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P-graph for Optimising Industrial Symbiotic Networks

Kathleen B. Aviso[a,]*, Anthony S.F. Chiu[b], Krista Danielle S. Yu[c], Michael Angelo B. Promentilla[a], Luis F. Razon[a], Aristotle T. Ubando[d], Charlle L. Sy[b], Raymond R. Tan[a]

[a]Chemical Engineering Department, De La Salle University Manila, Philippines
[b]Industrial Engineering Department, De La Salle Uniersity Manila, Philippines
[c]School of Economics, De La Salle University Manila, Philippines
[d]Mechanical Engineering Department, De La Salle UniversityManila, Philippines
kathleen.aviso@dlsu.edu.ph

Industrial symbiosis (IS) intends to reduce the consumption of resources as well as reduce the generation of waste streams through utilising by-products of other firms as raw materials of another firm. Mathematical optimisation models have been developed for identifying the optimal design of by-product exchange and utilisation to maximise the benefits of IS networks. However, these models are unable to provide alternative network structures which may have other desirable qualities such as a simpler design, but may be sub-optimal in their realisation of the objective function. Process graph (P-graph) theory is an alternative approach based on graph theory for optimising networks. It has been primarily used for the design and optimisation of process networks, but may be applied to structurally analogous systems. This work thus proposes the development of a P-graph approach for the optimization of IS networks. The methodology is demonstrated using a case study involving a combination of retrofit and grassroots design scenarios, representing existing as well as new plants within an eco-industrial park. The P-graph model is able to provide a graphical representation of the optimal IS system, as well as alternative near-optimal network designs.

1. Introduction

Industrial ecology (IE) was proposed as a framework for improving the sustainability of industrial systems using natural ecosystems as models (Frosch and Gallopoulos, 1989). The philosophy underlying IE is to encourage cyclic, rather than linear, material flows, through efficient utilisation of process residues. The concept of industrial symbiosis (IS) emerged within IE based on symbiotic relationships in natural ecosystems; it is based on mutually beneficial exchanges among companies or plants to minimise external flows of resources and wastes. Historically, it has been noted by Chertow (2007) that IS systems have self-organised spontaneously, as illustrated by the famous Kalundborg system in Denmark. On the other hand, more recently there have been attempts throughout the world to encourage IS through eco-industrial parks (EIPs). These EIPs are meant to provide geographic proximity and shared services which have proven to be beneficial to encouraging IS to emerge (Chertow, 2007).Systematic decision support tools have also been proposed to facilitate the planning of IS systems within EIPs and for various materials. Deng et al. (2014) utilised flowrate targeting techniques for the design of interplant hydrogen networks while a fuzzy programming approach for planning water reuse in an EIP was proposed by Aviso et al. (2010a). Subsequent extensions based on bi-level fuzzy optimisation models to reflect the role of a centralised authority in facilitating cooperation in both direct plant-to-plant exchanges (Aviso et al., 2010b) and EIPs with hub topology (Tan et al., 2011).
In addition to planning EIPs, it is also necessary to manage the risks that arise from operational issues. Kaplan and Garrick (1981) proposed three key questions in systematic analysis:

- What can go wrong?
- What is the likelihood of each adverse event?
- What are the consequences of each adverse event?

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In the context of EIPs, companies become vulnerable to ripple effects as a consequence of increased connectivity, which makes it essential to systematically address the third issue above. One approach has recently been proposed by Benjamin et al. (2014) to identify the criticality of each plant within an EIP. The methodology is based indirectly on linear models of infrastructure systems (Haimes and Jiang, 2001). There have also been related methods derived from such linear models to determine the optimal abnormal operating states for various systems under crisis conditions. For example, a mixed integer linear programming (MILP) model was proposed by Kasivisvanathan et al. (2013) for polygeneration plants and biorefineries. An equivalent method based on P-graph approach was proposed by Tan et al. (2014), using the process synthesis framework initially proposed by Friedler et al. (1992). However, the approach has yet to be shown to be suitable for modelling abnormal operating conditions for systems, such as EIPs, at an intermediate scale. In this work, a P-graph approach to the planning of optimal adjustment for EIPs under abnormal or crisis conditions is proposed. The rest of the paper is organised as follows. Section 2 gives the formal problem statement, while Section 3 describes the model formulation. A case study based on the work of Keckler and Allen (1998) is then solved in Section 4 considering the design of an optimal network and a scenario of partial system failure. Finally conclusions and prospects for future work are given in Section 5.

