CHEMICAL ENGINEERING TRANSACTIONS

VOL. 45, 2015

A publication of AIDIC
The Italian Association of Chemical Engineering
www.aidic.it/cet

Guest Editors: Petar Sabev Varbanov, Jiří Jaromír Klemeš, Sharifah Rafidah Wan Alwi, Jun Yow Yong, Xia Liu

ISBN 978-88-95608-36-5; **ISSN** 2283-9216 DOI: 10.3303/CET1545227

P-Graph Methodology for Bi-objective Optimisation of Bioenergy Supply Chains: Economic and Safety Perspectives

Rex T. L. Ng[a]*, Raymond R. Tan[b], Mimi H. Hassim[c]

[a]Department of Chemical and Biological Engineering, University of Wisconsin – Madison, WI 53706, USA
[b]Chemical Engineering Department, De La Salle University, 2401 Taft Avenue, 0922 Manila, Philippines
[c]Faculty of Chemical Engineering/Institute of Hydrogen Economy, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia
ngtonglip@gmail.com

This paper presents an approach to the planning of bioenergy supply chains, taking into account both total cost minimisation and supply chain risk reduction via Process graph (P-graph). The supply chain risk is accounted for in terms of transportation fatalities computed in an actuarial manner. An illustrative example based on Malaysian palm-based bioenergy supply chain is solved to illustrate the proposed approach.

1. Introduction

Widespread adoption of bioenergy for electricity generation could lead to a globally greener environment, with significant climatic and waste management benefits. Numerous methodologies have been developed to optimise the performance of bioenergy supply chains with different objective functions (e.g., profitability, carbon footprint, etc.); these are usually based on conventional mathematical optimisation techniques. Such techniques are usually based on single-objective formulations, and are able to determine unique optimal solutions. Process network synthesis (PNS) is a systematic approach to the design of networks with the aid of graph theoretic tools. This methodology, which is now known as P-graph (process graph), dates back to the establishment of key axioms and theorems in the seminal work of Friedler et al. (1992a). A subsequent paper discussed the development of solution algorithms for PNS (Friedler et al., 1992b). The algorithm for the generation of maximal structures containing all possible networks from a given set of processes was proposed by Friedler et al. (1993). Unlike the conventional mathematical optimisation techniques, this method offers the capability to identify both optimal and near-optimal solutions.

The PNS framework was initially applied mainly to the design of process plants and identification of chemical reaction pathways, but numerous new applications have since been documented in the literature. One notable area of application in recent years is the optimal synthesis of supply chains, particularly for renewable energy. The initial work of Lam et al. (2010) was first proposing for the PNS approach to biomass supply chain planning. This work was later extended to open-structure supply chains (Lam et al., 2013). In order to address the variations inherent in renewable energy supply chains, Stile et al. (2011) proposed an extension capable of integrating uncertainties within the P-graph framework. Many of these recent applications are documented in a review by Lam (2013). Later, Vance et al. (2014) proposed a multi-objective P-graph approach to enable Pareto optimal solutions to be identified. Maier and Narodoslawsky (2014) proposed a P-graph approach to the planning of provision of clean energy for smart cities. The fundamentals of P-graph approach can be found in modern textbooks (e.g., Klemeš et al., 2010), while software for implementation of PNS is available at www.p-graph.com (P-graph, 2014).

None of the previous works reported have accounted for safety risks in supply chains within the P-graph framework. The risk may be involved in the transportation, loading/unloading activities, storage, manufacturing, etc. Different assessment methods (e.g., hazard and operability study (HAZOP), layer of protection analysis (LOPA), fault tree and event tree analysis, quantitative risk assessment, etc.) can be

Please cite this article as: Ng R.T.L., Tan R.R., Hassim M.H., 2015, P-graph methodology for bi-objective optimisation of bioenergy supply chains: economic and safety perspectives, Chemical Engineering Transactions, 45, 1357-1362 DOI:10.3303/CET1545227

adopted to assess safety risks. Actuarial approaches have been proposed to estimate how technological changes may affect cumulative fatalities on a life-cycle basis, throughout an energy supply chain. In particular, it was reported that large-scale implementation of carbon capture and storage (CCS) will result in a significant increase in fatalities, particularly in coal mining activities (Ha-Duong and Loisel, 2011). A mathematical programming approach to life-cycle based optimisation with consideration of fatalities in biomass supply chains was developed by Ramadhan et al. (2014) and applied to palm waste biomass in Malaysia. This paper extends the latter work by using a P-graph approach as an alternative to mathematical programming. The rest of this paper is organized as follows: P-graph methodology is presented in the next section and it is followed by problem statement and formulation. An example is solved to illustrate the proposed approach. Finally, conclusion and future works are given.

