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VIKOR - P-graph Method for Optimal Synthesis of Philippine Agricultural Waste-Based Sustainable Integrated Biorefinery

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A sustainable integrated biorefinery (SIBR) is a biomass processing facility that converts agricultural wastes or residues into a wide range of valuable products where both economic sustainability and environmental sustainability are optimized. This work proposed a hybrid method that incorporates Vlsekriterijumska Optimizacija I Kompromisno Resenje (VIKOR), a widely used multi-criteria decision-making (MCDM) tool with the P-graph (process-graph) framework. The proposed VIKOR - P-graph model can (i) generate a set of combinatorically feasible solutions, and (ii) rank the solution sets using VIKOR method, simultaneously in the same P-graph model. In other words, all the drawbacks attributed to the sequential optimization methods can, therefore, be avoided. To demonstrate the effectiveness of the proposed hybrid methodology, a case study in the Philippines is presented in this paper. The hybrid P-graph model generated a total of 7 feasible solutions with different configuration for the SIBR based on the overall profit (i.e., economic goal) and carbon emissions (i.e., environmental goal). Results show that the best compromised solution can be obtained when majority (70 %) of the rice husk is used to produce bioethanol, where the required power is supplied by combusting the remaining rice husk and by importing external power. It offers an hourly profit of 161 $/h with a lower (~38.6 %) carbon emissions as compared to the most profitable option (3.504 tCO_2-eq/h). This research is essentially a guide for policymakers to make informed decisions that can maximise the benefits of SIBR on a national scale.

1. Introduction

The utilization of biomass to produce bioenergy and other high-value added products is an important step of a country to increase local energy supply and thus lessen its dependence on imported fuels. One way of achieving this is via the development of sustainable integrated biorefineries (SIBR). SIBR is a processing facility that use biomass as feedstock to produce various bioenergy products. Biomass raw materials are converted to biofuels or biochemicals via mechanical, thermochemical, or biochemical processes. The efficiency of this system is further enhanced using process integration by identifying potential material or energy synergies between process units. Aside from this, economic and environmental benefits consideration are possible through integration of process units that could increase farmer revenues and decreased carbon emissions, respectively. Among the available biomass, lignocellulosic materials such as wood waste, herbaceous crops, and residues from agricultural processes can be used in SIBR. In the Philippines and Asia in general, a huge amount of agricultural waste (i.e., from harvesting rice, corn, or sugarcane) remains to be tapped for bioenergy production. In particular, residues from rice production and processing can be utilized as these comprise largely the available waste (Sangalang et al., 2021). About 20 Mt of rice are annually produced and its residues, straw, husk, and bran are potential feedstock for the SIBR (PSA, 2019). The establishment of a SIBR is a novel work in the Philippines as there are limited studies on this research area and agricultural waste are yet to be utilized for bioenergy production in the country.
The design and synthesis of SIBR are challenging tasks and not straightforward as this will entail factors such as type of biomass, products to be generated, the capacity of process units, network topology, and cost

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parameters. Traditional mathematical programming approaches are usually employed to deal with this process network synthesis (PNS) problem. The P-graph method which was developed by Friedler et al. (1992), has been used to solve various PNS problems given the versatility of this approach. Its extended applications were outlined in Friedler et al. (2019). Recent works on the application of P-graph to design various systems include, but not limited to, solid waste management (Fan et al., 2020), oil supply chains (Wang et al., 2020), and biohydrogen network (Lee et al., 2020). Various efforts have been committed to extending P-graph framework into multi-objective optimization, e.g., TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) (Lim et al., 2021), weighted-sum approach (Lam et al., 2017), and fuzzy optimization (Aviso and Tan, 2018).
VIKOR (VIsekriterijumska Optimizacija I Kompromisno Resenje) is one of the widely applied multi-criteria decision-making (MCDM) methods where the optimality of each alternative is measured based on the measure of "closeness" to the "ideal" solution (Opricovic, 1998). In general, VIKOR stands out from the other MCDMs since it derives the ranking order of each alternative by maximizing the group utility of the majority (i.e., the weighted summed satisfaction) and minimizing the individual regrets (i.e., level of dissatisfactory of each goal) (Suh et al., 2019). Its capability has been proven *via* various applications, e.g., debottlenecking strategies selection in oil refinery (Teng et al., 2020), and eco-industrial park configuration evaluation (Teh et al., 2021). To the best of the authors' knowledge, none of the previous works has attempted to incorporate VIKOR calculation into the P-graph framework.
In this work, a novel VIKOR - P-graph method was developed to optimally synthesize a rice-based sustainable integrated biorefinery. The hybrid and simultaneous approach utilized the decision-making capabilities of VIKOR and the efficient algorithms of the P-graph to achieve the economic and environmental goals of the SIBR.

