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P-graph Approach to Criticality Analysis in Bioenergy Parks under Uncertainty

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A bioenergy park is an integrated network of biomass processing industries that optimally allocate products, by-products, wastes, and utilities in order to improve sustainability. However, such systems are also characterized as having inherent vulnerability to cascading disruptions due to inoperability (i.e., capacity reduction) of one or more of its component plants. The inoperability of bioenergy plants can be caused by supply-side disruptions due to reductions in the available biomass feedstocks. It is therefore necessary to incorporate risk analysis when designing bioenergy parks. A previous study developed a risk-based criticality analysis in integrated bioenergy systems (IBS) based on P-graph methodology. This approach utilizes the algorithmic capabilities of the P-graph framework in order to identify critical facilities in an IBS. However, uncertainties in the demand for bioenergy products are not yet considered in the framework. This work thus proposes an extension to the P-graph based method for criticality analysis in bioenergy parks with demand perturbation scenarios. The method can be used in long-term planning and developing robust bioenergy parks. A case study is presented to demonstrate the applicability of the proposed approach.

1. Introduction

The demand for bioenergy continues to increase as production facilities pursue sustainability by looking for alternatives to fossil fuels (Hong et al., 2016). Also, the use of bioenergy is seen as a potential strategy to mitigate climate risks via the reduction in the atmospheric greenhouse gas (GHG) emissions. Bioenergy parks are interconnected biomass-based production plants that achieve sustainable operations through material and energy exchanges. It is a specific type of an industrial symbiosis (IS) network that optimally allocates products, by-products, wastes, and utilities of component plants within the network. The bioenergy park concept is proposed by Martin and Eklund (2011) to increase the performance of biofuel production facilities and to address related sustainability issues (e.g., energy efficiency). This industrial complex-type integrated bioenergy system (IBS) is proven to reduce carbon emissions and increase the profitability of each participating plant. However, such integrated systems are known to be inherently vulnerable to cascading failures caused by the inoperability of one or more of its components (e.g., bioenergy plants). This capacity disruption results in a deviation from a baseline state (i.e., net output) of the bioenergy park. Climate change-induced events such as drought and extreme weather can cause this supply-side disruption. Bioenergy production is dependent on available biomass feedstocks, thus, any reduction in supply will greatly affect the entire supply chain including biomass-based facilities (Langholtz et al., 2014). A risk analysis framework is therefore necessary prior implementing the bioenergy park strategy.
Criticality analysis is a method developed by Benjamin et al. (2015) to determine the effect of capacity disruptions in various integrated energy systems. This approach quantifies the reduction in the net output of a product stream brought about by the reduction in the production level of a component plant (or process unit). The plants in the entire network are then ranked based on criticality to determine the most crucial component and which will require greater risk mitigation strategies (e.g., increasing redundancy). The model is developed using the concepts derived from input-output (I-O) analysis, a method used to determine linear relationships between components of a complex system (Leontief, 1936). The I-O method is traditionally used in analyzing the interdependency of global economic sectors but now widely used in similarly-structured systems such as a bioenergy park.

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A recent work of Benjamin et al. (2016) used a P-graph approach to criticality analysis in bioenergy parks and demonstrated that it can be an alternative to the I-O based method. P-graph is a graph theory and combinatorial algorithm-based methodology that is developed by Friedler et al. (1992a) to solve process network synthesis (PNS) problems. The advantages of this approach are the P-graph software's ability to model I-O systems and accordingly display results through a graphical interface. The P-graph based criticality analysis is extended in this study to account for changes in the product demand for bioenergy parks. Demand uncertainty is defined by Awudu and Zhang (2012) as the unpredictability of the variation in the amount (and timing) of demand in the biofuel supply chain. This parameter is considered in this study since it will greatly affect the sustainability of an IBS in terms of economic profitability. Hong et al. (2016) also noted the importance of developing robust and flexible supply chains by anticipating fluctuations in the demand for bioenergy.

