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Process Integration and Climate Change: From Carbon Emissions Pinch Analysis to Carbon Management Networks

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Carbon Emissions Pinch Analysis (CEPA) is a branch of Process Integration (PI) that was developed as a systematic methodology for planning the optimal allocation of energy to various demands under carbon-constrained conditions. Since its inception in 2007, the body of CEPA literature has branched out into distinct areas. The first branch consists of direct applications of CEPA to specific geographic regions or nations, which includes early applications in Ireland and New Zealand, leading to more recent applications to parts of China and the United States. The second branch consists of methodological extensions of the original graphical CEPA procedure. These developments include algebraic and Mathematical Programming (MP) variants. The third branch of CEPA literature extends its principles to other measures of sustainability, such as various environmental footprints; recent attempts to allow the methodology to simultaneously handle multiple sustainability metrics have also been published. Finally, in the fourth branch, CEPA has also been extended to handle special problem structures such as segregated targeting for multiple geographic zones, or deployment of CO_2 capture and storage (CCS). Also included here are CEPA variants for carbon-constrained planning at different levels, ranging from enterprise scale, to supply chains and sector level (e.g., transportation or waste disposal), and finally to economy-wide analysis when integrated with established tools such as Input-Output Analysis (IOA). This paper discusses key developments in CEPA literature, with emphasis on the most recent developments (2016 to the present), as well as further prospects for the development of this PI sub-area.

1. Introduction

Climate change driven by man-made emissions of greenhouse gases (GHGs) such as CO_2 is now a major environmental issue. The level of CO_2 in the atmosphere is now above 400 ppm, and exceeds safe limits proposed based on pre-industrial benchmark levels; furthermore, this problem also has complex links to other sustainability issues such as water stress, land use and biodiversity loss (Rockström et al., 2009). Thus, there are efforts by the global scientific community to mitigate its impacts, and also to develop adaptation strategies. The field of Process Integration (PI) has the potential to make significant contributions to these efforts due to its emphasis on industrial efficiency, which results in reduced resource consumption and emissions release (Foo et al., 2017). The extent of both methodologies and applications of PI has expanded from the early narrow focus on heat recovery via Pinch Analysis (PA) (Klemeš et al., 2013). The most important international developments from the first four decades of PI are summarized in a handbook devoted to this topic (Klemeš, 2013). Many non-conventional applications of PI/PA have also been proposed (Tan et al., 2015). One important extension of PI/PA is its application to the problem of carbon-constrained energy planning via Carbon Emissions Pinch Analysis (CEPA), which was first developed by Tan and Foo (2007).
A review paper by Foo and Tan (2016) describe in detail the key developments in CEPA literature until the end of 2015. However, there have been subsequent developments from 2016 onward. Thus, this paper gives and updated survey of CEPA literature, with greater emphasis on the period not covered by the previous review. The rest of this paper is organized as follows. Section 2 gives a brief history of the development of CEPA.

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Section 3 then provides a bibliometric analysis of CEPA literature. Section 4 describes prospects for further research based on the most recent developments. Conclusions are then given in Section 5.

2. A brief history of CEPA

There are two main methodological predecessors of CEPA. First, the link between efficiency enhancement and reduction of air emissions was first considered in the context of optimizing Total Sites (TS) by Dhole and Linnhoff (1993). Second, Tahara et al. (2005) proposed a graphical methodology for benchmarking the carbon intensity of a specific firm relative to the industry average. These two works led to the key insight on the application of graphical targeting to allocate energy sources to energy demands, using carbon intensity as the quality index (Tan and Foo, 2007). It should be noted that the initial work dealt with the allocation of primary energy across multiple geographic regions that act as demands. The term CEPA was first proposed by Crilly and Zhelev (2008) in a paper applying the methodology to electricity generation in Ireland. Many of the developments related to CEPA that followed were first presented during the course of the past decade at PRES conferences (and subsequently published in special issues) along with other important PI innovations (Klemeš et al., 2017). Developments in modified CEPA methodology and their applications are described in the review paper of Foo and Tan (2016). Manan et al. (2017) further proposed to classify CO_2 management strategies into supply-side, demand-side and end-of-pipe categories. In addition, the extensions of CEPA to energy systems using different measures of sustainability are described in a handbook chapter (Tan and Foo, 2013). A brief tutorial is also given in a recent encyclopaedia chapter (Tan and Foo, 2017).