2. P-graph Methodology

P-graph methodology is based on three key procedures:

- Maximal structure generation (MSG) is used to identify the overall structure comprises of all component processes identified earlier. The maximal structure is the union of all possible networks that can be generated.
- Solution structure generation (SSG) is used to identify all possible subsets of the maximal structure, each of which defines a feasible topology to be optimised.
- Accelerated branch and bound (ABB) determines optimal solutions to the problem by optimising within each solution structure. For large combinatorial problems, elimination of physically infeasible networks enables significant reduction in computational effort, as compared to the conventional branch and bound algorithm.

3. Problem Statement

Generic superstructure of bioenergy supply chain is shown in Figure 1. Given biomass generated from the source $i \in I$ is allocated to the sink $j \in J$ with the amount of $F_{i,j}$ for power generation. The amount of biomass in the source i and sink j are denoted as F_i^{SR} and F_j^{SK} whereas power generated at the sink j is given as E_j. In this work, the total supply chain risk, r is defined as the summation of potential number of transportation fatalities as functions of transportation distance ($D_{i,j}$) and the amount of biomass ($F_{i,j}$) from the source i and sink j. The main objective of this work is to minimise the total operating cost while keeping the supply chain risk as low as reasonably practicable.

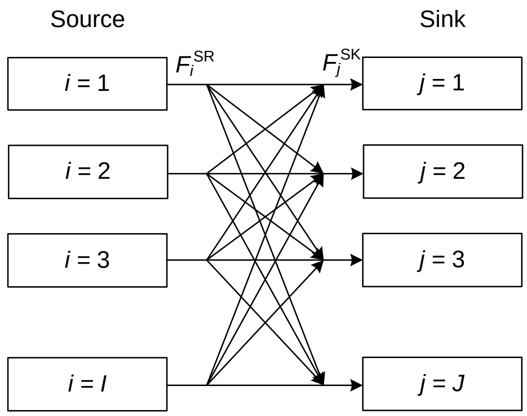

Figure 1: Generic superstructure of bioenergy supply chain

4. Figure 1: Generic superstructureProblem Formulation

The problem formulation of this work is stated as follows:
The total amount of biomass ($F_{i,j}$) should not exceed its availability (F_i^{SR}) from the source i.

$$\sum_j F_{i,j} \le F_i^{SR} \qquad \forall i \tag{1}$$

The total amount of biomass should match with the desired amount of biomass for power generation at the sink j.

$$\sum_i F_{i,j} = F_j^{\mathrm{SK}} \qquad \forall j \tag{2}$$

The allocated biomass flow has to take non-negative values:

$$F_{i,j} \geq 0 \qquad \forall i, j \tag{3}$$

At the sink j, biomass is converted into power energy E_j with the given conversion of x^{e}:

$$E_j = \sum_i F_{i,j} \mathrm{x}^{\mathrm{e}} \qquad \forall j \tag{4}$$

Additional constraint is added to ensure that the total power generated is at all times greater than or equal to the power demand at each sink j.

$$E_j \geq E_j^{\mathrm{REQ}} \qquad \forall j \tag{5}$$

The total risk r can be determined in different way. Based on the availability of data of the potential fatalities, in this paper, r is determined by the total number of potential fatalities for each route ($\mathrm{T}_{i,j}$) multiplied with the amount of biomass ($F_{i,j}$) and the distance travelled ($\mathrm{D}_{i,j}$). Thus, r is given as:

$$r = \sum_{i,j} \mathrm{T}_{i,j} \mathrm{D}_{i,j} F_{i,j} \tag{6}$$

where the unit of r is potential fatality and $\mathrm{T}_{i,j}$ is potential fatalities/kt-km.
In this work, the optimisation model is solved via the proposed P-graph approach. In order to observe the effect of the supply chain risk to the optimisation objective (minimisation of total cost in this work), potential penalty cost due to fatality (C^{P}) is included in the optimisation objective. C^{P} is given as:

$$C^{\mathrm{P}} = \mathrm{C}^{\mathrm{R}} r \tag{7}$$

where C^{R} is potential penalty unit cost (US$/potential fatality).

