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P-Graph Approach to Planning Biochar-Based Carbon Management Networks

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Biochar application to soil is a potentially scalable carbon sequestration strategy. In practice, the amount of biochar that can be added to soil is constrained by the presence of contaminants such as salts, heavy metals, or dioxins. Process Systems Engineering (PSE) and Process Integration (PI) methods can be developed to optimize the reduction of greenhouse gas (GHG) emissions in such biochar-based Carbon Management Networks (CMNs). Previous works have proposed Mathematical Programming (MP) and Pinch Analysis (PA) approaches to the planning of these systems but are subject to the inherent methodological limitations. In this work, an alternative approach using Process Graph (P-graph) is developed, based on the source-sink matching problem being treated as a special Process Network Synthesis (PNS) problem. A case study is solved to illustrate the P-graph approach. In particular, optimal and near-optimal solutions are generated for the problem, which in real applications presents improved flexibility for purposes of practical decision support.

1. Introduction

Climate change due to anthropogenic emissions of greenhouse gases (GHGs) such as CO_2 is widely regarded as a serious environmental problem. In addition to mitigation efforts such as switching to low-carbon fuels or enhancing energy efficiency, the scale of the problem may soon require the deployment of Negative Emissions Technologies (NETs) to remove atmospheric CO_2 (McGlashan et al., 2012). One promising alternative is the application of biochar to soil, which is a management strategy that is of intermediate technological maturity at the system level (McLaren et al., 2012); however, component technologies are mostly well-developed when analysed separately. Biochar systems achieve net removal of carbon from the atmosphere in three steps. First, plant growth fixes carbon in biomass via photosynthesis. Then, thermochemical treatment (i.e., gasification or pyrolysis) converts biomass into a solid, carbon-rich material (biochar); typically, most of the carbon in the biochar is in recalcitrant or chemically stable form, with only a small fraction being labile or reactive. Finally, application of the biochar in soil results in the sequestration of the recalcitrant carbon content, typically over the time scale of multiple centuries (Lehmann et al., 2011). The system-level effect is the net transfer of carbon from the atmosphere into the ground (Woolf et al., 2010).
In practice, the operation of biochar systems needs to account for potential contamination of soil by undesirable impurities in the biochar, such as salts, heavy metals and dioxins (Kuppusamy et al., 2016). The effect of biochar on releases of other GHGs from soil should also be taken into account (He et al., 2017). Crombie et al. (2015) also discussed the need to balance energy production with carbon sequestration. Process Systems Engineering (PSE) tools offer potential solutions for the analysis, planning and optimization of biochar-based systems (Belmonte et al., 2017a). For example, Life Cycle Analysis (LCA) of biochar systems have been done, focusing on carbon footprint determination (Bartocci et al., 2016), “hot spot” identification (Muñoz et al., 2017), as well as comprehensive analysis of energy, economic and climate aspects (Roberts et al., 2010).

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Process Integration (PI) has developed since the 1970s as a sub-area of (PSE) dedicated to the development and use of rigorous methodologies to improve the efficiency of industrial systems and hence reduce emissions (Klemeš et al., 2013). The most common problem-solving approaches in PI are Pinch Analysis (PA) and Mathematical Programming (MP); other allied techniques include Process Graph (P-graph) methodology. The application of PI to carbon-constrained energy planning problems was proposed by Tan and Foo (2007) in their seminal work that introduced Carbon Emissions Pinch Analysis (CEPA) methodology. Many of the developments arising from CEPA are discussed in a review paper (Foo and Tan, 2016). A recent development is the application of P-graph methodology to the generic CEPA problem, coupled with the introduction of the term "Carbon Management Network" (CMN) as a natural extension of the heat exchanger network (HEN) concept dating back to the earliest applications of PI (Tan et al., 2017a). The latter paper proposed a mapping of the P-graph framework to the source-sink allocation problem structure of CEPA. The resulting approach was subsequently applied to two specific types of CMN, namely, carbon-constrained energy networks and CO_2 capture and storage (CCS) networks.

The systematic planning of biochar-based CMNs has thus far only been addressed using MP (Tan, 2016) or PA approaches (Tan et al., 2017b). Belmonte et al. (2017b) also proposed a modified two-stage MP approach. This paper presents the first P-graph based approach to solve such problems. The rest of this paper is organized as follows. Section 2 describes the P-graph framework as well as its extension to the planning of biochar-based CMNs. A case study is then presented in Section 3 to illustrate the methodology. Finally, conclusions and prospects for future work are given in Section 4.

