Presented at the DLSU Research Congress 2016
De La Salle University, Manila, Philippines
March 7-9, 2016

P-graph Approach to Optimization of Polygeneration Systems Under Uncertainty

James S. Okusa[1*], Jonathan Carlo R. Dulatre[1], Venn Royce F. Madria[1], Kathleen B. Aviso[1], and Raymond Girard R. Tan[1]
[1] *Chemical Engineering Department, De La Salle University – Manila*

**Corresponding Author: james_okusa@dlsu.edu.ph*

Abstract: To address the problem of increased greenhouse gas emissions and depleting fossil fuels, the study of polygeneration systems is developed. These systems can be optimized by determining the appropriate flow rate of streams and the adequate sizes for process units in order to maximize the profitability of the plant. However, uncertainties in product demands and raw materials availability may be present which may lead to non-optimal design solutions if not addressed. In this study, a robust model for optimal design of the polygeneration system in terms of profitability is presented. To cope with changes in demand or supply, the process units can operate within given feasible operating ranges. The model is developed utilizing a P-graph framework and demonstrated with a case study.

Key Words: polygeneration system; optimization; uncertainty; P-graph

1. INTRODUCTION

The continuous utilization of fossil fuels as feedstock in energy production has resulted in an increase in global emissions of greenhouse gases (GHG) which is said to be the cause of climate change. With this, optimally designing energy systems is important to reduce GHG emissions per unit of product output by minimizing usage of fuels and utilization of energy (Serra et. al., 2009). Various studies have been made in designing energy systems to address this issue.

Recent studies have proposed various methodologies for the design of polygeneration systems which can simultaneously produce two or more energy or chemical products (Serra et. al., 2009). This has a major advantage over a single-generation system since it produces more energy while reducing GHG emissions and operational cost (Zhang et. al., 2014). While these are still relatively new and are undergoing extensive research, various industries are highly interested with these (Kasivisvanathan et. al., 2013). Few of the proposed polygeneration plants are those which can simultaneously produce methanol, syngas, heat, and power (Zheng et. al., 2003), and those which can produce heat, electricity, cooling and treated water simultaneously with natural gas as fuel source (Kasivisvanathan et. al., 2013).

Identifying objective and constraint functions is relevant in designing polygeneration systems. In this study, the objective function is in terms of profitability while constraint functions include material balances of flow streams, operating cost, and capacity range of each process unit. These can be introduced into traditional mathematical programming methods such as mixed integer linear programming (MILP) and mixed integer nonlinear programming (MINLP) to determine the optimal capacity of process units and to account for the profit gained from the designed polygeneration system (Grossmann and Santibanez, 1980). These programming methods however can be disadvantageous whenever the size of the problem is large, and computations become difficult to perform due to the combinatorial nature of large process networks (Friedler et. al., 1992b).

Process graph (P-graph), a graph-theoretic and combinatorial approach, will be used to address this problem. This can be used in process synthesis to automatically generate the superstructure of the system. It can provide both optimal solutions and n-best suboptimal solutions (Friedler et. al., 1992b). Operating units, materials, and flow streams can be drawn and are represented with distinct symbols in this P-graph software. Properties of the system such as cost functions, capacities of process units, product demand, flow streams, and name of materials and process units can also be defined. This approach has previously been used to optimally design a plant under conditions of process inoperability (Tan et. al., 2014).

In the operation of a plant, uncertainties are always present. Uncertainties such as seasonal product demands, and raw material supplies should be considered since it can result in erroneous and expensive decisions in the design of energy systems if not considered (Akbari et. al., 2014). Different scenarios may arise due to these aforementioned uncertainties. Changes in product demand or raw material supply will result in changes in the required capacity of a particular process unit. A more realistic model in the operation of the system can be made whenever uncertainties are accounted for based on the set objective in terms of profitability and identified constraints. In this study, optimal and sub-optimal solutions will be represented in P-graph considering every given scenario with uncertainties.

