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A P-Graph Model for Multi-period Optimization of Isolated Energy Systems

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Reliable isolated energy systems are necessary for supplying energy to remote areas where grid extension is not feasible. It may also be required to harness renewable energy to reduce the use of conventional fuel that involves potentially high transportation cost and carbon emissions. Polygeneration systems are suitable for distributed energy supply in remote areas with the advantages of compactness and operational flexibility. Also, the simultaneous production of multiple utilities and products provides the opportunity for process integration, hence increased fuel efficiency and reduced carbon emissions. The challenge is to identify the optimal design of the processes such that the system remains in operation regardless of anticipated changes in raw material supply and product demand during multi-period operations. Graph theoretic models in the form of a P-graph (process graph) have previously been developed for synthesizing single period polygeneration systems. This work aims to develop a P-graph model to handle multi-period operations of isolated energy systems. The resulting network is thus more robust since it is able to operate amidst changes in the availability of raw material supply and/or variations in product demand. In addition, the P-graph model is also capable of generating near-optimal solutions which provide insights into other intangible parameters that may be significant to decision-makers. A case study will be presented to demonstrate the proposed approach.

1. Introduction

Green energy technologies are an essential component of the global response to the challenges posed by climate change, which is rapidly approaching crisis levels (Rockström et al., 2009). In particular, the Process Integration (PI) research community has focused on the development of systematic tools for the optimal synthesis, design and operation of such clean, low-carbon systems (Yong et al., 2016). In particular, emphasis on the utilization of internally available resources is one of the principles emphasized to achieve optimal efficiency. Two major groups of methodologies, Pinch Analysis and Mathematical Programming, have developed into complementary strategies over the course of four decades, with the former being useful for insight-based decision-making, and the latter for detailed treatment of system features (Klemeš and Kravanja, 2013). A recent review paper highlights the potential for further integration of the process graph (P-graph) framework to complement these approaches (Klemeš et al., 2013). P-graph methodology was initially developed through the fundamental axioms of Process Network Synthesis (PNS) proposed by Friedler et al. (1992a). Subsequent papers developed algorithms for synthesis (Friedler et al., 1992b) and rigorous generation of maximal structures (Friedler et al., 1993). Various applications emerged in the subsequent two-decade period, as documented in the review by Lam (2013). Since its inception, P-graph methodology has started to become accepted by the mainstream chemical engineering community, as evidenced by its appearance in modern textbooks (Peters et al., 2003) and professional magazines (Cabezas et al., 2015). More detailed treatment is given in specialized reference books (e.g., Klemeš et al., 2011). Furthermore, recent papers have documented the geographic and disciplinal spread of P-graphs (Klemeš and Varbanov, 2015) as well as its integration into undergraduate curriculum for the synthesis of Green Processes (Lam et al., 2016).

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In this work, a P-graph based methodology is developed for the optimal synthesis of isolated energy systems for multi-period operations. The proposed methodology uses a modification of the multi-period P-graph framework proposed by Heckl et al. (2015); an innovative feature of the approach presented here is the integration of part load operating limits for process units, using a more elegant representation that the original method recently developed by Tan and Aviso (2016). The rest of this paper is organized as follows. A formal problem statement is given in Section 2. Then, a brief description of P-graph methodology is given in Section 3. Then, an illustrative case study is solved in Section 4. Finally, conclusions and prospects for future work are given in Section 5.

2. Problem Statement

The formal problem statement can be given as follows: There are *N* energy sources available for the off-grid supply of electricity in remote areas. There are *M* energy demands. There are *P* periods considered such that both energy source and demand vary between periods. The objective is to develop a P-graph model for identifying all feasible network structures in the design of a hybrid renewable energy system (HRES) such that the optimal network minimizes the total cost of the system.

3. P-graph methodology

P-graph methodology was originally developed for PNS problems in chemical engineering applications, although it has also proven to be suitable for addressing other problems of analogous structure. It is a bipartite graph with two kinds of vertices, i.e., process units (O-type vertices shown as horizontal bars) and material streams (M-type vertices shown as dots); arcs are then used to signify relationships between the process units and the materials. P-graph methodology is based on five axioms stated by Friedler et al. (1992a) as follows:

- Every final product is represented in the graph.
- A vertex of the M-type has no input if and only if it represents a raw material.
- Every vertex of the O-type represents an operating unit defined in the synthesis problem.
- Every vertex of the O-type has at least one path leading to a vertex of the M-type representing a final product.
- If a vertex of the M-type belongs to the graph, it must be an input to or output from at least one vertex of the O-type in the graph.