Notable developments in the CEPA literature fall under four main groups or branches. The first branch consists of energy planning applications in such countries as Ireland (Crilly and Zhelev, 2008), New Zealand (Atkins et al., 2010), India (Krishna Priya and Bandyopadhyay, 2013), the United States (Walmsey et al., 2015a), China (Jia et al., 2016), and the United Arab Emirates (Lim et al., 2018). The original CEPA paper dealt with primary energy allocation in three major geographic regions in the Philippines (Tan and Foo, 2007); this problem has recently been revisited based on economic sectors, in the context of analysing this country's intended nationally determined contribution (INDC) to the Paris Accord (Tan et al., 2018). The original analysis of New Zealand's electricity mix (Atkins et al., 2010) has recently been extended to 2050 (Walmsley et al., 2014). Another work gives an analysis of the country's transportation sector (Walmsley et al., 2015b).

The second branch of CEPA extensions are methodological extensions. As discussed by Bandyopadhyay (2015), different PA methods share a common mathematical basis, which allow them to solve problems of similar structure. The first CEPA variant was an algebraic procedure developed by Foo et al. (2008). An Automated Targeting Technique (ATT) was then proposed which formulated the targeting problem as a MP model (Lee et al., 2009). Furthermore, the equivalence of the basic CEPA problem to a conventional source-sink Linear Programming (LP) model was originally discussed by Tan and Foo (2007). While CEPA literature puts emphasis on targeting, the use of the Nearest Neighbour Algorithm (NNA) to determine energy allocation networks that meet carbon emissions targets was proposed by Shenoy (2010). A method for simultaneous targeting and network design was also developed by Francisco et al. (2014).

Extensions of CEPA methodology using alternative sustainability metrics have also been proposed, leading to an important branch of the literature. Many of these variants use footprint metrics, whose role in measuring sustainability are discussed extensively in a review paper by Čuček et al. (2012). For example, for bioenergy systems, CEPA variants using Land Footprint (LF) (Foo et al., 2008) and Water Footprint (WF) (Tan et al., 2009a) have been proposed. Other metrics that have been used include: Emergy transformity, which measures the amount of "solar energy memory" embedded in energy streams (Bandyopadhyay et al., 2010); inoperability, which measures risk of partial supply failure (Tan and Foo, 2013); Energy Return on Investment (EROI), which measures the total input-output energy ratio over the lifetime of an energy system (Walmsley et al., 2014); and risk to humans as measured via statistical fatalities (Jia et al., 2016). In addition, Tan and Foo (2013) discuss the fundamental similarity of PA-based energy planning using diverse energy quality metrics, as well as the equivalent LP formulation; the LP model is also able to handle multiple indices simultaneously, which PA cannot. There have been two recent attempts to address this gap in multiple-index capability in the CEPA literature. Jia et al. (2016) proposed a sequential approach that involves generating PA for each sustainability index. This method was applied to the problem of grid planning in China but is cumbersome to implement. A more elegant approach that uses the Analytic Hierarchy Process (AHP) to combine different sustainability metrics into a single composite quality index was developed by Patole et al. (2017).

CEPA was originally proposed to deal with highly simplified systems where the allocation of energy from sources to demands limited only by thermodynamic and carbon emissions constraints; the problem structure otherwise assumes full interchangeability. The original Philippine case involved the national-scale allocation of four major energy sources across three major geographic regions (Tan and Foo, 2007). Crilly and Zhelev (2008) first proposed to narrow down the problem scope to electricity generation in particular. This interpretation of CEPA has been used in many subsequent applications. In particular, the application of CEPA to planning the implementation of CO_2 capture and storage (CCS) was proposed by Tan et al. (2009b). Resulting developments in the area of CO_2 capture, utilization and storage (CCUS) are discussed in a recent review paper (Tapia et al., 2018). Another early extension was the assumption of distinct geographic zones which prevent full interchangeability of energy resources. This problem was solved via a segregated targeting algorithm (Lee et al., 2007), for which rigorous mathematical proof was then derived by Bandyopadhyay et al. (2010). CEPA methodology has also been applied at the scale of industrial plants, such as chlor-alkali (Tjan et al., 2010) and methanol processes (Qin et al., 2017), industrial parks (Jia et al., 2009), cities (Jia et al., 2018), and regional supply chains (Li et al., 2016). Applications to specific sectors such as transportation (Walmsley et al., 2015b) and solid waste management (Tan et al., 2015b) have also been developed. These developments indicate that the underlying principles of CEPA apply to systems at multiple scales. In addition, CEPA has also been combined with other methodologies such as P-graph and Monte Carlo simulation (Tan et al., 2017) and Input-Output Analysis (IOA) (Tan et al., 2018) to expand its capabilities.