P-graph based approaches are used in designing IBS in order to attain sustainability (Lam et al., 2012). Recent developments, as well as future directions, in the application of P-graph are discussed in the review paper of Klemeš and Varbanov (2015). The P-graph method is also used to solve similarly structured problems in polygeneration systems (Tan et al., 2014), biorefineries (Atkins et al., 2016), industrial complexes (Tan et al., 2016), urban infrastructures (Tan et al., 2015), and economic sectors (Aviso et al., 2015). However, to date, P-graph is not yet applied to criticality analysis with uncertainty in bioenergy parks or IBS in general.

In this work, a P-graph approach is used in criticality analysis of bioenergy parks while considering uncertainties in product demands. This method is important in determining appropriate risk mitigation strategies for potential demand perturbation scenarios. The rest of the paper is as follows: a problem statement and the general framework are presented next. The P-graph based methodology is then shown and the corresponding bioenergy park case study to demonstrate the proposed approach. Finally, conclusions and future research works related to this study are presented towards the end of the paper.

2. Problem Statement

The general framework for uncertainty analysis is stated as follows:

- A bioenergy park with *n* number of bioenergy plants is assumed. Each component plant produces a specific product stream and is characterized by fixed ratios of input and output streams using material or energy balance. The network topology (i.e., input-output links) is also known.
- Using a baseline net output of product streams, the capacity of each bioenergy plant is determined via the P-graph software. Criticality analysis is then performed to determine the reduction in the net output of a particular product stream. The capacity of a component plant is assumed to be reduced and this value is encoded in the software as an exogenous input. The reduction in the corresponding product stream is then solved. The detailed methodology for criticality analysis is found in Benjamin et al. (2015).
- To determine the effect of uncertainty to criticality, *m* number of demand perturbation scenarios is assumed. For each scenario, the demand for one product stream is increased to determine its effect in the performance of the bioenergy park during capacity disruptions. Criticality analysis is again conducted to show the sensitivity of the net output of each product stream in various demand change scenarios.

Figure 1 shows the general framework for criticality analysis in bioenergy parks under uncertainty using P-graph.

3. P-graph Methodology

The P-graph methodology is a graph theoretic framework developed to solve PNS (Friedler et al., 1992b). The approach is based on five axioms (Friedler et al., 1992a) and utilizes an efficient algorithm for determining maximal structures (Friedler et al., 1993). These axioms describe in detail the information that present is in PNS problems. One of the advantages of this method is its capability to determine both optimal and near-optimal solutions of a given problem. Also, P-graph's interface enables the user to determine the results visually.

The P-graph uses two kinds of vertices to form the bipartite graph. The M-type vertex (i.e., dots) represents material or energy flows and the O-type vertex (i.e., horizontal bars) represents the operating units in a given network. In this work, the M-type vertices are the bioenergy products (as well as raw materials) and the O-type vertices are the bioenergy plants or process units. These vertices are then connected by arcs in order for the P-graph framework determines the solution to the PNS problem. However, recent studies demonstrate that these vertices may represent other materials or activity such as monetary units in an economic sector. Thus, the P-graph framework can be further extended to solve analogous structures beyond the traditional PNS problems.

On the hand, the three algorithms embedded in the P-graph method are as follows. First, the maximal generation structure (MSG) is a rigorous superstructure generated from all possible solution structures (i.e., the number of ways producing the final product). Second, using this information, the solution structure generator (SSG) determines then the subset of all combinatorially feasible structures. Lastly, the accelerated branch-and-bound

(ABB) algorithm efficiently determines the optimal as well as non-optimal solutions of the PNS. These main algorithms also utilize the information set by the five axioms and the given constraints of a particular problem.
The P-graph Studio software (www.p-graph.com) is used in developing the structure of the PNS. This includes drawing the respective operating units, the corresponding product streams, and the connecting arcs. The software also enables the user to encode exogenously defined parameters such as measurement units, unit capacities, material flows, and costs.
In this work, the capacity disruption and the net output of unaffected product streams are encoded as constraints in the P-graph software. The resulting reduction in the net output is solved after running the model. This approach will be repeated in all demand perturbation scenarios and the results will then be compared.

