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A review on process integration techniques for carbon emissions and environmental footprint problems

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ABSTRACT

Sustainability has become a major focus for industrial sectors and government agencies in the global community. In particular, climate change is now seen as the most critical environmental problem of the world. Various techniques have thus been developed in the past decades to guide planners to reduce greenhouse gas emissions at various scales, ranging from plant-level combustion emissions to regional or national carbon footprints. Process integration techniques that were previously developed for energy, mass and property integration have now been extended to various emission and environmentally-constrained problems, taking into account footprint metrics that measure environmental impacts other than global warming. This paper discusses the historical evolution of the recently developed process integration techniques for various emission- and footprint-related problems, along with their contributions and limitations. Some recent applications for specific countries are also reviewed.

1. Introduction

It is well understood that human activities place significant stress on natural ecological systems. For example, climate change is widely regarded as the single most important environmental issue facing the world today (Rockström et al., 2009; Steffen et al., 2015). Emissions of greenhouse gases, such as carbon dioxide (CO_2) from industrial activities, or methane and nitrous oxide from agriculture are known to be major contributors to global warming. This increased climate consciousness has led to greater interest in the increased use of low-carbon energy technologies. These technologies include non-combustion sources with inherently low carbon footprints (e.g., renewable energy sources such as wind, solar or nuclear), as well as combustion-based ones with reduced carbon footprints due to upstream or downstream carbon sequestration. For example, in biomass systems, carbon fixation during photosynthesis offsets carbon emissions from burning biofuels; while in the case of fossil fuel-fired systems, *carbon capture and storage* (CCS) technologies can allow drastic reductions in carbon footprint to be achieved. All of these technologies present their own unique advantages and disadvantages, and thus there has been increased research as well on the development of various techniques to optimize the deployment of appropriate technologies in order to meet environmental goals, while simultaneously considering relevant technical and economic constraints. In addition to climate change, other impacts of significant note on a global scale include land use, water consumption and imbalance of nutrient (i.e., nitrogen and phosphorus) cycles (Rockström et al.,

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2009). Thus, methods have been proposed to measure impacts of man-made systems to support decision-making, using so-called "footprint" metrics. For example, De Benedetto and Klemeš (2009) proposed an approach making use of five footprint components; a more comprehensive review of important environmental footprints has also been published (Čuček et al., 2012).

In the process systems engineering (PSE) community, the development of *process integration* techniques has seen active progress in solving various emission reduction problems in the past half-decade. Process integration techniques are family of methodologies for combining operations within a process or several processes to reduce consumption of resources and/or harmful emissions (Klemeš, 2013). Two broad categories of process integration methodologies are *pinch analysis* and *mathematical optimization* techniques. The former were originally developed for the synthesis of *heat exchanger networks* (Hohmann, 1971; Linnhoff and Flower, 1978), which then became an important tool for energy conservation in process plants during the global oil shocks of the 1970s. Subsequently, the techniques were then extended for other *heat integration* applications, such as the appropriate placement of heat pumps, distillation columns, etc. which are now well documented in review papers (Gundersen and Naess, 1988; Linnhoff, 1993; Furman and Sahinidis, 2002), industrial handbooks (Klemeš et al., 2008; Klemeš, 2013) and various textbooks for specific topic on heat recovery systems (Linnhoff et al., 1982; Shenoy, 1995; Kemp, 2007) as well as for general chemical process design (Smith, 1995, 2016; Seider et al., 2003, 2009; Klemeš et al., 2010). These early applications focused on the largely economic implications of energy and fuel savings, but the enhanced energy efficiency also contributed significantly to carbon emission reduction of process plants as a secondary benefit, even before climate issues became an important design criterion. It is worth mentioning that one of the early extension of heat integration applications that included emission targets has been proposed for *total sites analysis*, where energy optimization was conducted for several plants that are serviced by centralized utility system (Dhole and Linnhoff, 1993; Linnhoff and Dhole, 1993); this early work was a significant forerunner of the many tools developed since, in terms of CO_2 emission reduction. Some extensions were reported for this area of work in recent years. For instance, Manesh et al. (2013) proposed an approach for planning cogeneration in total sites, while considering energy use, emissions, cost as well as emission taxes, while Al-Mayyahi et al. (2013) developed a graphical method for utility systems optimization.