3. Bibliometric analysis

According to the Scopus database, the original CEPA paper (Tan and Foo, 2007) has now been cited 170 times, of which 99 citations have come from 2014 to the present. These figures signify growing scientific interest in CEPA and its extensions. The largest numbers of these citing documents appear in the Journal of Cleaner Production (19), Chemical Engineering Transactions (18), Energy (17), Applied Energy (15) and Clean Technologies and Environmental Policy (14), while the rest are distributed over a wide range of journals, conferences and books. Indirect influence of the work can be further gauged by second-order citations. The 170 publications that cite Tan and Foo (2007) have themselves been cited a combined 2,969 times. The two-level citation network can be visualized as shown in Figure 1.

4. The future of CEPA: Carbon Management Networks

Tan et al. (2017) introduced the term Carbon Management Network (CMN) as a new class of PI networks in addition to well-established ones such as Heat Exchanger Networks (HENs), Resource Conservation Networks (RCNs), Chilled Water Networks (CWNs), etc. The original applications of CEPA dealt with CMNs where energy streams are characterized by their embedded Carbon Footprint (CF). More recent examples of CMNs deal with material streams with physical carbon content. The term CMN signifies a holistic approach that can account for both desirable and undesirable flows of carbon; specialized variants of the term, such as Fugitive Carbon Management Network (FCMN), may be used to describe specific types of carbon streams based on definitions proposed by McDonough (2016).

CCUS offers a framework for managing CO_2 by identifying opportunities for its profitable use and/or direct sequestration. Munir et al. (2012) first developed a graphical CEPA variant for allocating CO_2 streams from sources to sinks in an industrial park. They also proposed a Carbon Management Hierarchy (CMH) to facilitate systematic planning of GHG mitigation efforts. An algebraic cascade version of this methodology was then proposed by Manan et al. (2014). Pressure drop considerations also need to be accounted for in such CO_2 networks (Mohd Nawi et al., 2016). This concept of Carbon Integration (CI) in industrial parks was developed further using an MP-based approach by Al-Mohannadi and Linke, (2016). Al-Mohannadi et al. (2016) subsequently developed a multi-period extension to address progressive targets in emissions reduction. Hassiba et al. (2017) developed a combined approach for carbon and heat integration. Foo et al. (2016) also developed a related PI-based methodology for the optimal allocation of CO_2 in an oil and gas field for purposes of Enhanced Oil recovery (EOR).

A variant of CEPA methodology has been applied to the selection of Negative Emissions Technologies (NETs), which may need to be deployed at scale in the future to allow reductions in atmospheric CO_2 levels to be achieved (Foo, 2017). Biochar application to soil is one particular NET that has been considered in recent PI research. Such systems achieve negative emissions because plants remove CO_2 from the air via photosynthesis; when plant biomass is then carbonized and subsequently applied to soil, most of the fixed carbon is stored in chemically recalcitrant form. At the system level, the overall result is the net removal of carbon from the atmosphere and its transfer into the ground. Biochar-based CMNs offer the prospect of large-scale sequestration of solid carbon via soil application; such networks consist of biochar sources (i.e., pyrolysis or gasification plants) and land sinks, which can also be optimally matched using PI tools (Belmonte et al., 2017a). In addition to carbon sequestration, the other main consideration is to limit the amount of biochar-borne impurities (e.g., heavy metals or dioxins) that enter the receiving soil. MP models have been proposed using single-step (Tan, 2016) and two-step solution procedures (Belmonte et al., 2017b). A graphical PA approach to optimizing biochar-based CMNs has also been developed (Tan et al., 2017b).