2. PROBLEM STATEMENT

A polygeneration system which consists of various interdependent process units is given. Each process unit is considered as a block box where the ratio of the flow streams is fixed. The process units are to operate within the set operating range. A process unit is considered to be shut off when the required capacity is below or above the operating range. The polygeneration system is designed to be operated in the baseline scenario but can be adjusted to meet new product demands or changes in raw material supply. The objective is to maximize the profit in the operation of the plant in consideration of uncertainties.

3. THEORETICAL FRAMEWORK

A polygeneration system model developed using P-graph approach is advantageous against other traditional linear programming methods because it can generate the optimal structure and other suboptimal solutions. These sub-optimal solutions are critical for decision making. The P-graph framework utilizes a directed bipartite graph to uniquely represent process structures (Friedler et. al., 1992a). It utilizes two types of vertices – M-type and O-type vertices which are connected by directed arcs. The M-type (material type) vertex is designated by a circle which represents material and energy flows within the system. The O-type (operating unit type) vertex is designated by a horizontal bar which represents the operating units in the system.

The P-graph framework has three algorithms – Maximal Structure Generation (MSG) algorithm, Solution Structure Generation (SSG) algorithm, and Acceleration Branch-and-Bound (ABB) algorithm. The MSG algorithm generates the maximal structure of the system. A set of five axioms are needed to satisfy in order to generate the optimal structure of the system (Friedler et. al., 1992b). The maximal structure of the system is the union of all the combinatorially feasible structures (Friedler et. al., 1993). The MSG algorithm has two parts – reduction and composition. The first part is the reduction part and it excludes process units and materials that must not appear in the maximal structure. The second part is the composition part and it is done by mapping operation in the algorithm, considering all the possible pathways from a raw material, an intermediate or by-product to a process unit and an end product.

The SSG algorithm generates all the solution structures from the maximal structure. A solution structure of a system is a combinatorially feasible structure of the system. The generation of the solution structures from the maximal structure is based on decision mapping (Friedler et. al., 1992a). The SSG algorithm is recursive and is proven to generate all solution structures exactly once without generating non-feasible solutions.

The ABB algorithm is used to solve the global optima and the n-best suboptimal structures (Bertok et. al., 2013). The importance of generating the suboptimal solutions is to provide options during decision making.

4. CASE STUDY

The P-graph Studio Program (Friedler et al., 2015) was used to optimize the polygeneration systems under study. The polygeneration system is a quadgeneration system producing heat, power, cooling, and treated water simultaneously with fuel oil and fresh water as raw materials. The product demands were considered as uncertain. The process flow diagram of the quadgeneration system is shown in Fig. 1.

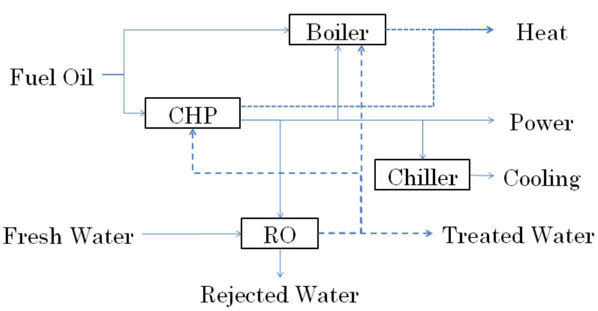

Fig. 1. Process flow diagram of polygeneration system for the Case study (Kasivisvanathan et. al., 2013)

For the polygeneration system above, the equivalent P-graph model is shown in Fig. 2.