P-graph methodology is comprised of the following algorithms:

- *Maximal structure generation* (MSG) – mathematically rigorous elucidation of a maximal structure (i.e., superstructure) based on the five axioms.
- *Solution structure generation* (SSG) – mathematically rigorous enumeration of combinatorially feasible subsets of the maximal structure. This algorithm is the basis for ability of P-graph to elucidate multiple near-optimal solutions, a feature which is useful for practical energy systems synthesis (Voll et al., 2015).
- *Accelerated branch-and-bound* (ABB) – efficient determination of optimal network given a specified objective function and lower limit constraints. ABB uses unique information implicit in PNS problems to execute efficient search of the solution space compared with conventional branch-and-bound.

Free software (i.e., P-graph Studio, which integrates the earlier PNS Draw and PNS Studio software into one program), tutorials and on-line support are available at the website (www.p-graph.com). Although the generic PNS problem assumed steady-state operation, recently a multi-period approach was proposed by Heckl et al. (2015); then, Tan and Aviso (2016) developed an extension that allows part load operating limits of process units to be considered. In this work, an improvement of the latter work is proposed. A process unit that needs to operate under multiple periods with part load limits (below which operation becomes infeasible or unstable) can be represented similar to the example shown in Figure 1. Figure 1 shows the flows for a diesel engine which has an efficiency of 36 % and operates for two different seasons of equal period length (8,000 hours in a year). The proportion of the period length with respect to the total operating period of the system is indicated by the streams stemming out of the process unit labeled PHYS_UNIT. For this example, the flow rate of each stream is 0.5 u/y. In addition, the diesel engine has an operating range of 30 % - 100 %. The part load limit of 0.3 is indicated in the flowrate of the stream exiting the node labeled PL. Note that a fictitious process unit is added to represent the ratio between the lower part load limit and the rated capacity. This is added to the fictitious unit proposed by Heckl et al. (2015) to represent the rated capacity of the process unit. In this work, it is assumed that any process unit installed runs continuously within its operating limits; furthermore, no provision for energy storage is considered, which limits this approach to long-term seasonal variations in supply and demand.

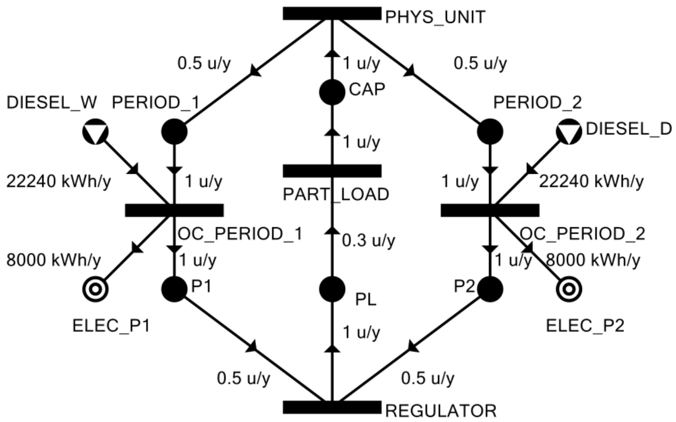

Figure 1. Multi-period P-graph representation for Diesel Engine

4. Case Study

This case study illustrates the application of the P-graph model for the design and development of a Hybrid Renewable Energy System (HRES) for an isolated rural community. Many such communities exist in developing countries such as the Philippines, or in more developed economies such as Taiwan, where geographic conditions (e.g., islands) cause the isolation. In such cases, local populations and energy demand may be too small to justify grid connectivity, thus requiring the installation of off-grid systems that utilize local energy resources such as rivers or crop residues. However, seasonal variations in power demand and supply of such resources will often result in the need to hybridize the renewable energy units with conventional power sources. Other Process Integration methods have been applied for the design of such systems (e.g., Bandyopadhyay, 2011). The case considered here considers four potential process units:

- *Micro-hydropower* – these are small-scale hydroelectric turbines rated at 100 kW to 1 MW, which are highly suited to remote locations with a river of suitable head and water flowrate.
- *Biomass-fired external combustion gas turbine* (ECGT) – these are gas turbines whose working fluids are heated via indirect heat transfer from combustion gases. The working fluids may circulate using an open cycle (atmospheric air) or a closed cycle. This configuration allows the use of fuels of poor and variable quality, such as residual biomass from farms.
- *Biomass-fired Stirling engine* – these are reciprocating external combustion engines with working fluids circulating in a closed circuit, thus offering similar advantages as ECGTs.
- *Diesel engine* – these are conventional compression ignition (CI) engines that are typically used as back up units in small HRES. Their main disadvantage is the need to import the diesel fuel into remote locations.