2. Problem Statement

Given a set of biomass-processing units *t* which can be used to convert rice husk and rice straw into a set of valuable products *p*. Suppose the material unit prices, the conversion rate, power consumption and carbon emissions of each processing unit are known, an optimal rice-based SIBR is determined with the consideration of both economic (i.e., total annual profit) and environmental (i.e., total emissions) benefits (indicators are denoted as *i*). The list of feasible configurations of rice-based SIBR is denoted as *j*.

3. P-graph construction

This section demonstrates how VIKOR can be represented in the P-graph framework.

3.1 Normalization

The values of each indicator are usually expressed on a different scale. Therefore, in order to enable a fair comparison between these indicators, data normalization is performed. The original data x_{ij} can be normalized to y_{ij} via max-min aggregation method, where ${x_{ij}}^{best}$ and ${x_{ij}}^{worst}$ refer to the best and the worst obtained value of x_{ij}. As shown in Figure 1, the P-graph model is constructed differently depending on the type of the indicators (benefit indicator or cost indicator). Following the red arrow, one can convert the original data to weighted normalized data. For detailed description of this step, please refer to Aviso and Tan (2018).

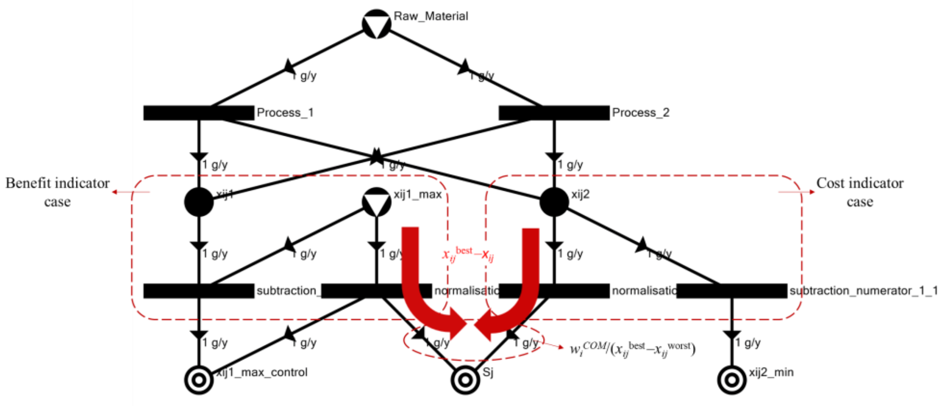

Figure 1: P-graph representation for normalization and determination of S_j (red fonts indicates the flow magnitude for the arrows)