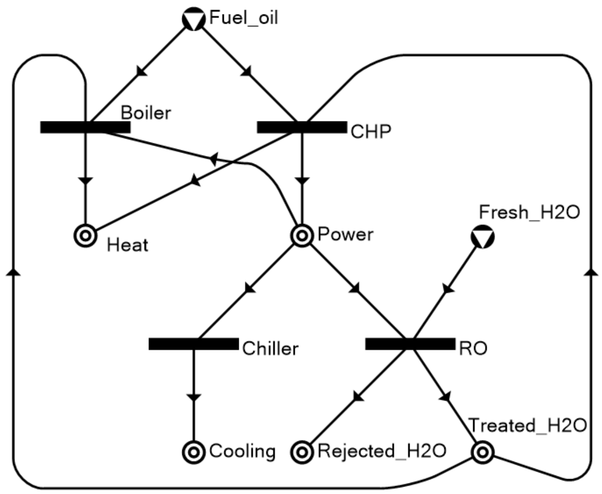

Fig. 2. P-graph model of the polygeneration system for the Case study

The process data and costs for the polygeneration system was taken from Kasivisvanathan et. al. (2013). The capacity of the operating unit is determined by the amount of the main product it produces. The main products of the boiler, CHP, chiller and RO module are heat, power, cooling and treated water, respectively. The feasible operating ranges of the operating units were also taken from Kasivisvanathan et. al. (2013). The feasible operating range for RO module will be assumed to be 60% to 110% in this case study. A summary of the baseline capacities and feasible operating ranges of the process units are shown in Table 1.

Table 1. Baseline capacity and feasible operating range of the process units in the polygeneration system

Process Unit	Baseline Capacity	Feasible Operating Range (%)
Boiler	6,881 kW	80-120
CHP	12,079 kW	90-125
Chiller	8000 kW	90-110
RO module	137 L/s	60-110

Aside from the baseline operating condition (Scenario 1), two other demand scenarios will be considered. In Scenario 2, it will be assumed that the demand of heat and power both decrease by 10% while the demand of cooling is retained and demand for treated water increases by 5% relative to the

ISSN 2449-3309

baseline scenario. In Scenario 3, it will be assumed that the demand for heat will increase by 10%, power will increase by 15% while the demand for cooling will decrease by 10% and the demand for treated water will decrease by 10% relative to the baseline scenario. Table 2 summarizes the product demands for each scenario.

Table 2. Product demands for each scenario with uncertain raw material supply

Product	Baseline scenario	Scenario 2	Scenario 3
Heat (kW)	25,000	22,500	27,500
Power (kW)	10,000	9,000	11,500
Cooling (kW)	8,000	8,000	7,200
Treated Water (L/s)	100	105	90

5. RESULTS AND DISCUSSION

By using P-graph studio, the solutions were obtained and are shown in Table 3.

Table 3. Process unit capacities and profit calculated for each scenario in case study 1

Process Unit	Baseline Scenario	Scenario 2	Scenario 3
Boiler	1	0.856	1.07
CHP	1	0.917	1.11
Chiller	1	1	0.9
RO	1	1.01	0.956
Profit	4121.6 $ / h	4904 $ /h	2836.8 $ /h

From the results, it can be seen that the capacities of the process units change as demands change. The new capacities are within the feasible operating ranges for each process units. Given the scenarios, the polygeneration system will still operate at a profitable level following changes in demand.

To demonstrate the suboptimal solutions of P-graph, the product demands were changed to a range of within 20% of the demands at baseline scenario. For this case, two solutions were found. The results are shown in Table 4.

Table 4. Process unit capacities and profit calculated for the new demands

Process Unit	Solution 1	Solution 2
Boiler	0.8	0
CHP	1.1	1.1
Chiller	0.9	1.1
RO	1.1	1.1
Profit	6053.9 $ / h	5355.4 $ / h

The optimal solution is the solution 1 which generates a profit of 6053.9 $/h while the suboptimal solution is the solution 2 which generates a profit of 5355.4 $/h. By operating under the conditions of solution 2, the loss relative to solution 1 would be 698.5 $/h. In solution 2, the boiler is shut off which shows that the plant can be operated at a different configuration. Fig 3 shows the P-graph representation of this alternative configuration.