In this hypothetical case study, the site is assumed to experience dry and wet seasons, each comprising approximately 6 months per year. The electricity demand and availability of energy sources vary depending on the season. It is assumed that the process units operate at 4,000 hours per season or a total of 8,000 hours per year and have service lives lasting for 15 years. The limiting data for the energy supply and demand are given in Table 1. It can be seen that for renewable sources of energy, the availability varies with each season. The technology matrix which contains the process flows for each process is shown in Table 2. The part-load coefficients and cost data associated with the process units are shown in Table 3. In addition, the selling price for electricity is $ 0.36 per kWh and the cost for diesel fuel is $0.058 per kWh. Each process unit is thus represented in the P-graph framework and the maximal structure is as shown in Figure 2. The multi-period nature of this case study is represented using a modified approach which was initially proposed by Heckl et al. (2015) and later on extended by Tan and Aviso (2016) to account for part-load requirement in process units. The P-graph optimizes the system with the objective of minimizing the total annual cost of the system. Upon optimization, the optimal network is as shown in Figure 3.

Table 1: Limiting data for energy sources and demand for wet and dry season

		Wet Season (W)	Dry Season (D)
Energy Source			
	Micro-hydropower	720 MWh/y (180 kW)	480 MWh/y (120 kW)
	Biomass	2,000 MWh/y (500 kW)	1,000 MWh/y (250 kW)
	Diesel Fuel	1,200 MWh/y (300 kW)	1,200 MWh/y (300 kW)
Energy Demand			
	Electricity	800 MWh/y (200 kW)	1,000 MWh/y (250 kW)

Table 2: Technology matrix for process flows (units in kW)

	Micro-hydropower	ECGT	Stirling Engine	Diesel Engine
Hydropower	-1.25	0.00	0.00	0.00
Biomass	0.00	-3.57	-4.55	0.00
Diesel	0.00	0.00	0.00	-2.78
Electricity	1.00	1.00	1.00	1.00

Table 3: Part-load coefficients and capital costs associated with process units

	Part-load	Fixed Cost $	Variable Cost $/kW
Hydropower	0.20	22,240	210
ECGT	0.40	45,240	500
Stirling Engine	0.40	50,240	750
Diesel Engine	0.30	24,240	280