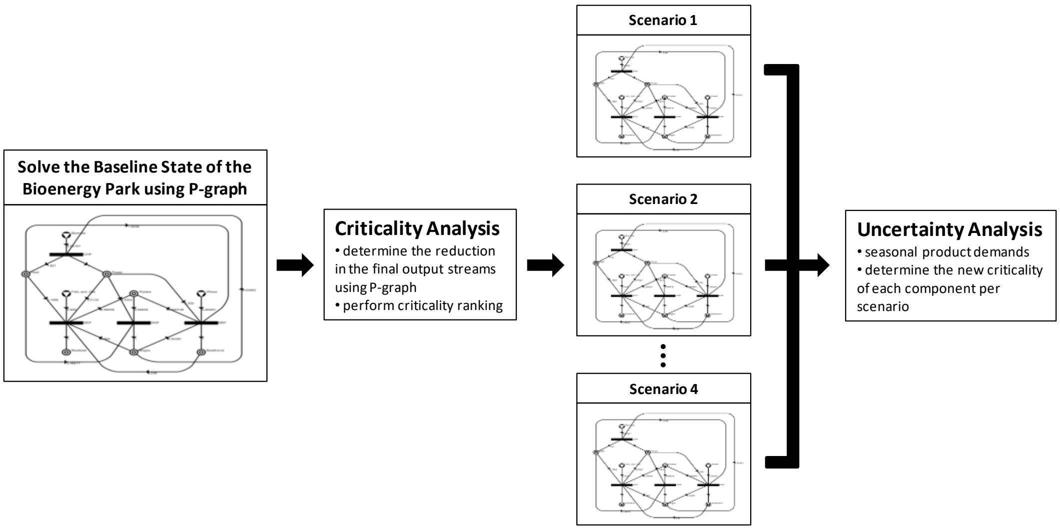

Figure 1: General framework for criticality analysis under demand uncertainty using P-graph.

4. Case Study: Bioenergy Park

The hypothetical bioenergy park case study is adapted from Benjamin et al. (2015). It consists of the following bioenergy plants and product streams. Bioethanol is produced from a wheat-based bioethanol plant (BEP) and vegetable oils are used to produce biodiesel in the biodiesel plant (BDP). The biogas plant (BGP) utilizes wastes from other bioenergy plants and external sources in order to generate biogas. Lastly, biomass feedstocks are used to produce heat and power in a combined heat and power (CHP) plant. The CHP plant provides these utilities to other component plants as seen from the linkages in Figure 2.
Table 1 shows the material and energy balance ratio for each bioenergy plant based on the primary product stream. The net output of the product streams is also shown and this will be the baseline demand. On the other hand, the baseline state (i.e., flows of raw materials and capacity of component plants) of the bioenergy park is shown in Figure 2. The values in the figure were determined using P-graph. It can be seen from the figure that the resulting capacities of bioenergy plants exceeds the net output due to internal requirements within the network. The P-graph version of the input-output flow diagram of the bioenergy parks is shown in Figure 3.
For the criticality analysis, a 5 % reduction in the production level of each bioenergy plant is assumed. This represents a proportional supply-side disruption in the availability of biomass feedstocks and other raw materials. The method assumes that this will result in a decreased net output in the corresponding product stream. Aside from this, the internal demands within the bioenergy park must be satisfied first, thus the reduction is not necessary proportional to the disruption value. The percentage capacity disruption and the baseline demand for unaffected product streams are encoded in the P-graph software as constraint. After running the model, the reduction in the net output for the baseline scenario is presented in Table 2.