2. Problem Statement

The formal problem statement is given as follows: Given that there are *n* material sources and *m* possible sinks. Each source is characterised by the maximum available flowrate and resource quality while each sink is characterised by its required resource intake and desired resource quality. Furthermore, there is an available virgin material outside of the system. The objective then is to develop a P-graph model for identifying all feasible network structures with particular interest in the optimal network which will minimise the consumption of fresh resource. Furthermore, given the optimal symbiotic network between sources and sinks and given the possibility that failures can occur, it is important to identify how this will affect the system.

3. P-graph for optimizing symbiotic networks

The optimal structure of a symbiotic network for a particular material *k* can be solved using the MILP model given in Eq(1) to (4) wherein the over-all objective is to minimize the total cost of the system which is dependent on the utilization of fresh resource *k* in the system and the investment cost Eq(1) subject to sink balance Eq(2), source balance Eq(3) and sink quality requirement Eq(4) constraints where F_{jk} is the amount of fresh resource *k* used by sink j, P_k is the unit cost for fresh resource *k,* ACC_j is the annualized investment cost for established process units, R_{ij} is the amount of resource *k* used from source i and sent to sink j, D_j is the amount of resource *k* required by sink j, S_i is the amount of resource *k* available for use from source i, C_i is the contaminant concentration of source i, and Q_j is the maximum contaminant concentration that sink j can accept. Note that this model can be extended to accommodate a number of material resources *k.*

$$\min = \sum_{j=1}^{m} F_{jk} P_k + \sum_{j=1}^{m} ACC_j \tag{1}$$

$$\sum_{i=1}^{n} R_{ij} + F_j = D_j \qquad \forall j \in J \tag{2}$$

$$\sum_{j=1}^{m} R_{ij} \le S_i \qquad \forall i \in I \tag{3}$$

$$\sum_{i=1}^{n} R_{ij} C_i + F_j C_F \le D_j Q_j \qquad \forall j \in J \tag{4}$$

In the context of industrial symbiosis, the MILP can be transformed into the p-graph model by representing a sink into a process unit which can accommodate resource *k* of a particular quality to manufacture goods, products or services. Alternatively, sources can be represented as process units which generate a particular quality of resource *k.* Fresh resources are treated as raw materials. The available resources which can be utilized within the system can then be represented by vertices such that each vertex represents a certain quality of the resource.

The P-graph methodology works by utilising three algorithms. The Maximal Structure Generation (MSG) identifies the union of all possible networks, the Solution Structure Generation (SSG) identifies all feasible network structures based on the maximal structure while the Advanced Branch and Bound (ABB) identifies the optimal solution structure based from the identified feasible structures.

4. Case study

The case study considered is adapted from the work of Keckler and Allen (1998) which considers three independently operating plants (M, O and P), three types of water treatment process (A, B and C), an external water supply (S) and a holding pond (H). Water quality is indicated by three parameters namely: total organic carbon (TOC), total suspended solids (TSS) and total dissolved solids (TDS). In this case study, the resource being considered is that of water and the objective is to identify the optimal network which will minimise the over-all cost of the system due to freshwater consumption and the investment in the treatment plants. The resulting solution should identify the recycle streams and the level of water treatment required by the system. The water limiting data for the plants are shown in Table 1. Two scenarios are considered such that the first scenario identifies the optimal structure while the second scenario considers the partial failure of an operating plant after the optimal structure has been established. The water quality and costs associated with the treatment processes are shown in Table 2. The purchase cost for freshwater is 0.20 $/m^3$.

Table 1: Water limiting data for Case Study (adapted from Keckler and Allen, 1999)

Plant	Symbol	Water need (m^3/d)	Input quality (ppm) (TOC, TSS, TDS)	Output quality (ppm) (TOC, TSS, TDS)
Maintenance	M	42	25, 500, 2,500	1,928, 2,639, 7,824
Organic Chemicals	O	3,600	25, 25, 200	484, 105, 904
Plastics	P	4,940	5, 100, 500	8, 22, 276
Fresh water	S	n/a	n/a	0, 1, 140

Table 2: Water quality and associated costs for treatment processes (adapted from Keckler and Allen, 1998)