The optimisation objective in Eq (8) is set to minimize total cost (C) of biomass from the source i to sink j, given by:

$$\mathrm{Min}\, C = \sum_{i,j} \mathrm{C}^{\mathrm{T}} \mathrm{D}_{i,j} F_{i,j} + \sum_i \mathrm{C}_i^{\mathrm{M}} \sum_j F_{i,j} + C^{\mathrm{P}} \tag{8}$$

where first term represents transportation cost; whereas second term is raw material cost. C^{T} is transportation cost per unit of distance travelled and amount of biomass (US$/km-kt); $\mathrm{C}_i^{\mathrm{M}}$ is cost of biomass sold from the source i (US$/t);

5. Illustrative Example

An illustrative example of palm-based bioenergy supply chain is used to demonstrate the proposed approach. Note that this example is simplified from the case study in the northern part of Borneo Island (Sabah) in Malaysia that has been presented by Foo et al. (2013). In this example, empty fruit bunches (EFBs) are chosen as feedstock to be transported and fed into power generation plants. EFBs are generated as by-products after oil palm fruits were separated from bunches in the palm oil mill. Table 1 shows the data for EFB suppliers and consumers. Three palm oil mills (SR1, SR2 and SR3) with various selling prices and availabilities of EFB are considered in this example. EFBs can be sent to two power generation plant (SK1 and SK2) and power is generated based on the desired power demand. In this example, it is assumed that all source plants and sinks already exist, and no capacity extensions are allowed. Based on the interview with an industrial partner, the calculated transportation unit cost (C^{T}) for EFB in Malaysia is US$ 205/km/kt. In actual practice, the concept of Value of a Statistical Life (VSL) can be used to determine the penalty cost per potential fatality (Mrozek and Taylor, 2002). It is assumed that the potential penalty unit cost is given as MUS$ 2 per potential fatality (Mrozek and Taylor, 2002).
The value of potential fatality is determined based on the ten years transport statistics (2003 – 2012) which is available from the Ministry of Transport Malaysia (2013) and is summarised in Table 2. As shown, the probability of death caused by lorry accident in Sabah is equal to 4×10^{-3}. Based on the annual distance

travelled and the capacity of each lorry, the potential fatality is calculated and has been found to be equal to 3×10^{-6} fatalities/kt-km. Please note that realistically, some road accidents were not reported to the authorities, thus not appearing in the official statistics (Ramadhan et al., 2014). In this example, the potential fatalities of each route are set to a minimum value of 3×10^{-6} fatalities/kt-km. For illustration purpose, the potential fatalities for each route are varied and shown in Table 1.

Table 1: Data for EFB suppliers and consumers

Source, *i* /Sink, *j*	EFB Price, C_i^M (US$/kt)	Source availability, F_i^{SR} (kt)	Distance, $D_{i,j}$ (km)		Potential fatality, $T_{i,j}$ (10^{-6} potential fatality/kt-km)	
			SK1	SK2	SK1	SK2
SR1	6,400	120	11.9	154.0	4	70
SR2	5,800	90	77.8	132.0	30	100
SR3	6,100	70	168.0	7.1	100	80
Desired power demand, E^{REQ}_j (MW)			5	6		

Table 2: Potential fatalities of lorry involved in road accident (2003 – 2012)