3.2 Determination of S_j

In VIKOR, the value of S_j is minimized to ensure the obtained solution is with maximum group utility. It can be determined by summing up all the weighted-normalized values as shown in Eq(1):

$$S_j = \sum_i w_i \frac{x_{ij}^{best} - x_{ij}}{x_{ij}^{best} - x_{ij}^{worst}} = \sum_i S_{i,j} \qquad \forall j \in J \tag{1}$$

where w_i refers to the weightage assigned to each indicator. It can be determined through numerous approaches (e.g., analytical hierarchy process (AHP) (Saaty, 1980)). For this work, the indicators are assumed to be equally important. Note that Eq(1) has also been modelled in Figure 1. As shown the input and output ratio across the "normalization" nodes is set as 1: $\frac{w_i^{COM}}{x_{ij}^{max} - x_{ij}^{min}}$. Since the input is equal to $x_{ij}^{best} - x_{ij}$, the output will therefore be $w_i \frac{x_{ij}^{best} - x_{ij}}{x_{ij}^{best} - x_{ij}^{worst}}$ (or $S_{i,j}$). Finally, the summed value is denoted as S_j.

3.3 Determination of R_j

R_j is the counterpart of S_j which is minimised in VIKOR to ensure the obtained solution is with minimal individual regrets. It is defined in Eq(2). Figure 2 demonstrates how such "MAX function" can be represented in P-graph model. This is the first attempt of using P-graph to model "MAX function".

$$R_j = Max^{i \in I} \left\{ w_i \frac{x_{ij}^{best} - x_{ij}}{x_{ij}^{best} - x_{ij}^{worst}} \right\} = Max^{i \in I} \{S_{i,j}\} \qquad \forall j \in J \tag{2}$$

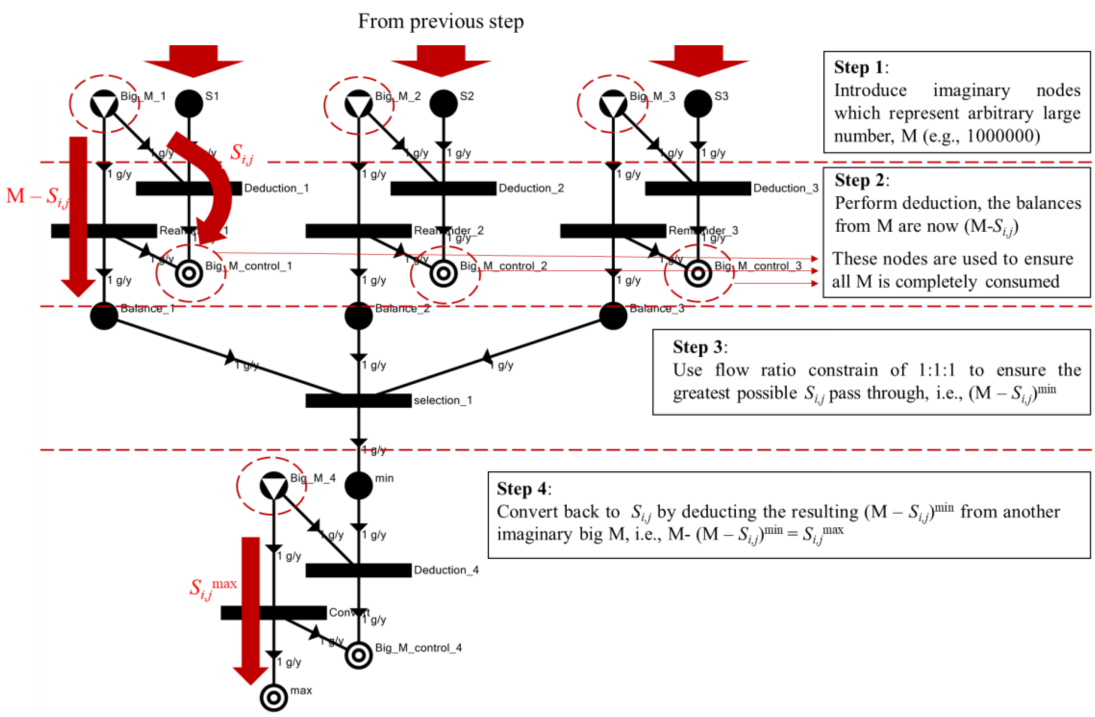

Figure 2: P-graph representation for determination of R_j (red fonts indicates the flow magnitude for the arrows)

In the first two steps, an arbitrarily large number, "M" is introduced, such that the resulting product will be $M - S_{i,j}$. Then, the remainders are "mixed" with an input flow ratio of 1:1:1 and an output ratio of 1. As a result, the minimum value among the remainders will therefore become the maximum possible value for the output. Finally, to convert back to its original form $((S_{i,j})^{max})$, the same arbitrary large number is subtracted from the resulting number $(M - (M - S_{i,j})^{min})$. Note that the M-vertex which is labelled as "max", represents the value of R_j.