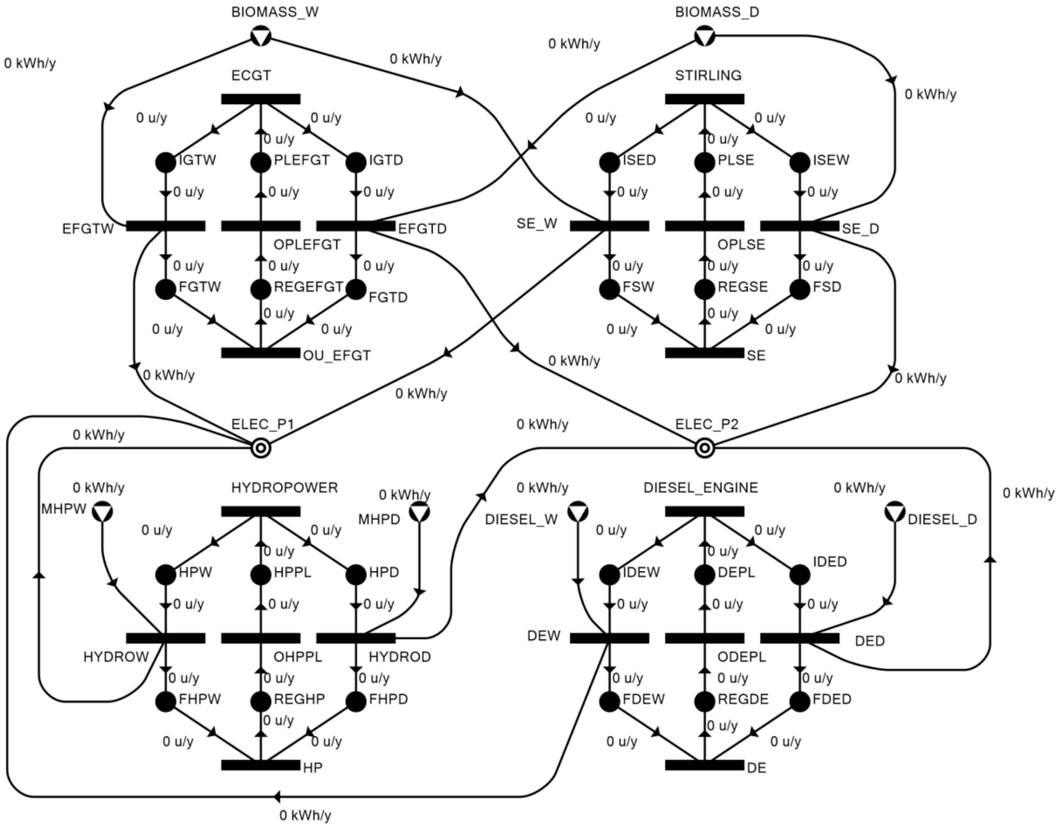

Figure 2: Maximal structure of electricity generation network for case study

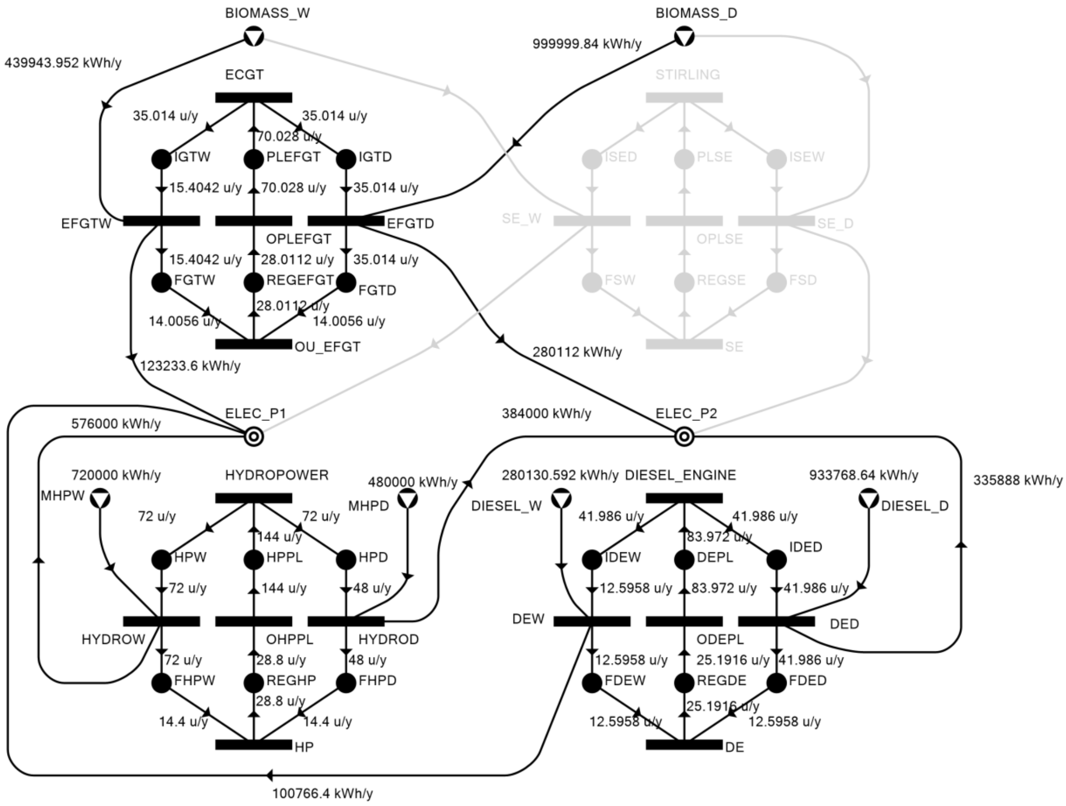

Figure 3: Optimal network for case study

Table 4: Process flows for optimal network in kW for wet and dry season

	Wet Season				Dry Season			
	Micro-Hydro	ECGT	Stirling Engine	Diesel Engine	Micro-Hydro	ECGT	Stirling Engine	Diesel Engine
Hydropower	-180.00	0.00	0.00	0.00	-120.00	0.00	0.00	0.00
Biomass	0.00	-109.99	0.00	0.00	0	-250.00	0.00	0.00
Diesel	0.00	0.00	0.00	-70.03	0	0.00	0.00	-233.44
Electricity	144.00	30.81	0.00	25.19	96.00	70.03	0.00	83.97