Table 1: Process data for the baseline state of the bioenergy park (adapted from Benjamin et al., 2015)

Product stream	CHP	BEP	BDP	BGP	Final output
Power, kW	1	–0.2590	–0.0132	–0.4354	22,000
Bioethanol, L/h	0	1	–0.236	0	25,000
Biodiesel, L/h	0	0	1	0	20,000
Biogas, m^3/h	–0.02963	–0.003810	–0.004	1	1,000

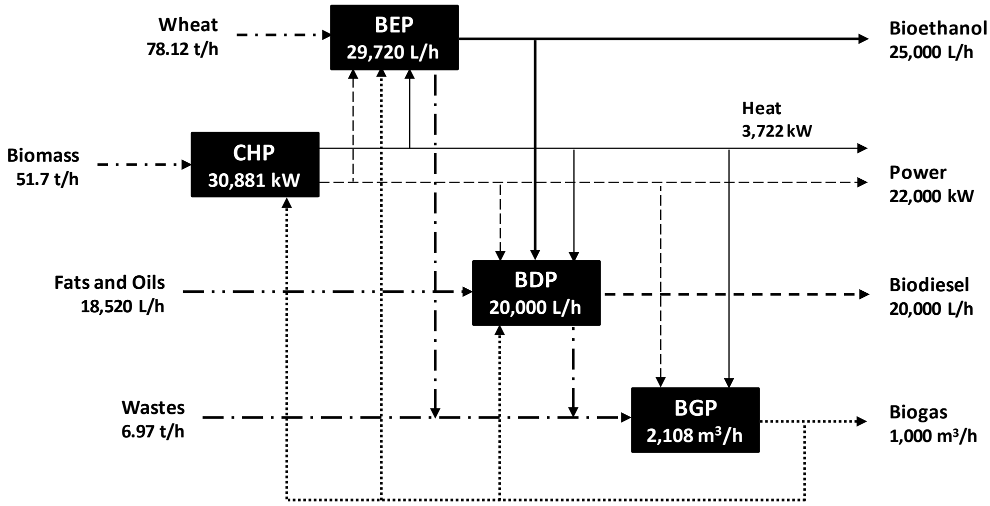

Figure 2: Baseline state of the bioenergy park (adapted from Benjamin et al., 2015).

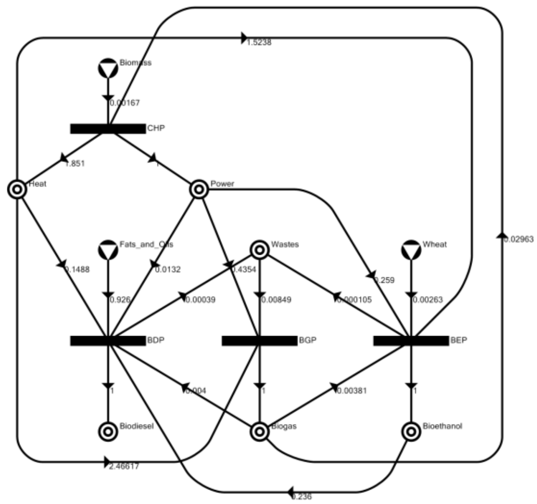

Figure 3: Input-output flow diagram of the bioenergy park using P-graph.

For the uncertainty analysis, the effect of changes in the product demand in the criticality was determined. For each scenario, the net output of one particular stream is increased by 5 % and the rest are at the baseline value. For example, in scenario 1 the demand for power is increased to 23,100 kW from 22,000 kW. Criticality analysis was again conducted per scenario and the results are presented in Table 2. It can be seen that reduction in the perturb demand scenarios is greater compared to the baseline demand scenario. This is due to the additional demand that must be supplied first by interdependent component plants. The changes in the demand causes further amplification of the disruption within the bioenergy park and thus, must be considered in risk mitigation.