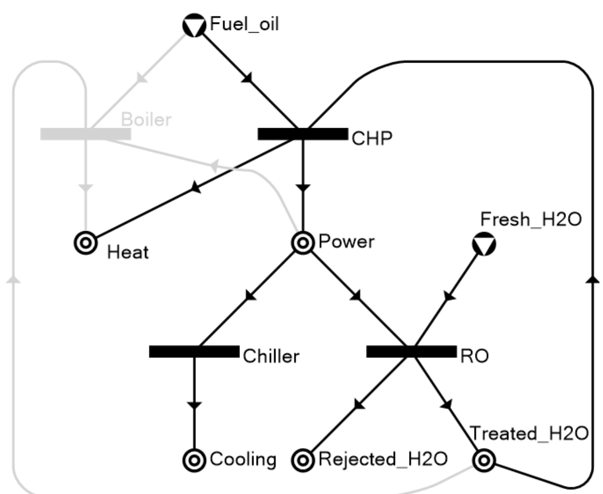

Fig. 3. P-graph representation of the alternative configuration in the operation of the plant.

6. CONCLUSION

A P-graph approach to optimization of a polygeneration system under uncertainty was developed. The use of P-graph in the optimization allows the user to easily see changes in the operating capacities and profit after changes in the product demands. Future work includes the use of a multi-period P-graph model to model the uncertainty in the operation of the plant.

7. ACKNOWLEDGEMENT

The authors would like to acknowledge De La Salle University for providing the venue for the conduct of research.

8. REFERENCES

Akbari, K., Nasiri, M.M., Jolai, F., & Ghaderi, S.F. (2014). Optimal investment and unit sizing of distributed energy systems under uncertainty: A robust optimization approach. *Energy and Buildings 85 (2014)*: 275-286.

Bertok, B., Barany, M., & Friedler, F. (2013). Generating and analyzing mathematical programming models of conceptual process design by p-graph software. *Industrial and Engineering Chemistry Research, 52* (1), 166-171.

Friedler, F., Fan, L.T., & Bertok, B. (n.d.). P-graph. Retrieved February 21, 2015, from www.p-graph.com.

Friedler, F., Tarjan, K., Huang, Y.W., & Fan, L.T. (1992a). Combinatorial algorithms for process synthesis. *Computers and Chemical Engineering, 16*, 313-320.

Friedler, F., Tarjan, K., Huang, Y.W., & Fan, L.T. (1992b). Graph-theoretic approach to process synthesis: axioms and theorems. *Chemical Engineering Science, 47* (8), 1973-1988.

Friedler, F., Tarjan, K., Huang, Y.W., & Fan, L.T. (1993). Graph-theoretic approach to process synthesis: Polynomial algorithm for maximal structure generation. *Computers and Chemical Engineering, 17* (9), 929-942.

Grossmann, I.E., & Santibanez, J. (1980). Applications of mixed-integer linear programming in process synthesis. *Computers and Chemical Engineering, 4*, 205-214.

Kasivisvanathan, H., Barilea, I.D.U., Ng, D.K.S., & Tan, R.R. (2013). Optimal operational adjustment in multi-functional energy systems in response to process inoperability. *Applied Energy 102 (2013)*: 492-500.

Serra, L.M., Lozano, M., Ramos, J., Ensinas, A.V., & Nebra, S. A. (2009). Polygeneration and efficient use of natural resources. *Energy, 34,* 575-586.

Tan, R.R., Cayamanda, C.D., & Aviso, K.B. (2014). P-graph approach to optimal operational adjustment in polygeneration plants under conditions of process inoperability. *Applied Energy, 135*, 402-406.

Zhang, J., Liu, P., Zhou, Z., Ma, L., Li, Z. & Ni, W. (2014). A mixed-integer nonlinear programming approach to the optimal design of heat network in a polygeneration energy system. *Applied Energy, 114*, 146-154.

Zheng, L., Weidou, N., Hongtao, Z., & Linwei, M. (2003). Polygeneration energy system based on coal gasification. *Energy for Sustainable Development, 7*, 2359-2371.