3.4 Ranking of alternatives

Conventionally, the objective function for VIKOR method is expressed as Eq(3), where the superscriptions of "max" and "min" indicate its upper and lower limits respectively. It integrates both S_j and R_j by using a pre-defined constant, v (takes as 0.5 in this work) which represents the weight of strategy of maximum group utility

(Shemshadi et al., 2011). In this VIKOR - P-graph method, a reversed function, Q'_j is used instead (Eq(4)). With this expression, alternative with larger Q'_j is more preferable. By assigning a unit price (e.g., 1 \$/t) to the Q'_j, the model will rank all the alternative according to the Q'_j value (Figure 3).

$$Q_j = v\frac{S_j - S_j{}^{min}}{S_j{}^{max} - S_j{}^{min}} + (1 - v)\ \frac{R_j - R_j{}^{min}}{R_j{}^{max} - R_j{}^{min}} \qquad \forall j \in J \tag{3}$$

$$Q'_j = v\frac{S_j{}^{max} - S_j}{S_j{}^{max} - S_j{}^{min}} + (1 - v)\ \frac{R_j{}^{max} - R_j}{R_j{}^{max} - R_j{}^{min}} \qquad \forall j \in J \tag{4}$$

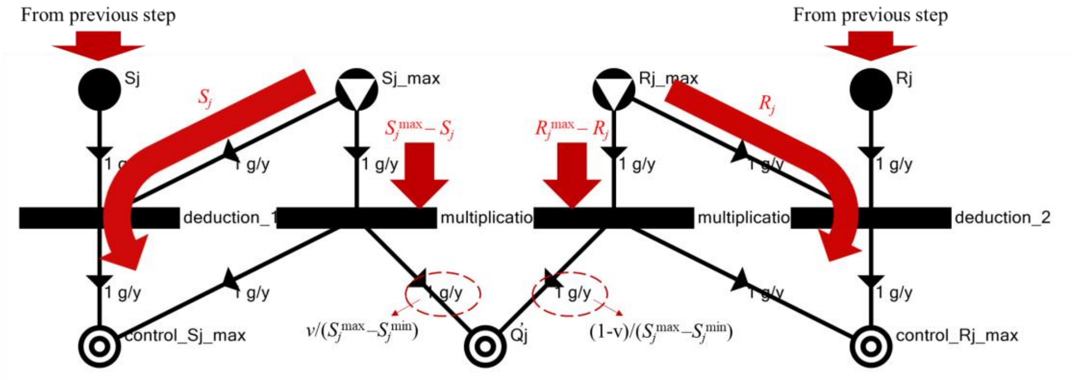

Figure 3: Ranking of alternative using Q'j (red fonts indicates the flow magnitude for the arrows)

4. Case study demonstration

In this hypothetical case study, three conversion units, i.e., fermentation, combustion and carbonization units are considered to convert rice straw (5.0 t/h) and rice husk (0.8 t/h) into valuable products (i.e., bioethanol, electricity, and solid fuel). Table 1 tabulates the process and material cost data for each considered unit; while the operating cost and fixed investment cost for each unit are shown in Table 2. Note that the electricity generated from combustion unit can be sold to the grid (0.1458 USD/kWh) or supplied to other units. In addition, the power requirement can also be supplied by the imported electricity (assumed import prize as 0.176 \$/kWh with 0.000691 tCO_2-eq CO_2/kWh of emissions (Climate Transparency Report 2020)).

