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Automated targeting for conventional and bilateral property-based resource conservation network

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ABSTRACT

Resource conservation is an effective way to reduce operation cost and to maintain business sustainability. Most previous works have been restricted to "chemo-centric" or concentration-based systems where the characterisation of the streams and constraints on the process sinks are described in terms of the concentration of pollutants. However, there are many applications in which stream quality is characterised by physical or chemical properties rather than pollutant concentration. In this work, the automated targeting approach originally developed for the synthesis of composition-based resource conservation network is extended for property-based network. In particular, targeting for the property-based networks with process modification and interception processes are addressed. Based on the concept of insight-based targeting approach, the automated targeting technique is formulated as a linear programming (LP) model for which the global optimum is guaranteed if a solution exists. In case(s) where process modification is involved, the automated targeting technique is formulated as a non-linear programming (NLP) model, in which is solved globally by commercial optimisation software. In addition, a new approach for the bilateral property integration problem is also presented in this work. Literature and industrial case studies are solved to illustrate the proposed approach.

1. Introduction

In the past decades, process industries have been focusing on conventional end-of-pipe waste treatment in order to comply with environmental legislation. However, recent trend shows that the industries are now diverging towards the reduction of the generated waste and the search for better alternatives in securing sustainable manufacturing processes. This is mainly due to the increase of public awareness towards environmental sustainability, the raise of manufacturing cost (i.e. raw material, utilities, end-of-pipe waste treatment, etc.) as well as the more stringent environmental legislation. One of the cost effective solutions in responding to the above needs is resource conservation activities where materials are reused/recycled within processes without adversely affecting the process performance. In this regard, process integration has been commonly accepted as an effective tool in evaluating various resource conservation alternatives.

El-Halwagi [1,2] defined process integration as *a holistic approach to process design, retrofitting and operation which emphasises the unity of the process*. In most cases, both fresh material consumption and waste generation are reduced simultaneously by carrying out resource conservation activities [1–4]. Over the past decade, extensive works have been reported for the synthesis of water and utility gas (mainly on hydrogen integration) networks as special cases of *mass integration*, ranging from both insight-based [5–30] and mathematical optimisation approaches [31–52].

The seminal work of insight-based approach for water network synthesis was proposed by Wang and Smith [5], focusing on mass-transfer processes (often known as the *fixed load problem*). The authors presented the limiting composite curve to locate the minimum water flowrates, i.e. fresh water consumption and wastewater generation, prior to detailed network design. Later, the proposed work was extended to cases where regeneration processes are used to purify process streams before they are further reused/recycled [6–8]. Later works in this area investigated the more generalised *fixed flowrate problem* where non-mass transfer processes are considered [9–24]. In addition, the early works in mathematical optimisation approaches for water network synthesis were reported by Takama et al. [31,32]. Later works on this

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technique may be broadly categorised as deterministic [33–44] and stochastic optimisation [45–49] approaches.

On the other hand, various insight-based targeting techniques were developed for utility gas network synthesis such as value composite curves [25], hydrogen surplus diagram [26,30], material recovery pinch diagram [12,29], limiting composite curves [16] and cascade analysis technique [27]. Besides, the use of mathematical optimisation approaches has also been reported for utility gas network synthesis [50–52].

It is worth mentioning that the combined use of both insight-based and mathematical optimisation techniques were also reported [53–56]. Among these, the automated targeting approach by Ng et al. [56] incorporates the targeting concept of insight-based technique into the mathematical optimisation model to locate the minimum flowrate/cost targets for a resource conservation network (RCN). The flexibility in changing the objective function is one of the advantages of the automated targeting approach over the conventional insight-based techniques. In addition, automated targeting still provides similar insights for process design that can be drawn from the insight-based techniques.

Notwithstanding the importance of mass integration, the previous proposed approaches are limited to address problems that characterise process streams in terms of pollutant concentration. However, design specifications are based on the satisfaction of stream property constraints in many cases [57–59]. For instance, the design and performance of a paper-making machine is based on the properties of reflectivity, opacity, or density; rather than the composition of paper [59]. In addition, effluent legislation is often defined in term of properties (e.g. pH, turbidity, toxicity, colour) apart from pollutant concentration (e.g. COD, suspended solids, etc.). In order to address design problems that are governed by functionalities and properties, the framework of *property integration* was introduced by El-Halwagi and co-workers [57–63]. El-Halwagi et al. [57] defined property integration as *a functionality-based, holistic approach to the allocation and manipulation of streams and processing units, which is based on the tracking, adjustment, assignment, and matching of functionalities throughout the process*.