Treatment Step	Symbol	Output quality (ppm) (TOC, TSS, TDS)	Treatment cost $/m^3$
Primary and Secondary	A	20, 30, 1,000	1.45
Filtration and Precipitation	B	5, 10, 500	0.11
Reverse Osmosis	C	5, 1, 10	1.58
Freshwater supplier	S	0, 1, 140	n/a
Transport	H	n/a	0.53

A P-graph model of this case study is designed based on a preliminary inspection of the quality requirement of the sinks versus the quality of the available sources in terms of the three quality indicators. This identifies the feasible network structures such that any water source that meets the quality requirement of a sink are considered to be of equal quality. All feasible links can then be identified and this makes up the maximal structure of the network and is shown in Figure 1 with the flows shown in m^3/d. Furthermore, it is assumed that at the minimum any wastewater generated should be treated by step A and sent to the hub (H) prior to reuse or to disposal to the environment. For Scenario 1, minimising the total cost of the network results in a cost of 7,871.38 $/d and corresponds to the structure shown in Figure 2. The flow rates and cost distribution for Figure 2 are also shown in Table 3. It can be seen that to minimise the cost the optimal network requires that fresh water be utilized for Plant P and treated wastewater generated by the system using treatment steps A and B satisfy the rest of the water requirements.

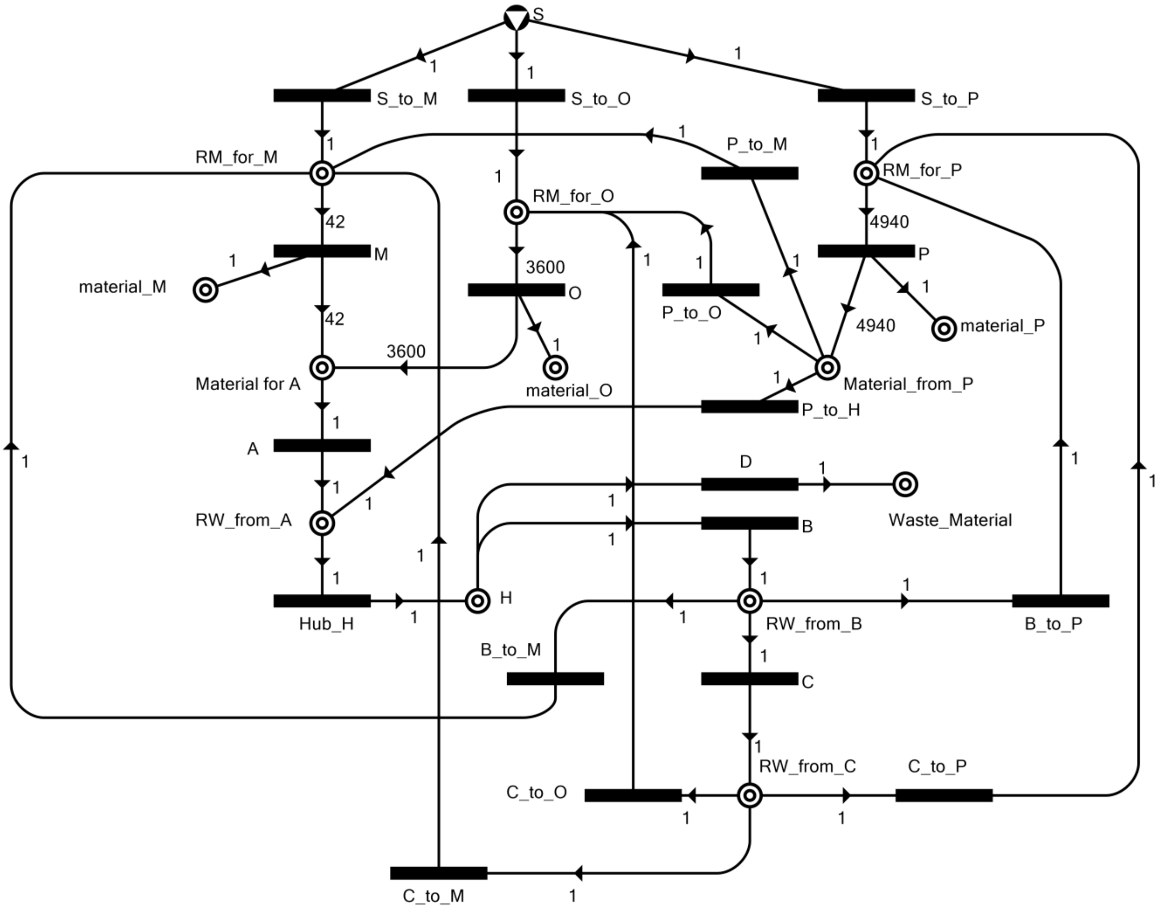

Figure 1: Maximal structure of Case Study

In Scenario 2, it is assumed that the optimal network shown in Figure 2 has been established such that no additional connections between processing and water treatment plants can occur and a 40 % failure in operating capacity of Plant P is experienced. Therefore, Plant P can only produce 60 % of the material used in the symbiotic exchange which is equivalent to 2,964 m3/d of used water. This reduction in available material will obviously impact the operations of Plants M and O if there is no contingency measure.

Table 3: Optimal water flows and cost distribution for Scenario 1 in m^3/d

	Sink						
	M	O	P	A	H	B	COST
M	n/a	n/a	n/a	42	n/a	n/a	60.90
O	n/a	n/a	n/a	3,600	n/a	n/a	5,220.00
P	42	3,600	n/a	n/a	n/a	n/a	0.00
A	n/a	n/a	n/a	n/a	3,642	n/a	1,930.26
H	n/a	n/a	n/a	n/a	n/a	3,642	400.62
B	n/a	n/a	3,642	n/a	n/a	n/a	0.00
S	0	0	1,298	0	0	0	259.60
TOTAL	42	3,600	4,940	3,642	3,642	3,642	7,871.38

