sigma_{Si}^F \ \forall i \tag{7}$$

$$\sum_i f_{ij}\mu_{Si}^q + f_{Rj}\mu_R^q + z_\alpha \sqrt{\sum_i f_{ij}^2(\sigma_{Si}^q)^2 + f_{Rj}^2(\sigma_R^q)^2} \leq f_{Dj}q_{Dj} \ \ \forall j \tag{8}$$

where z_α represents the inverse cumulative standard Gaussian normal distribution function for given reliability of α. Eq(2) has to be replaced by Eq(7) if only source flows are uncertain. Similarly, Eq(4) has to be replaced by Eq(8) if source and resource qualities are uncertain. Otherwise, both the equations are to be replaced. Note that Eq(8) is a non-linear equation, and it cannot be incorporated in the Pinch Analysis directly. Eq(8) can be replaced by a conservative linear approximation (Arya et al., 2018) to apply Pinch Analysis.

$$\sum_i f_{ij}\mu_{Si}^q + f_{Rj}\mu_R^q + z_\alpha \left(\sum_i f_{ij}\sigma_{Si}^q + f_{Rj}\sigma_R^q\right) \leq f_{Dj}q_{Dj} \ \ \forall j \tag{9}$$

The original constraints, Eq(2) and Eq(4), may be compared with the equivalent constraints, Eq(7) and Eq(9). Pinch Analysis can be used directly to solve source-sink problems with probabilistic uncertainties by replacing original source flows (f_{Si}) with modified source flows ($\mu_{Si}^F - z_\alpha\sigma_{Si}^F$), original source qualities (q_{Si}) with modified qualities ($\mu_{Si}^q + z_\alpha\sigma_{Si}^q$), and original resource quality (q_R) with modified resource quality ($\mu_R^q + z_\alpha\sigma_R^q$).

2.2 Epistemic uncertainties

Models for probabilistic uncertainties require knowledge about the parameters' past variations to determine the probability associated with them. Time-series data acquisition can be challenging and costly (Wenzel et al., 2002). Moreover, there are epistemic uncertainties due to a deficiency of proper understanding of the operations. Designers rely on guesswork or arbitrary safety factors (Bagajewicz, 2000). To quantitatively solve an optimisation problem with epistemic uncertainties, possibility theory-based approaches such as interval programming (Ben-Israel and Robers, 1970) or fuzzy programming (Zimmermann, 1978) may be adopted. In source-sink problems, fuzzy programming approaches are applied in water reuse network (Tan and Cruz, 2004), carbon sequestration (Tan et al., 2010), managing carbon capture and storage options (Tapia and Tan, 2014), resource conservation in eco-industrial parks (Kolluri et al., 2016), etc. Tan (2011) adopted a fuzzy non-linear programming approach to conserving freshwater in a source-sink network with interval numbers representing parametric uncertainties. Bandyopadhyay (2020) recently converted interval linear programming to interval Pinch Analysis and applied it to resource conservation networks.

Interval numbers help in representing epistemic uncertainties associated with flows and qualities. An interval number $[x^L, x^R]$ represents an interval of confidence with x^L and x^R representing the lower and the upper bounds. The underlying mathematical optimisation problems for source-sink resource conservation networks are modified to incorporate interval numbers. A set of *N* sources is given with interval flow $[f_{Si}^L, f_{Si}^R]$ and interval quality $[q_{Si}^L, q_{Si}^R]$. A set of *M* demands is available with interval flow $[f_{Dj}^L, f_{Dj}^R]$ and interval quality $[q_{Dj}^L, q_{Dj}^R]$. Note that the quality limits for the demands are usually estimated, and this is one of the primary sources of epistemic uncertainties. Resource quality is also assumed to be an interval number $[q_R^L, q_R^R]$. With an objective of resource minimisation (Eq1), constraints (Eq2-Eq4) are modified as follows:

$$\sum_j f_{ij} + f_{iW} = [f_{Si}^L, f_{Si}^R] \ \ \forall i \tag{10}$$

$$\sum_i f_{ij} + f_{Rj} = [f_{Dj}^L, f_{Dj}^R] \ \forall j \tag{11}$$

$$\sum_i f_{ij}[q_{Si}^L, q_{Si}^R] + f_{Rj}[q_R^L, q_R^R] \leq [f_{Dj}^L, f_{Dj}^R] \times [q_{Dj}^L, q_{Dj}^R] \ \forall j \tag{12}$$