Table 2: Reduction in final output of product streams in demand perturbation scenarios

Disrupted bioenergy plant	Affected product stream	Baseline final output	Reduced final output				
			Baseline scenario	Scenario 1	Scenario 2	Scenario 3	Scenario 4
CHP	Power, kW	22,000	22,476	20,476	20,150	20,340	20,454
BEP	Bioethanol, L/h	25,000	23,514	23,514	23,514	23,278	23, 514
BDP	Biodiesel, L/h	20,000	19,000	19,000	19,000	19,000	19,000
BGP	Biogas, m^3/h	1,000	896	864	882	889	896

The percentage change in the final output of the bioenergy plants in the demand perturbation scenarios are presented in Figure 4. The figure shows the sensitivity of the net output (i.e., criticality) to the variations in the demand of a particular product stream. It can be seen in all scenarios that the criticality of the perturb product stream is increased compared to the baseline demand due to additional requirements outside the network. Such seasonal occurrence should be anticipated in the planning stage of the bioenergy park. The system should be designed to allow operational flexibility in production capacity. In the baseline demand, the criticality rankings are shown in Table 3. This provides an insight to risk managers on which is the most critical component in the network that needs the greatest attention. However, it can be seen in the same table that the risk rankings are influenced by changes in the demand. This observation is important since it will have an impact in the appropriate risk management steps to be implemented. For example in scenario 2, the second most critical bioenergy plant is the BEP not the CHP. This shows that each demand perturbation scenario requires a different strategy to address criticality.

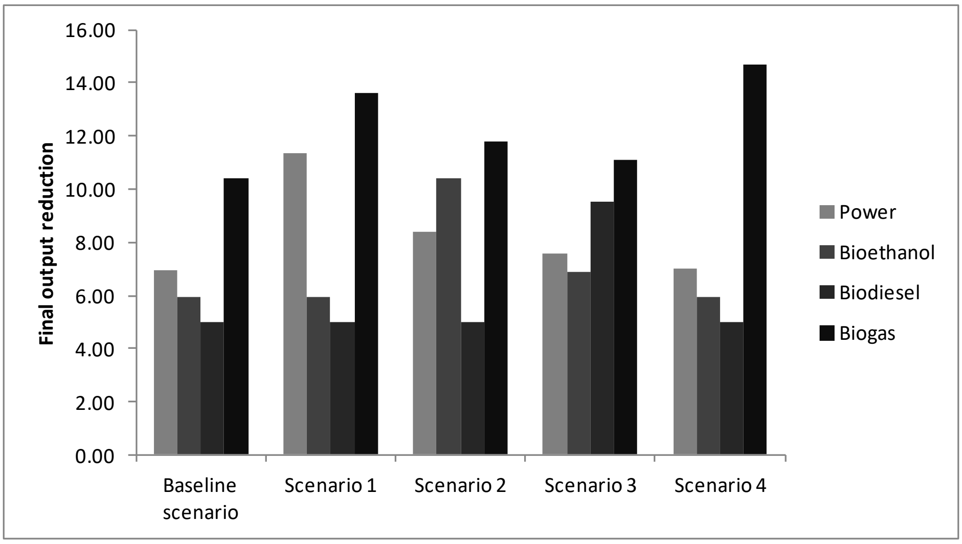

Figure 4: Percentage change in final output of bioenergy park in demand perturbation scenarios

Table 3: Risk ranking of bioenergy plants

Disrupted bioenergy plant	Baseline	Scenario 1	Scenario 2	Scenario 3	Scenario 4
BGP	1	1	1	1	1
CHP	2	2	3	3	2
BEP	3	3	2	4	3
BDP	4	4	4	2	4

5. Conclusions

A P-graph approach to criticality analysis in bioenergy parks with demand uncertainties was developed in this work. This is an extension of the P-graph method developed by Benjamin et al. (2016). The approach determines the reduction in the net output of a particular product stream during seasonal changes in the demand. The insights from this work can be used to develop flexible bioenergy parks that will tolerate anticipated demand perturbations. It can be seen that the criticality rankings of the bioenergy plants vary in the different scenarios, thus, this will require different risk management strategies. Criticality can be addressed by using the concept of redundancy as demonstrated in biomass-based polygeneration systems (Andiappan and Ng, 2016). Future works will focus on using a Monte Carlo simulation-based method in assessing the sensitivity of the bioenergy park from multiple parametric uncertainties.

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