Description	Data	Data basis
Average lorry involved in road accident (Malaysia) per annum, y_L	691,465	Ministry of Transport Malaysia (2013)
Average vehicles involved in road accident (Malaysia) per annum, y	46,535	Ministry of Transport Malaysia (2013)
Average death reported (Malaysia) per annum, d	6,521	Ministry of Transport Malaysia (2013)
Average death reported (Sabah) per annum, d_s	351	Ministry of Transport Malaysia (2013)
Probability of death (lorry) in Sabah per annum	4×10^{-3}	Calculated based on $y_L/y\times d/d_s$
Annual distance travelled (km)	67,200	Based 200 km/d for 336 d/y
Capacity of lorry (t)	20	
Potential fatalities (fatalities/kt-km)	3×10^{-6}	

The model is solved by minimising the total cost in Eq(8) subject to Eqs(1) – (7) and data in Table 1. This example with a total of 25 variables is solved by PNS studio via accelerated branch-and-bound (ABB). As shown in PNS studio, two optimal solutions are given. A screen shot of the proposed solutions is illustrated in Figure 2 and the detail biomass allocation is tabulated in Table 3. The first solution yields a total cost of MUS$ 4.47/y with the total risk of 0.705 and 5 MW power are generated. 83 % of the biomass (100 kt/y) in SR1 is sent to SK1 for 5 MW of power generation whereas all biomass (70 kt/y) in SR3 and 56 % of the biomass (50 kt/y) in SR2 are sent to SK2 for 6 MW of power generation. In Solution #2, a minimum risk of 0.652 is proposed with a total cost of MUS$ 5/y. In this solution, 70 kt/y of biomass from SR1 and 30 kt/y of biomass from SR2 are sent to SK1 whereas the remaining biomass (50 kt/y) from SR1 and all biomass in SR3 are sent to SK2. It is noted that Solutions #1 has the lowest cost whereas Solution #2 gives the lowest risk of the supply chain network.

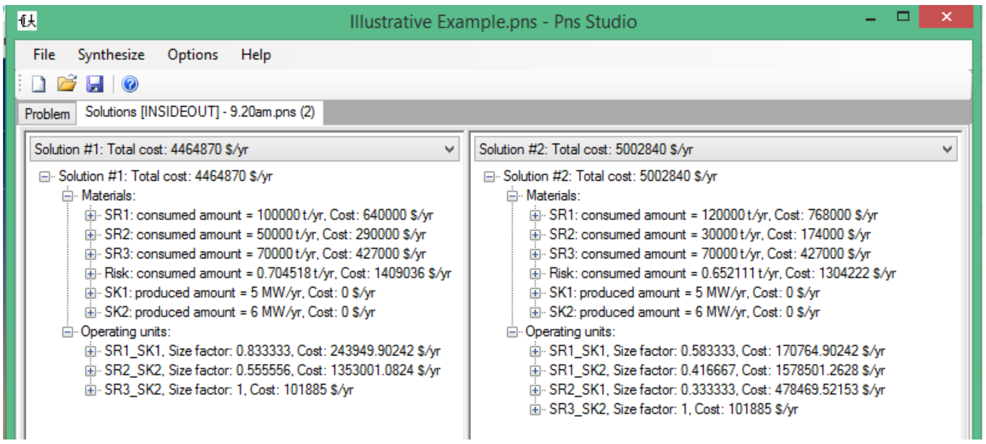

Figure 2: Screen shot of results in PNS studio

Based on the solutions given by PNS studio, the study of the correlation between total cost and total risk can be performed. By varying the risk (setting the maximum allowable risk from 0.652 to 0.705 in the PNS studio), the corresponding total cost are illustrated in Figure 3. Biomass allocations from SR1 and SR2 to SK1 and SK2 are shown in Figure 4. Biomass allocation of SR3 is not studied in this example as it remains the same in both optimal solutions. As the risk is decreased from 0.705 to 0.657 (RHS region), the total cost is also decreases at a constant gradient of 0.11. At the LHS region, the total cost decreases dramatically from MUS$ 4.47/y to MUS$ 5.00/y with a small decrement of the risk from 0.657 to 0.652.