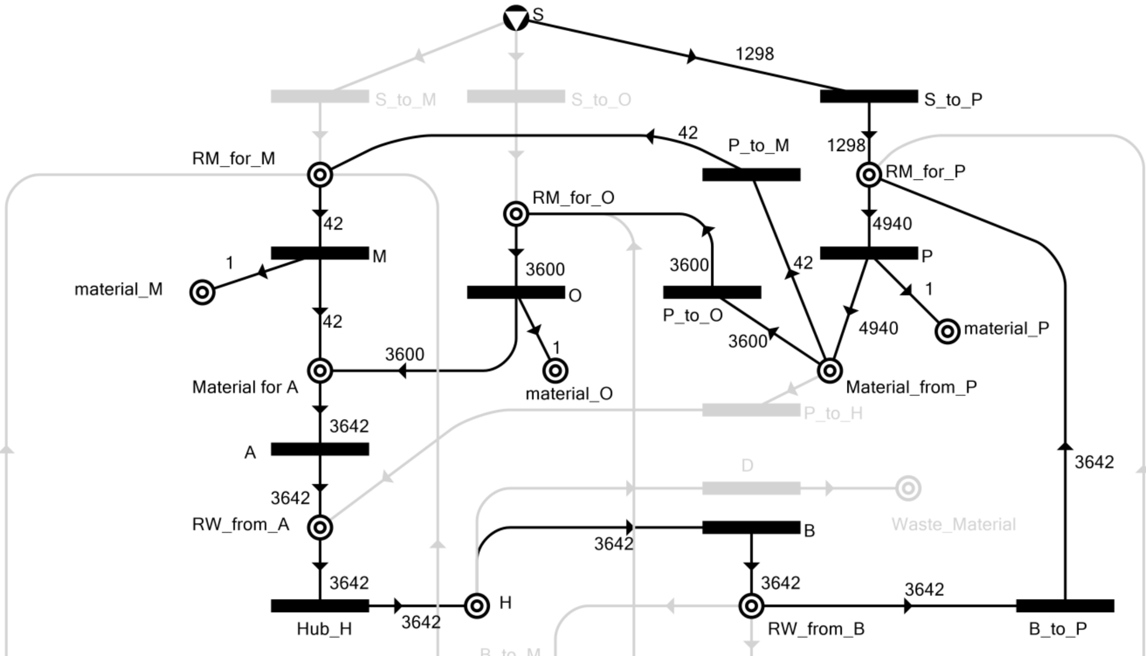

Figure 2: Optimal structure of Case Study for Scenario 1

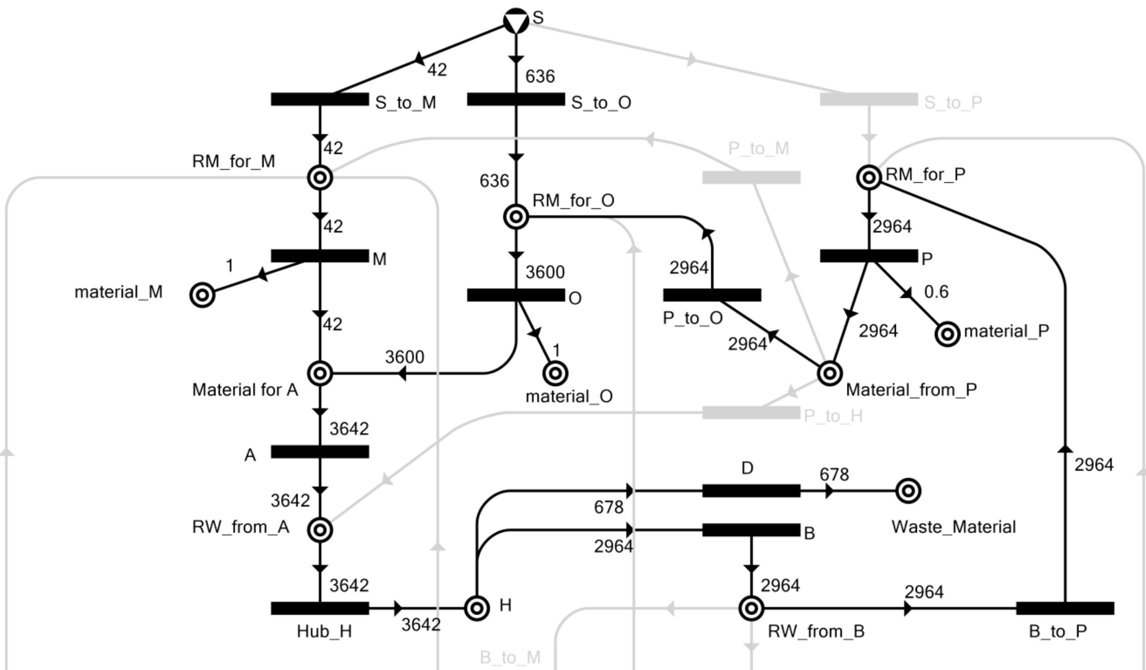

Figure 3. Optimal structure of Case Study for Scenario 2

*T*he result of the optimisation for Scenario 2 is shown in Figure 3 and summarized in Table 4. Results indicate that Plants M and O should now purchase freshwater from an external source because Plant P cannot provide for their requirements. The highlighted cells in Table 4 indicate the flowrates which differ from Scenario 1. The 40 % reduction in capacity of Plant P resulted only in a 2.5 % reduction in total cost. Furthermore, the optimisation using P-graph resulted in 9 feasible solution structures, 8 of which are sub-optimal. The feasible solution structures differ in the degree of recycling and water treatment. These information can be utilised for planning contingency measures in order to minimise the effects of disruption should certain components of the symbiotic network fail.

Table 4. Optimal water flows and cost distribution for Scenario 2 in m^3/d

	Sink						
	M	O	P	A	H	B	COST
M	n/a	n/a	n/a	42	n/a	n/a	60.90
O	n/a	n/a	n/a	3,600	n/a	n/a	5,220.00
P	0	2,964	n/a	n/a	n/a	n/a	0.00
A	n/a	n/a	n/a	n/a	3,642	n/a	1,930.26
H	n/a	n/a	n/a	n/a	n/a	2,964	326.04
B	n/a	n/a	2,964	n/a	n/a	n/a	0.00
S	42	636	0	0	0	0	135.60
TOTAL	42	3,600	2,964	3,642	3,642	2,964	7,672.80

5. Conclusions

A P-graph model for application in industrial symbiotic networks particularly for water exchange with the consideration of water treatment processes has been developed and applied in a case study. Unlike, the traditional MILP model, the P-graph model requires that materials being exchanged are classified based on their intended use within the system and this assumes complete substitutability of materials that fall within the same class. Furthermore, the P-graph model is able to identify not only the optimal but also the sub-optimal structures of the IS network. These are important when reliability and functional redundancy are considered in the development of the network. Identifying marginally sub-optimal structures also gives room for the use of judgment by decision makers after considering other factors not included in the model. Future work can focus on the evaluation of identified sub-optimal structures in consideration of additional criteria other than economic costs. The application of the P-graph model to other material exchange networks can also be considered.

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