2. P-graph framework

P-graph is a graph theoretic framework for Process Network Synthesis (PNS) problems whose development can be traced to the late 1970s (Friedler et al., 1979). It is based on five axioms (Friedler et al., 1992a) which serve as the basis for the development of efficient algorithms for PNS (Friedler et al., 1992b). There are three main component algorithms in the P-graph framework. First, the Maximal Structure Generation (MSG) algorithm is able to rigorously generate a complete superstructure (i.e., maximal structure) in polynomial time (Friedler et al., 1993). The maximal structure is the union of all possible structures for a PNS problem and differs from ad hoc superstructures used in many PSE problems in that it eliminates human error in problem definition. Next, the Solution Structure Generation (SSG) algorithm (Friedler et al., 1992b) can generate all combinatorially feasible structures for a PNS problem, even prior to the specification of flowrate constraints. SSG identifies subsets of the maximal structure for which potential solutions exist and eliminates all other structures to drastically reduce the solution space. Finally, Accelerated Branch-and-Bound (ABB) utilizes the information in PNS problems to eliminate combinatorially infeasible and redundant network structures during optimization (Friedler et al., 1996), thus leading to more efficient search than is possible using conventional algorithms such as branch-and-bound used for mixed integer linear programming (MILP) models in process synthesis.

P-graph methodology has matured sufficiently for inclusion in undergraduate chemical engineering textbooks (Peters et al., 2003) and advanced reference books (Klemeš et al., 2010). Free software (P-graph Studio), tutorials and other on-line resources are also available (P-graph, 2018). Lam et al. (2013) reviewed P-graph developments and applications, including conventional PNS problems as well as supply chain optimization. Klemeš and Varbanov (2015) then discussed further diversification and growth of P-graph as a sub-area of PSE. More recently, Varbanov et al. (2017) presented a roadmap for potential future P-graph applications. Specific CMN applications reported include CCS networks (Chong et al., 2014) and energy planning (Tan et al., 2017b). It has been noted that one important practical capability of P-graph for practical engineering is the potential to readily generate optimal as well as near-optimal (i.e., n-best) solutions (Promentilla et al., 2017). Such near-optimal solutions may prove to be more robust and pragmatic than the nominal mathematical optima (Voll et al., 2015).

Tan et al. (2017a) showed that the source-sink problems often encountered in PI applications (Foo et al. 2012) can be treated as a special case of PNS. This equivalency serves as the basis for this work. Source-sink problems can be represented in P-graph form as shown in Figure 1. The sources (blue node) and sinks (green node) can be represented as material nodes while the streams from one source to a sink can be represented as process units (black rectangles) such that all possible source-sink matches are represented. Furthermore, quality constraints which exist in the source-sink model are also represented by material nodes (shown as red nodes in Figure 1) such that the maximum limit is obtained by multiplying the total demand of the sink (Dj) by its quality limit (Qj). The source concentration (Ci) is then represented by the red edges flowing out of the red node.