Table 3: Biomass allocation for illustrative example

(a) Solution #1

Source/Sink	SK1	SK2	Supply
SR1	100	0	100
SR2	0	50	50
SR3	0	70	70
Demand	100	120	

All in the unit of kt/y

(b) Solution #2

Source/Sink	SK1	SK2	Supply
SR1	70	50	120
SR2	30	0	30
SR3	0	70	70
Demand	100	120	

All in the unit of kt/y

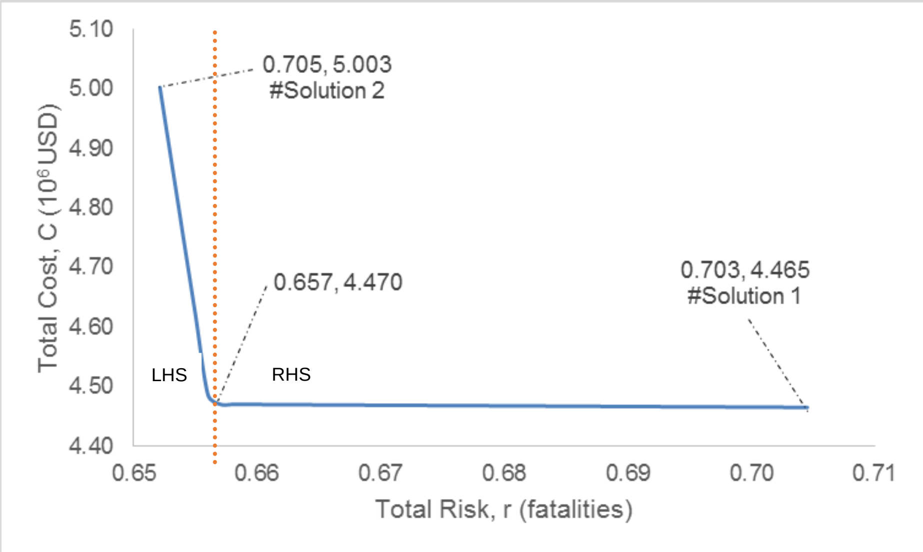

Figure 3: Correlation between total cost and total risk for illustrative example

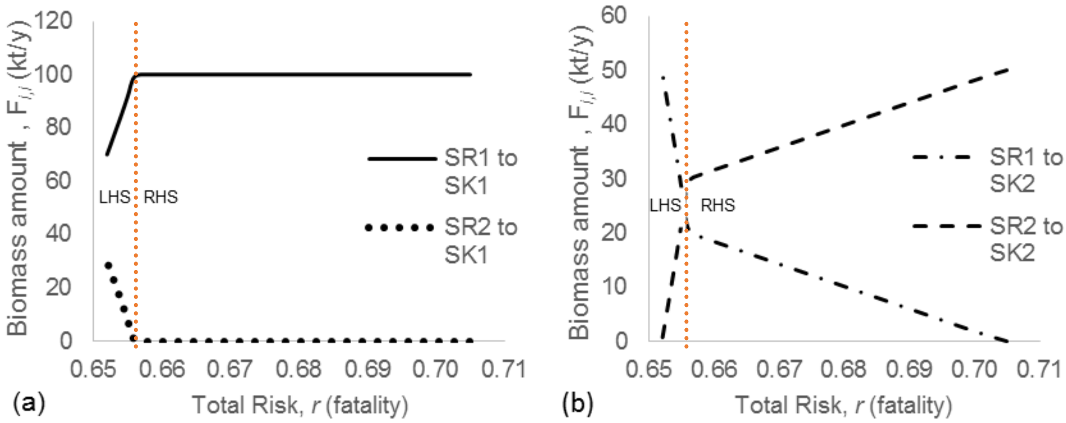

Figure 4: Allocation of biomass to (a) SK1 (b) SK2

At the RHS region, SR1 remains to supply biomass at the rate of 100 kt/y to SK 1 (Figure 4a, solid line) while there is no biomass supply from SR2 to SK1 (dot line). SK2 gets more biomass supplies from SR1

(Figure 4b, dash-dot line) with the decrease of the risk since the potential fatality from SR2 to SK2 is higher than from SR1 to SK2. At the LHS region, part of the biomass supplies to SK1 is replaced by SR2 (30 kt/y) whereas the supply of biomass from SR2 to SK2 becomes zero because a much lower risk from SR1 to SK2 is obtained.

