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P-Graph Approach to Optimal Allocation of Electricity to Economic Sectors in Crisis Conditions

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Abstract

Rational allocation of scarce resources in a crisis is an integral part of risk management. In the case of energy systems, for example, the onset of climate change is expected to increase the frequency of extreme weather events which will further affect not only the reliability of electricity transmission and fuel resource delivery but also test the integrity of energy infrastructure systems. Electricity supply is essential to all economic sectors and the onset of an energy crisis resulting from a calamity, an accident, an infrastructure failure or a political dispute will affect the productivity of the entire economy. Furthermore, the interdependencies between sectors can cause “ripple effects” to occur. Input-output models are an established methodology for quantifying such linkages in an economic system. During a power crisis, it is essential to provide a rational basis for allocation of limited energy supply in order to minimize its economic ripple effects. The best allocation for damage control can be determined by representing an input-output system as a P-graph model. The latter is a graph-theoretic approach originally developed for chemical process design applications, and the analogous problem structures allow it to be used for the optimal allocation of electricity to various economic sectors in the event of a power crisis. We demonstrate the methodology using a case study based on Philippine input-output data.

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Keywords: Energy crisis; allocation; P-graph; input-output analysis

1. Introduction

Input-output (I-O) analysis was originally developed for the analysis of highly interconnected economic sectors for purposes of forecasting and policy design [1,2]. Such I-O models represent economic systems via a system of linear equations that capture interdependencies. More recently, I-O

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based optimization models have been proposed for crisis management, such as to determine optimal allocation of scarce resources following a disaster [3-5]. Analogous approaches have been proposed for infrastructure systems [4,6]. In this work, we propose an alternative approach towards solving such problems using a graph-theoretic method known as P-graph, which was originally developed for chemical process design applications [7]. It has since been used for various network optimization problems such as supply chain design; a recent paper reviews the most important developments in the field [8]. A software implementation of this methodology is also available [9].

In this paper, we present the first attempt to utilize P-graphs for allocation of scarce energy resources in an economic system. The rest of the paper is organized as follows. Section 2 gives the formal problem statement while Section 3 gives an overview of P-graph methodology used here. Section 4 shows a Philippine case study to illustrate the methodology and Section 5 gives conclusions and future works.

2. Problem Statement

The problem statement may be formally stated as follows: given an economic I-O system comprised of n sectors and n commodities, and given a crisis event that creates a sudden shortage of the kth commodity, the problem is to determine the optimal allocation of commodity k in the system so as to minimize total reduction of gross domestic product (GDP).

3. P-Graph Methodology

Another method that can be used besides the Leontief's I-O model is to apply graph-theoretic approach for developing input-output model such as P-graph framework. Process graph or P-graph framework is used to determine the optimal solution of a process network system based on graph theory and combinatorial algorithms [7]. P-graph is used in several applications such as optimization of process systems, reduction of emissions and wastes, identification of reaction pathways, and sustainable energy supply chain [8]. P-graph is the graphical representation of matrix calculations such as mixed-integer linear and nonlinear programming (MILP and MINLP) to solve process synthesis problems. With this ability, P-graph can be used to solve I-O models for estimating risk assessment and optimal allocation of resources.

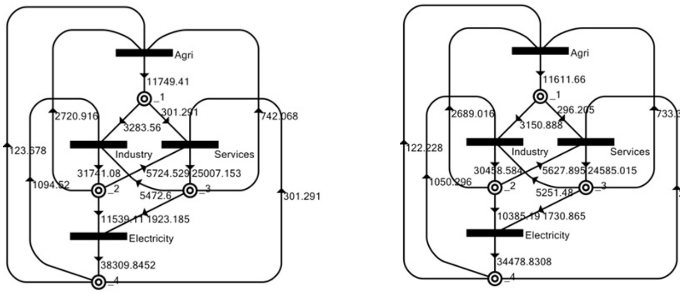
4. Case Study

This case study is based on the current power crisis in Mindanao, the southernmost major island of the Republic of the Philippines. Chronic electricity shortage is experienced in this island during the dry season due to over-dependency on hydroelectric power. This situation is expected to be compounded by climate change. We consider the case of Region XI, which comprises the most economically vibrant region of the island. A low-resolution, 4-sector I-O model of the economy of this region was derived from the most recent official national I-O model [10] using established regional disaggregation and sector aggregation methods [2], as shown in Table 1 with the total output and final demand rounded off to the nearest thousand pesos.

Table 1. Technical coefficients, total outputs and final demands for of 4-sector I-O model (Normal State)

	Agriculture	Industry	Services	Electricity Generation	Final Demand ('000 PhP)	Total Output ('000 PhP)
Agriculture	0.05	0.06	0.01	0.000	81,646	123,678
Industry	0.22	0.42	0.19	0.300	117,565	547,260
Services	0.06	0.10	0.17	0.050	168,693	301,291
Electricity Generation	0.01	0.02	0.01	0.004	367,904	384,637

The economic flows of the system in its baseline state are shown in Figure 1a. In the event of a 10% power shortage with the final demand of all sectors remaining the same, the optimal allocation of electricity to minimize GDP loss in the system can be determined via the Accelerated Branch-and-Boud Method (ABB) within the P-graph model. This result is shown in Figure 1b, with a corresponding 4.95 % reduction in GDP relative to the normal state. Table 2 shows the summary of the experienced reduction in final demand and total output resulting from the 10% power shortage relative to the normal state total output. It can be seen that the 10% shortage in electricity has resulted in a reduction in total output for all other sectors by virtue of their interdependence. The industry sector experiences the second highest loss of 4.04% next to the electricity sector while the agriculture sector has the least reduction in total output of 1.17%. However, even with the shortage in electricity, the final demands of the agriculture, industry and services sector were still satisfied while the demand of the electricity sector was reduced by 9.83%.



(a) (b)

Figure 1. Economic flows for (a) normal and (b) crisis state, units in 10,000 pesos

Table 2. Reduction in final demand and total output resulting from the 10% power shortage relative to normal state total output

Economic Sector	**% Reduction in Final Demand**	**% Reduction in Total Output**
Agriculture	0.00	1.17
Industry	0.00	4.04
Services	0.00	1.69
Electricity	9.83	10.00
Over-all	2.79	4.95

5. Conclusion

A P-graph based approach for the allocation of scarce energy resources under crisis conditions has been presented. The graph-theoretic approach allows for a visual representation of highly interconnected input-output systems, and also enables efficient identification of a globally optimal solution. This technique is demonstrated with a case study on power shortages in the Southern Philippines. In reality, more complex interactions between system components will have to be considered if a higher degree of resolution is desired in the results. Furthermore, since the approach identifies the key sectors which must be prioritized during a crisis, this approach can be utilized for developing strategies for disaster preparedness. Future work will focus on the integration of the P-graph approach within a comprehensive decision analysis framework for crisis management.

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Biography

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