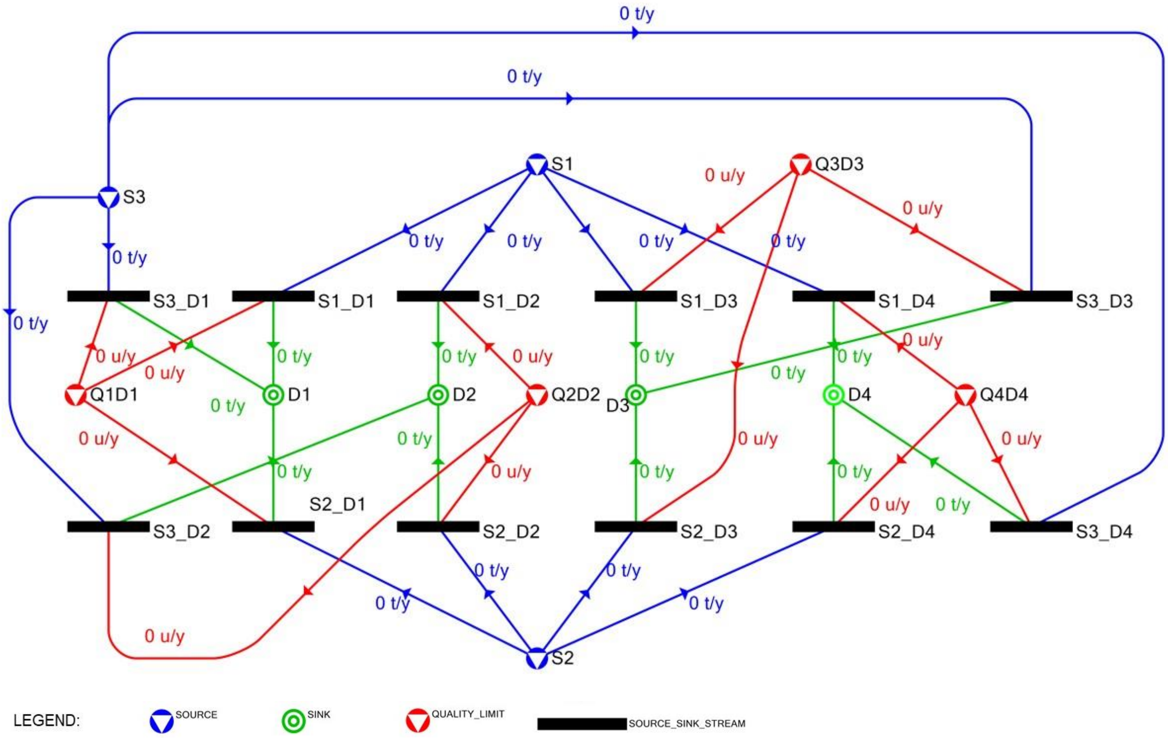

Figure 1: P-graph representation of the source-sink model (Tan et al., 2017a)

3. Problem statement

The problem statement is stated as follows. Given M biochar sources, each with a unique flowrate and contaminant level; given N biochar sinks, each with a unique biochar capacity limit and contaminant tolerance limit; the problem is to determine the optimal (and near-optimal) allocation of biochar from sources to sinks, in terms of overall carbon sequestered.

4. Case study

This section discusses a case study based on Tan et al. (2017b). The limiting data for both Sources and Sinks are given in Table 1. The maximal structure for the problem as generated using P-graph Studio is also represented by Figure 1. The contaminant of concern is PAH (polychlorinated aromatic hydrocarbons).

Table 1: Limiting data for source and sink

Sources (Si)	Biochar flowrate (kt/y C equivalent)	PAH concentration (ppm)	Sinks (Dj)	Biochar flowrate limit (kt/y C equivalent)	PAH concentration limit (ppm)
1	3.000	1	1	3.000	0.50
2	1.200	2	2	1.000	5.00
3	2.000	12	3	1.000	10.00
			4	1.000	15.00

An optimal solution can be determined using P-graph Studio as shown in Figure 2. This can be translated into the source-sink matrix given in Table 2. This configuration gives a carbon sequestration rate of 4.500 kt/y, and matches the solution reported by Tan et al. (2017b). It is also possible to find an additional 33 structures that also achieve this optimum, but these alternative networks are not shown due to space constraints. Some alternative solutions were also reported by Tan et al. (2017b) through the introduction of additional steps. By comparison, the P-graph approach is able to generate all optimal solutions automatically.
An added feature of P-graph is the capability to determine n-best solutions. In this case, the second-best solution is shown in Figure 4, and the corresponding source-sink matrices are given in Tables 4. The sequestration rate is a near-optimal 4.432 kt/y, which is only 1.5 % worse than the optimum in terms of absolute magnitude. Note

that there is no direct way to generate such a near-optimal solution using MP or PA, except by introducing additional steps and re-optimizing the problem.