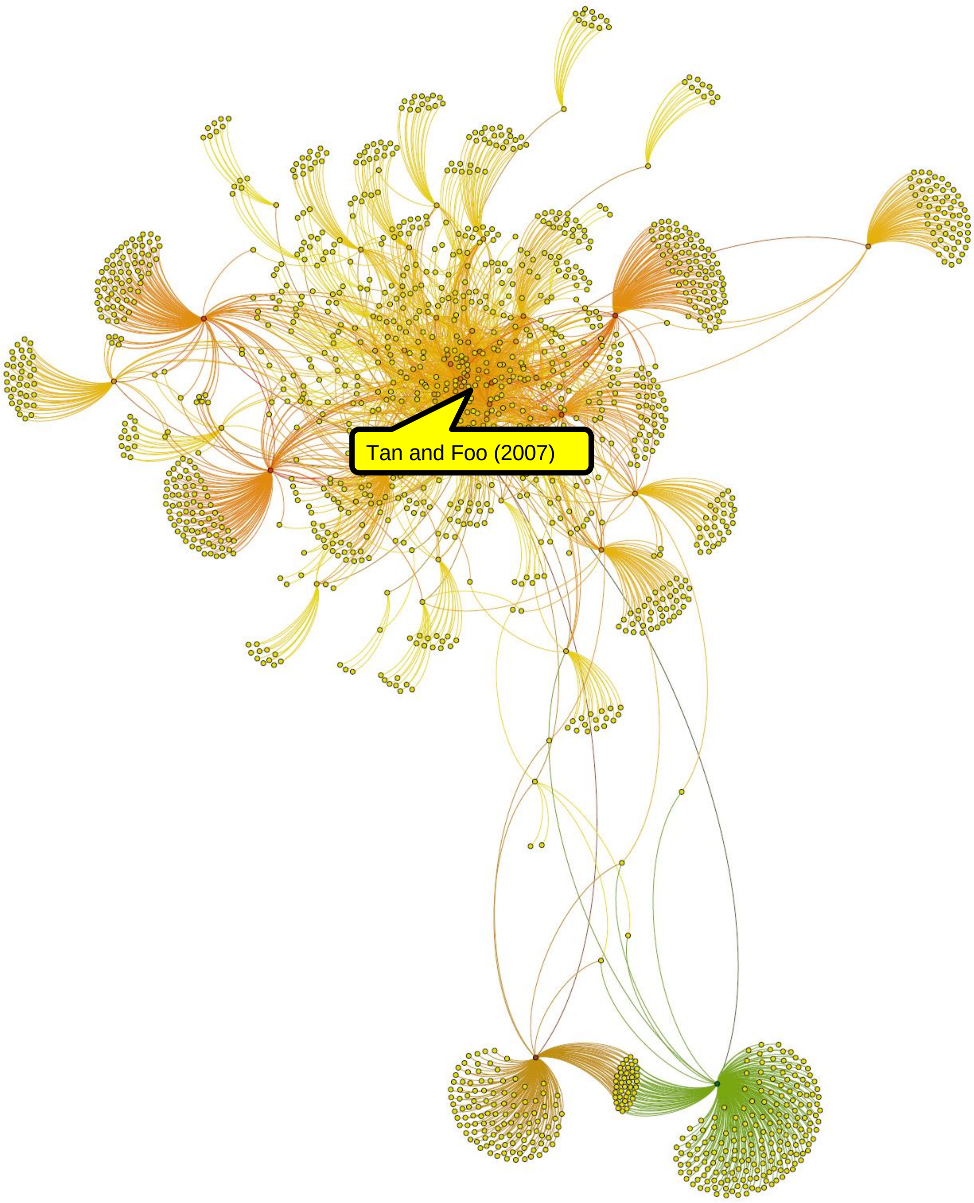

Figure 1: Visualization of two-level citation network of the seminal CEPA paper (Tan and Foo, 2007)

5. Conclusions

CEPA has emerged as important branch of PI for problems involving the management of GHG emissions. This method and its extensions present a set of useful PI tools for climate change mitigation measures and can be applied to systems of different scales and complexity levels. The methodology is also flexible and capable of being integrated with other tools to provide effective decision support. More than one decade after the initial CEPA paper was published, the CMN concept brings further prospects for the application of this PI tool to a broad range of practical problems, taking into account both desirable and undesirable carbon flows.

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