Table 1: Process input-output data of each conversion unit and respective material costs

Material	Fermentation	Combustion	Carbonization	Cost (\$/unit)
Bioethanol (L/h)	1.0000	0.0000	0.0000	1.1861 L^{-1}
Solid fuel (kW)	0.0000	0.0000	1.0000	0.065 kWh^{-1}
Electricity (kW)	-1.6074	1.0000	-0.7380	0.1458 kWh^{-1}
Rice straw (t/h)	-0.0036	-0.0019	0.0000	27.5 t^{-1}
Rice husk (t/h)	0.0000	0.0000	-0.00043	37.5 t^{-1}
Emission (tCO_2-eq/unit)	0.0030 L^{-1}	0.000067 kWh^{-1}	0.00045 kWh^{-1}	-
References	Sreekumar et al. (2020)	Unrean et al. (2018)	Aberilla et al. (2019)	Market data

Table 2: Operational and investment cost for each conversion unit

Cost	Fermentation	Combustion	Carbonization
Fixed investment cost (\$/h)	157.92	168.45	278.27
Operating cost (\$/unit)	0.3987 L^{-1}	0.0050 kWh^{-1}	0.0468 kWh^{-1}
References	Tefwik et al. (2015)	Unrean et al. (2018)	IRENA (2012)

The constructed VIKOR – P-graph model is presented in Figure 4. The model generated seven feasible configurations for the proposed case study (Table 3). Carbonization unit was not selected in any of the generated solutions. This is mainly due to the high investment cost which causes it to be economically-infeasible. It is worth noting the best solution at 1st rank is neither the solutions with the highest profit (ranked 5th at 405.271 \$/h) nor the lowest carbon emission (ranked 4th at 0.176 tCO_2-eq/h). This was due to the fact that the counter-part consideration in those solutions is the worst-case scenario, highest carbon emission at 5.709 tCO_2-eq/h and lowest profit at 0.000 $/h respectively. In contrast, the optimal solution suggested to partially consume the rice straw in both combustion unit (~30 % of the total feed) and fermentation unit (~70 % of the total feed). With this configuration, compromised sustainability performance in terms of both economic and environmental aspects can, therefore, be obtained (emissions reduced about 40 % with a reasonable profit margin). The results also reveal that having a mixed power supply is more favourable than having only combustion unit as the sole power supply despite that the cost of imported power is higher. This is due to the economic-competitiveness nature of a limited resource system, where the balanced amount of biomass should be used to generate power for local consumption and to be utilized in a more profitable process for bioethanol production.

Table 3: Solutions generated from P-graph model

Rank	Bioethanol (L/h)	Solid fuel (kW)	Import Power (kW)	Generated Power to recycle (kW)	Generated Power to be sold (kW)	Profit ($/h)	CO_2 (tCO_2-eq/h)	Q'
1st	972.179	0.000	773.124	789.556	0.000	161.606	3.504	1.11
2nd	751.421	0.000	0.000	1,207.83	0.000	121.76	2.335	0.99
3rd	941.753	0.000	1,513.77	0.000	847.205	130.529	3.928	0.92
4th	0.000	0.000	0.000	0.000	2,631.58	64.5763	0.176	0.87
5th	1,388.89	0.000	2,232.5	0.000	0.000	405.271	5.709	0.53
6th	326.078	0.000	0.000	524.137	1,489.61	0.000	1.113	0.46
7th	392.665	0.000	631.169	0.000	1,887.58	0.000	1.741	0.38