Recently, Nehi et al. (2020) reviewed different methods to solve interval linear programming problems. One of the popular approaches is the best-worst solution approach (Shaocheng, 1994). For the resource minimisation problem, the best-case solution represents the lowest resource requirement with the largest possible feasible region, and the worst-case solution represents the highest resource requirement with the least possible feasible region. With appropriately chosen extreme values of different parameters, the best-case and the worst-case solutions are obtained for an interval linear programming problem involving only inequality constraints. For a general interval linear programming problem involving equality constraints, many intermediate optimisation problems have to be solved to establish these extreme solutions (Chinneck and Ramadan, 2000). Bandyopadhyay (2020) combined the conceptual insights of Pinch Analysis to ascertain the extreme values of different parameters to calculate the limiting solutions without multiple intermediate steps.

The best-case solution represents the absolute minimum resource requirement with total dissatisfaction of all the constraints. Conversely, with the maximum resource requirement and total fulfilment of the constraints, the worst-case solution represents the most conservative value. Typically, other than these extreme solutions, intermediate solutions may also be selected on the basis of the designer's risk-taking ability. To determine an intermediate solution, a degree of satisfaction $(\lambda | 0 \leq \lambda \leq 1)$ is defined with $\lambda = 0$ representing the best-case solution and $\lambda = 1$ representing the worst-case solution. For a given λ, the constraints of the optimisation problem are represented as (Bandyopadhyay, 2020):

$$\sum_j f_{ij} + f_{iW} = \lambda f_{Si}^L + (1-\lambda) f_{Si}^R \quad \forall i \tag{13}$$

$$\sum_i f_{ij} + f_{Rj} = \lambda f_{Dj}^R + (1-\lambda) f_{Dj}^L \quad \forall j \tag{14}$$

$$\sum_i f_{ij}\left(\lambda q_{Si}^R + (1-\lambda) q_{Si}^L\right) + f_{Rj}\left(\lambda q_R^R + (1-\lambda) q_R^L\right) \leq \left(\lambda f_{Dj}^R + (1-\lambda) f_{Dj}^L\right) \times \left(\lambda q_{Dj}^L + (1-\lambda) q_{Dj}^R\right) \quad \forall j \tag{15}$$

By comparing the original deterministic constraints, Eq(2) - Eq(4), with the equivalent constraints for a given degree of satisfaction, Eq(13) - Eq(15), modified parameters for interval Pinch Analysis can be identified: modified source flows as $(\lambda f_{Si}^L + (1-\lambda) f_{Si}^R)$, modified source qualities as $(\lambda q_{Si}^R + (1-\lambda) q_{Si}^L)$, modified demand flows as $(\lambda f_{Dj}^R + (1-\lambda) f_{Dj}^L)$, modified demand qualities as $(\lambda q_{Dj}^L + (1-\lambda) q_{Dj}^R)$, and modified resource quality as $(\lambda q_R^R + (1-\lambda) q_R^L)$. Pinch Analysis can be used directly to solve source-sink resource conservation problems with epistemic uncertainties for a given degree of satisfaction with these modified parameters.

3. Illustrative example

A demonstrative example highlighting freshwater conservation in process industry is considered in this section. Required data of this example are listed in Table 1. These data are taken from Polley and Polley (2000) with modified freshwater contaminant as ten ppm. Applying the Pinch Analysis technique, the minimum requirement of freshwater is targeted to be 75 t/h. Hypothetical uncertainty margins for the network parameters are assumed to illustrate the applicability of the discussed frameworks.

Table 1: Source and demand data for the freshwater conservation example.