Following the analogy of heat and mass transfer, synthesis of *mass exchange networks* (El-Halwagi and Manousiousthakis, 1989) was first developed in the late 1980s, and later extended for other associated *mass integration* problems (El-Halwagi, 1997, 2006; El-Halwagi, 2011). Specialized adaptations were subsequently developed for various *resource conservation networks* (RCNs) (Foo, 2012), covering *water minimisation* (Wang and Smith, 1994; El-Halwagi et al., 2003; Foo, 2009), *refinery hydrogen network* (Alves and Towler, 2002) and *property integration* (Kazantzi and El-Halwagi, 2005; El-Halwagi, 2006). The latter makes use of physical properties instead of composition to measure stream quality (Shelley and El-Halwagi, 2000). Even though the various techniques developed for RCNs aim to address material recovery problems for process plants, their underlying principles serve as a basis for recently-developed techniques for various emission and environmental-footprint problems.

In this paper, various process integration techniques that have been developed for emission and environmental-footprint problems are reviewed. Many of these developments arise from a seminal paper on *carbon emissions pinch analysis* (CEPA) by Tan and Foo (2007), which led to a series of innovations that are cited among the most significant contributions to process integration research in the early 21st Century (Friedler, 2010). It is significant to note that such analogous problem structures have led to the emergence of these non-conventional pinch analysis problem domains, as noted first by Shenoy (2011) and later in the context of sustainable energy planning by Tan and Foo (2013). Furthermore, Tan et al. (2015a) give brief review of diverse applications of pinch principles as well as a prospective view of emerging research areas. Meanwhile, the common mathematical structure underlying various pinch problems and methods has recently been discussed by Bandyopadhyay (2015). The topics covered in the recent literature include the following: carbon- and footprint-constrained energy planning, sustainable power generation with CCS, biomass production planning enterprise-level carbon and environmental footprint reduction, as well as off-grid renewable systems. Besides, applications of these techniques for specific planning problems in different countries are also reviewed. Note that since process integration methodologies are broadly classified into pinch analysis and mathematical optimization techniques, we review the developed approaches in each problem separately. In the case of mathematical programming approaches, we place specific emphasis only on models whose structures are based on pinch analysis analogues.

2. Carbon- and footprint-constrained energy planning

The formal problem for *carbon-constrained energy planning* via CEPA may be defined as follows (Tan and Foo, 2007):

- Given a set of energy demands (e.g. geographical regions or economic sectors), designated as $\text{DEMANDS} = \{j | j = 1, 2, \ldots, M\}$. Each demand requires energy consumption of D_j and at the same time, restricted to a maximum emission limit of $E_{D,j}$. Dividing the emission limit by the energy consumption yield the emission factor for each demand, $C_{D,j}$.
- Given a set of energy sources, designated as $\text{SOURCES} = \{i | i = 1, 2, \ldots, N\}$, to be allocated to energy demands. Each source (e.g. coal, oil, etc.) has an available energy of S_i and is characterized by a fixed emission factor, $C_{S,i}$. Product of the available energy and the emission factor gives the total emission of the source $E_{S,i}$.

The problem may be summarized as a source-demand representation, such as that shown in Fig. 1. The objective is to determine the minimum CO_2-neutral and/or low-carbon energy sources that fulfill the energy demand. Note that this representation is analogous to the RCN problems, where usage of a valuable external fresh resource(s) is minimized. This was generalized in Foo (2012). Both pinch analysis and mathematical optimization techniques developed for this problem will be described next.

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