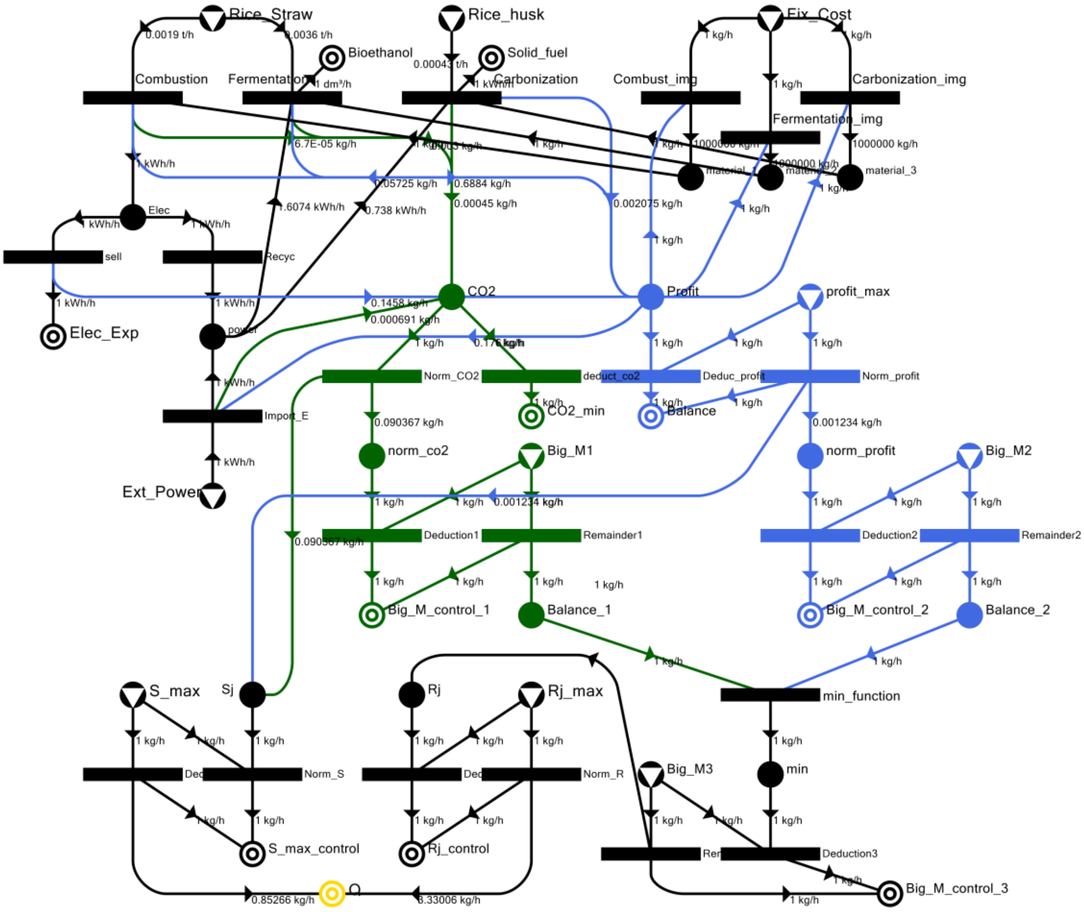

Figure 4: Representation of VIKOR - P-graph model for rice-based SIBR synthesis

5. Conclusions

A novel VIKOR – P-graph framework that can simultaneously yield feasible solutions and rank them based on VIKOR calculation, has been proposed in this work. In other words, one does not need to pre-determine a list of feasible solutions prior to the VIKOR optimization, which therefore can avoid the reliability issues of sequential model. In this work, the effectiveness of the proposed VIKOR – P-graph model is demonstrated using a rice-based SIBR case study. Overall, the model is proven capable of generating optimal compromised solution (not over-prioritizing any objective) where both economic and environmental goals are considered. A SIBR that encompasses fermentation and combustion technologies (which offers a profit of 161.6 $/h and emissions rate of 3.504 tCO_2-eq/h) has been synthesized. Future works include (i) extending the model in a complex system or other scale and (ii) incorporating grey relational analysis (GRA) with the current VIKOR – P-graph framework; this is to have better estimation of the closeness between each feasible solution with the ideal solution.

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