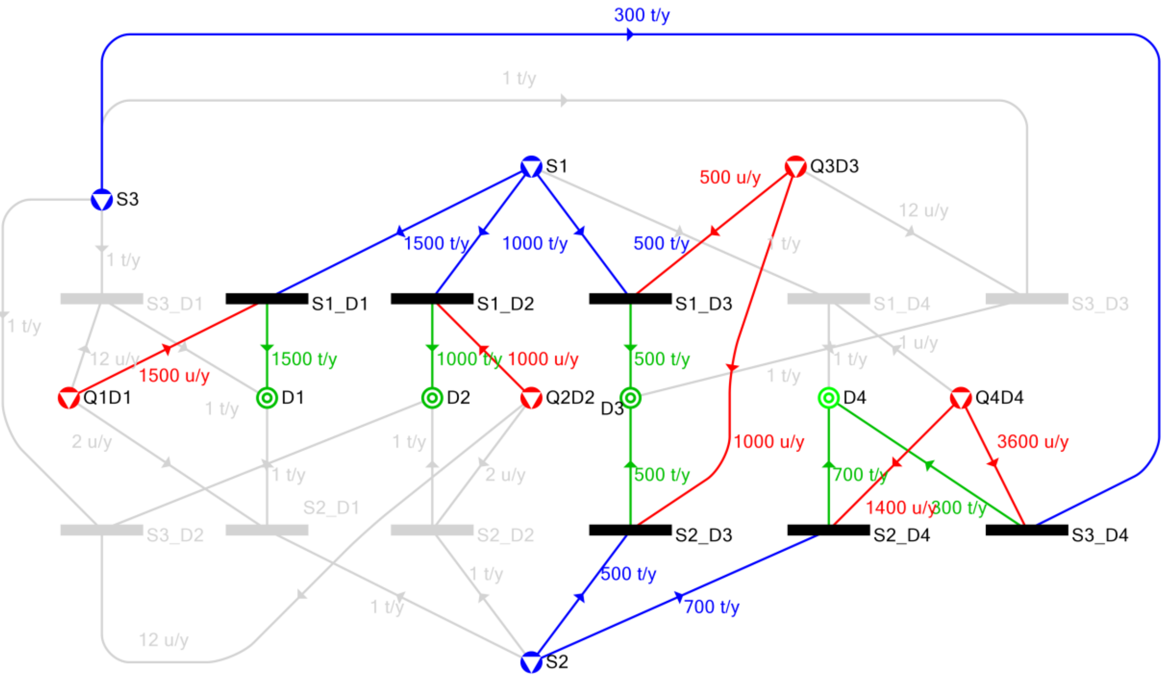

Figure 2: An optimal solution to the case study

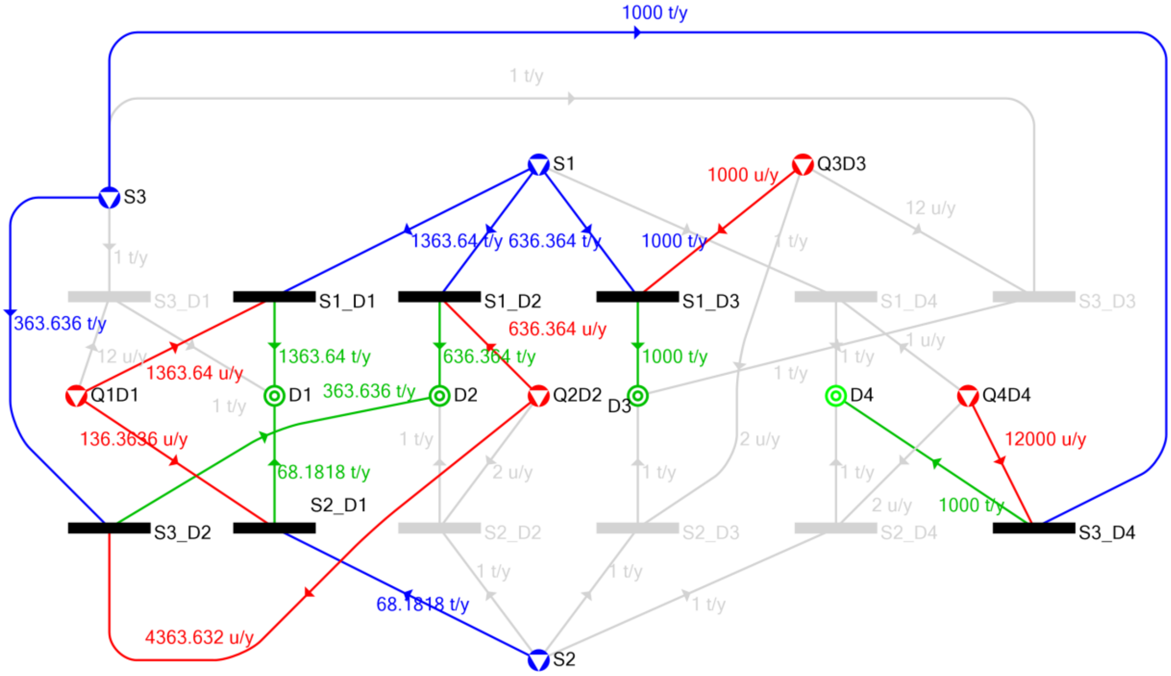

Figure 3: A near-optimal solution to the case study

Table 2: Source-sink equivalent of optimal solution (flowrates in kt/y C equivalent)

	D1	D2	D3	D4	Excess biochar
S1	1.500	1.000	0.500		
S2			0.500	0.700	
S3				0.300	1.700
Excess storage	1.500				

Table 3: Source-sink equivalent of near-optimal solution (flowrates in kt/y C equivalent)

	D1	D2	D3	D4	Excess biochar
S1	1.360	0.640	1.000		
S2	0.070				0.930
S3		0.360		1.000	0.640
Excess storage	1.570				

5. Conclusions

A P-graph based approach to the planning of biochar-based CMNs has been developed. This approach can facilitate the allocation of biochar streams from biomass pyrolysis or gasification plants to appropriate land sinks, while taking into account the level of harmful contaminants presents in the biochar. The use of P-graph allows both optimal and near-optimal solutions to be identified, which can provide useful alternatives for decision-makers; this feature can provide valuable decision support for the scale-up of biochar-based systems for carbon sequestration. The current model is limited to relatively simple static systems, but it can be extended in the future to allow for multi-period planning, and for multi-zone or multi-contaminant systems. Inherent system uncertainties can also be addressed using fuzzy or robust P-graph extensions.

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