The process flows associated with the optimal solution for both seasons are shown in Table 4. It can be seen that the optimal solution is to install hydropower, ECGT and a diesel engine. The total capital cost for the system amounts to $ 180,487 ($ 12,032 /y) to install a 144-kW micro-hydropower system, a 70.03-kW ECGT and an 83.97-kW diesel engine. It can be seen that the micro-hydropower operates at full capacity during the wet season and at 67 % of its capacity during the dry season, while the contrary is true for the ECGT and the diesel engine, which are at full capacity during the dry season while the ECGT operates at 44 % and the diesel engine at 30 % of their respective capacities during the wet season. Furthermore, the optimal solution has an annual profit of $ 514,209. A near optimal solution utilizing a 46.09-kW Stirling engine, a 144-kW micro-hydropower system and a 107.91-kW diesel engine can also be considered. This alternative system generates an annual profit of $ 499,762. In practice such near optimal solutions may be useful for decision-makers (Voll, 2015).

5. Conclusions

A P-graph based model for the optimization of isolated energy systems has been developed. This approach allows optimal hybrid systems to be synthesized taking into account the techno-economic characteristics of individual process units as well as seasonal variations in electricity demand and availability of resources. A novel P-graph representation of process units for multi-period operations with part load limits is also developed and integrated into the model. A case study involving a hybrid mini-hydro/biomass/diesel system for a remote rural community is solved to illustrate the P-graph model. Future work will focus on extending the P-graph approach to cover optimization disjunctions that arise from the possibility of switching off individual process units. Also, energy storage options need to be integrated into the model. These improvements will enable short-term variations (e.g., daily cycles) to be dealt with.

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Reference

Bandyopadhyay S., 2011. Design and optimization of isolated energy systems through pinch analysis. Asia-Pacific Journal of Chemical Engineering, 6, 518–526.

Cabezas H., Heckl I., Bertok B., Friedler F., 2015. Use the P-graph framework to design supply chains for sustainability. Chemical Engineering Progress, 111, 41-47.

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 and Chemical Engineering, 16, 313 – 320.

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

Heckl I., Halász L., Szlama A., Cabezas H., Friedler F., 2015. Process synthesis involving multi-period operations by the P-graph framework. Computers and Chemical Engineering, 83, 157-164.

Klemeš J.J., Friedler F., Bulatov I., Varbanov P., 2011. Sustainability in the Process Industry: Integration and Optimization. McGraw-Hill, New York, USA.

Klemeš J.J., Kravanja Z., 2013. Forty years of heat integration: pinch analysis (PA) and mathematical programming (MP). Current Opinion in Chemical Engineering, 2, 461-474.

Klemeš J.J., Varbanov P.S., Kravanja Z., 2013.Recent developments in Process Integration. Chemical Engineering Research and Design 91, 2037-2053.

Klemeš J.J., Varbanov P.S., 2015, Spreading the Message: P-graph Enhancements: Implementations and Applications. Chemical Engineering Transactions, 45, 1333-1338.

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

Lam H.L., Aviso K.B., Tan R.R., 2016. Implementation of P-Graph Modules in Undergraduate Chemical Engineering Degree Programs: Experiences in Malaysia and the Philippines. Journal of Claner Production, In press, DOI:10.1016/j.jclepro.2016.03.110.

P-graph, 2016, <www.p-graph.com> accessed 10.04.2016.

Peters M.S., Timmerhaus K., West R.E., 2003. Plant Design and Economics for Chemical Engineers (5th ed.). McGraw-Hill, New York, USA.

Rockström J., Steffen W., Noone K., Persson A., Chapin F.S., Lambin E.F., Lenton T.M., Scheffer M., Folke C., Schellnhuber H.J., Niykvist B., De Wit C.A., Hughes T., Van der Leeuw S., Rodhe H., Sorlin S., Snyder P. K., Constanza R., Svedin U., Falkenmark M., Karlberg L., Corell R.W., Fabry V.J., Hansen J., Walker B., Liverman D., Richardson K., Crutzen P., Foley J. A., 2009. A safe operating space for humanity. Nature 461, 472-475.

Tan R.R., Aviso K.B., 2016. An extended P-graph approach to process network synthesis for multi-period operations. Computers and Chemical Engineering, 85, 40-42.

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.

Voll P., Jennings M., Hennen M., Shah N., Bardow A., 2015. The optimum is not enough: A near-optimal solution paradigm for energy systems synthesis. Energy, 82, 446-456.

Yong J.Y., Klemeš J.J., Varbanov P.S., Huisingh D., 2016. Cleaner energy for cleaner production: modelling, simulation, optimisation and waste management. Journal of Cleaner Production 111, 1- 16.