In this example, all possible solutions are provided in PNS studio. Alternate solutions are good for decision-makers in practical applications. Besides, this approach generates fast and feasible solutions, by eliminating non-feasible solutions within the network. Although the presented example is rather small and simple, the problem can be easily extended into a large-scale supply chain problem and it is proven in previous works (Lam et al., 2010) and reviewed extensively thereafter (Lam,2013) that there is no problem in solving the large-scale problems with P-graph methodology.

6. Conclusions

This paper presents a P-graph methodology for planning of bioenergy supply chains, taking into account both total cost minimisation and supply chain risk reduction. Risk is accounted for as the expected rate of statistical fatalities associated with each process or activity. The P-graph approach enables embedded algorithms for solution structure generation and optimisation to be used for planning the supply chain. Future work will focus on a multi-objective synthesis of supply chains, taking into further consideration additional aspects such as water, land and nitrogen footprints. Furthermore, the effect of parametric uncertainties can also be integrated within the optimisation framework.

References

Friedler F., Tarjan K., Huang Y.W., Fan L.T., 1992a, Graph-theoretic approach to process synthesis: axioms and theorems, Chemical Engineering Science 47, 1973 – 1988.

Friedler, F., Tarjan, K., Huang, Y.W., Fan L.T., 1992b, Combinatorial algorithms for process synthesis, Computers & Chemical Engineering 16, 313 – 320.

Friedler F., Tarjan K., Huang Y.W., and Fan L.T., 1993, Graph-theoretic approach to process synthesis: polynomial algorithm for maximal structure generation, Computers & Chemical Engineering 17, 929 – 942.

Foo D.C.Y., Tan R.R., Lam H.L., Abdul Aziz M.K., Klemeš J.J., 2013, Robust models for the synthesis of flexible palm oil-based regional bioenergy supply chain, Energy 55, 68 – 73.

Ha-Duong M., Loisel R., 2011, Actuarial Risk Assessment of Expected Fatalities Attributable to Carbon Capture and Storage in 2050, International Journal of Greenhouse Gas Control 5, 1346 – 1368.

Lam H.L., Varbanov P.S., Klemeš J.J., 2010, Optimisation of Regional Energy Supply Chains Utilising Renewables: P-Graph Approach, Computers & Chemical Engineering 34, 782 – 792.

Lam H.L., Varbanov P.S., Klemeš, J.J., Kravanja, Z., 2013, P-graph synthesis of open-structure biomass networks, Industrial & Engineering Chemistry Research 52, 172 – 180.

Lam H.L., 2013, Extended P-graph applications in supply chain and process network synthesis, Current Opinion in Chemical Engineering 2, 475 – 486.

Klemeš J., Friedler F., Bulatov I., Varbanov P., 2010, Sustainability in the Process Industry: Integration and Optimization, McGraw-Hill, New York, USA.

Maier S., Narodoslawsky M., 2014, Optimal Renewable Energy Systems for Smart Cities, Computer Aided Chemical Engineering 33, 1849 – 1854.

Ministry of Transport Malaysia, 2013, Transport Statistics Malaysia 2012, <www.mot.gov.my/my/Publication/Official/Statistik%20Pengangkutan%20Malaysia%202012.pdf> accessed 17.09.2014.

Mrozek, J. R., Taylor, L. O., 2002, What determines the value of life? A meta-analysis. Journal of Policy Analysis and Management 21, 253 – 270.

Ramadhan, N., Wan, Y.K., Ng R.T.L., Ng D.K.S., Hassim M.H., Aviso K.B., Tan R.R., 2014, Life Cycle Optimisation (LCO) of Product Systems with Consideration of Occupational Fatalities, Process Safety and Environmental Protection 92, 390 – 405.

Stile Z., Bertok B, Friedler F., Fan L.T., 2011, Optimal design of supply chains by P-graph framework under uncertainties, Chemical Engineering Transactions 25, 453 – 458.

Vance L., Heckl I., Bertok B., Cabezas H., Friedler F., 2014, Designing energy supply chains with the p-graph framework under cost constraints and sustainability considerations, Computer Aided Chemical Engineering 33, 1009 – 1014.

P-graph, 2014, <www.p-graph.com> accessed 21.06.2014.