Sources	Flow (t/h)	Quality (ppm)	Demands	Flow (t/h)	Quality (ppm)
S1	50	50	D1	50	20
S2	100	100	D2	100	50
S3	70	150	D3	80	100
S4	60	250	D4	70	200
Freshwater (resource)		10			

For probabilistic uncertainties, the values given in Table 1 are assumed to be mean values. The coefficient of variations (defined as the ratio of the standard deviation to the mean) is considered to be 10 %. For 50 % reliability, the target for the minimum freshwater requirement matches the deterministic value of 75 t/h. For 90 % and 95 % reliabilities, the minimum freshwater requirements increase to 95.5 t/h and 100.9 t/h. Source Composite Curves for 50 % and 90 % reliabilities are shown in Figure 2(a).

To demonstrate the applicability for epistemic uncertainties, demand parameters are assumed to be deterministic, and uncertainties are assumed to be with sources. For source quality, values given in Table 1 are considered to be the lower bounds, and the higher bounds are assumed to be 10 % more. For source flow, values given in Table 1 are considered to be the higher bounds, and the lower bounds are assumed to be 10 % less. For the best-case solution with $\lambda = 0$, the minimum requirement of freshwater is 75 t/h. For the total fulfilment of all the constraints (worst-case solution with $\lambda = 1$), the minimum freshwater requirement increases to 91.2 t/h (21.6 % increase). Limiting Composite Curves for $\lambda = 0$ and $\lambda = 1$ are shown in Figure 2(b).

For both cases, networks satisfying these targets are not shown for brevity. Using simple procedures of Pinch Analysis, multiple networks can be synthesised.

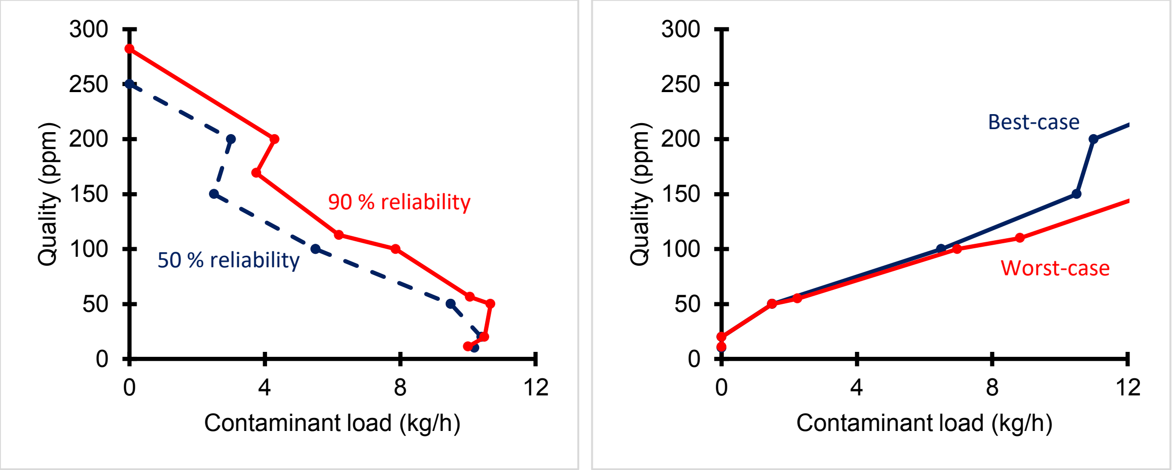

Figure 2: (a) Source Composite Curves for different reliabilities of the networks and (b) Limiting Composite Curves for different degrees of the fulfilment of the constraints.

4. Conclusions

Pinch Analysis has been applied to conserved resources in a source-sink network with precise parameters. It is of paramount interest to incorporate uncertainties associated with network parameters for synthesising a reliable resource conservation network. Depending on the availability of data and operations of different equipment/processes, parametric uncertainties can be modelled as probabilistic or epistemic. Recent developments in synthesising reliable source-sink resource conservation through Pinch Analysis are discussed briefly in this paper. Incorporation of these uncertainties is critical to synthesise structurally similar problems such as carbon management networks, carbon-constrained systems planning, etc. Future research includes improvement of the modelling approaches and integration of both types of uncertainties.

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