Shelley and El-Halwagi [58] developed the concept of property-based clusters to enable the tracking of properties in a RCN. Later, El-Halwagi et al. [57] presented a visualised tool to design property-based RCN with three properties. Next, Kazantzi and El-Halwagi [59] presented graphical approaches to locate minimum resource consumption targets for a reuse/recycle scheme. Besides, process modification has been considered by Kazantzi and El-Halwagi [59]. Algebraic tools were later developed to locate rigorous targets for single [60] and multiple properties [61]. Recent works also reported the extension of the developed techniques to dynamic systems [62,63].

In this work, the automated targeting technique that was proposed for the synthesis of mass exchange network [1] and concentration-based RCN [56] is extended for locating the minimum flowrate/cost targets for a property-based RCN. Besides, process modification and pre-treatment system are explored; where the latter scenario has not been previously reported [57–63]. Another new variant of the *bilateral property integration problem* is also introduced in which the property operator values of the process sinks and sources exist in between the property operator values of external fresh resources. This concept is important whenever a nominal desired or targeted sink property operator value exists that is neither being the highest (superior) nor the lowest (inferior) to other operator values of the process sources and sinks, as in the conventional cases [59,60]. In other words, the situation is different from the conventional cases where one is simply trying to minimise the *single* fresh resource that has a property value that is either superior or inferior to other process sources and sinks. For instance, a sink may be characterised by pH with a nominal desired value of 7 (neutral); while the pH values of the process sources may be higher and lower than this desired value. Hence, sources with pH close to 7 are considered as high quality, while sources with pH far above or below 7 are regarded as poor quality.

2. Problem statement

The problem for a RCN with single property may be stated as follows:

Given a set of N_{sources} sources in a process. Each process source is process stream that may be considered for reuse/recycle or discharge. Each source has a flowrate, F_i and is characterised by a property p_i. Given also a set of N_{sinks} process sinks that are process units that can accept sources. Each sink requires a flowrate, F_j and an admissible inlet property, p_j from the source(s), which complies with the predetermined allowable property constraints as follows:

$$p_j^{\min} \le p_j \le p_j^{\max} \tag{1}$$

where $p_j^{\min}$ and $p_j^{\max}$ are the specified lower and upper bounds of the admissible properties to sink j. Besides, a set of N_{fresh} external fresh resources may be purchased to fulfil the requirement of the sink(s). In most cases, the property values of the fresh resources are either being superior or inferior to other property operators of the sinks and sources [59,60]. Hence, this can be considered as a *single-sided* property integration problem, as only fresh resource of either end of the property operator level is being minimised. In this work, a *dual-sided* case is introduced, where two high-quality fresh resources are to be minimised, and one of these exists at the highest property operator value, while the other exists at the lowest property operator level. This variant of problem is termed as *bilateral property integration*.

A general linearised property mixing rule is needed to define all possible mixing patterns among the individual properties. One such form of mixing rule takes the following expression [58]:

$$\psi(\bar{p}) = \sum_i x_i\, \psi(p_i) \tag{2}$$

where $\psi(p_i)$ and $\psi(\bar{p})$ are operators on source property p_i and mixture property $\bar{p}$, respectively; while x_i is the fractional contribution of stream i in the total mixture flowrate.

The objective of this work is to locate the minimum flowrate/cost targets for a property-based RCN prior to detailed design. Different scenarios are analysed. This includes direct material reuse/recycle, process modification, as well as the placement of interception and pre-treatment systems. Literature and industrial case studies are solved to illustrate the proposed approach.

3. Automated targeting approach

The automated targeting technique was originally developed by El-Halwagi [1] for mass exchanger network synthesis. Recently, Ng et al. [56] extended the approach for synthesis of composition-based RCN based on the concept of algebraic targeting technique of cascade analysis [13,17], with the removal of the dual-step procedure. It is worth noting that in all cascade analysis techniques, infeasible cascades with material flow balances are first generated to determine the largest material deficit, which is then added as fresh resource in the second step to remove all deficits and yield a feasible material cascade. Successful application is seen in water network [13,15,17,20,21,24], utility gas network [27] and